EXTENDING CLOUD-BASED APPLICATIONS IN CHALLENGED ENVIRONMENTS WITH MOBILE OPPORTUNISTIC NETWORKS

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Abstract

With the tremendous growth of mobile devices, e.g, smartphones, tablets and PDAs in recent years, users 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. Essentially applications require 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 mobile opportunistic networks may be extended to avail cloud-based applications to the user.

In this thesis we explore the emergence of extending cloud-based applications with mobile opportunistic networks in challenged environments and observe how local user's social interactions and collaborations help to improve the overall message delivery performance in the network. With real-world trace-driven simulations, we compare and contrast the different user's behaviours in message forwarding, the impact of the various network loads (e.g., number of messages) along with the long-sized messages and the impact of different wireless networking technologies, in various opportunistic routing protocols in a challenged environment.

Acknowledgements

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I would like to express my eternal gratitude to my parents, my brother and my sister for their everlasting love and support.

Declaration

Candidate's Declarations

I, Shantanu Pal, hereby certify that this thesis, which is approximately 40,000 words in length, has been written by me, that it is the record of work carried out by me and that it has not been submitted in any previous application for a higher degree.

I was admitted as a research student and as a candidate for the degree of Master of Philosophy in 2012; the higher study for which this is a record was carried out in the University of St Andrews between 2012 and 2015.

Date:

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To my late grandparents …

"If we knew what it was we were doing,
it would not be called research, would it?"
– Albert Einstein

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Chapter 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 with users due to the greater proximity/access to data according to the user's specific interests [1]. In addition, the rise of cloud-based applications have significantly enhanced the computing resources (e.g., processing and storage) to the resource-constrained mobile devices using an available Internet connection [2]. 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 [3] 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' [4] 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. The 'cloud' can be viewed as an unlimited resource pool e.g., infrastructure, storage, applications, networks, etc., that are all connected to the users' com-

[1] https://www.ibm.com/developerworks/cloud/library/cl-mobilecloudcomputing/
[2] https://www.google.com/

puters (via desktop or smart mobile devices), enabling ubiquitous, on-demand access to those resources (cf. Fig. 1.1). This can also be considered as *"a type of parallel and distributed system consisting of a collection of interconnected and virtualised computers that are dynamically provisioned and presented as one or more unified computing resources based on service-level agreements"* [5].

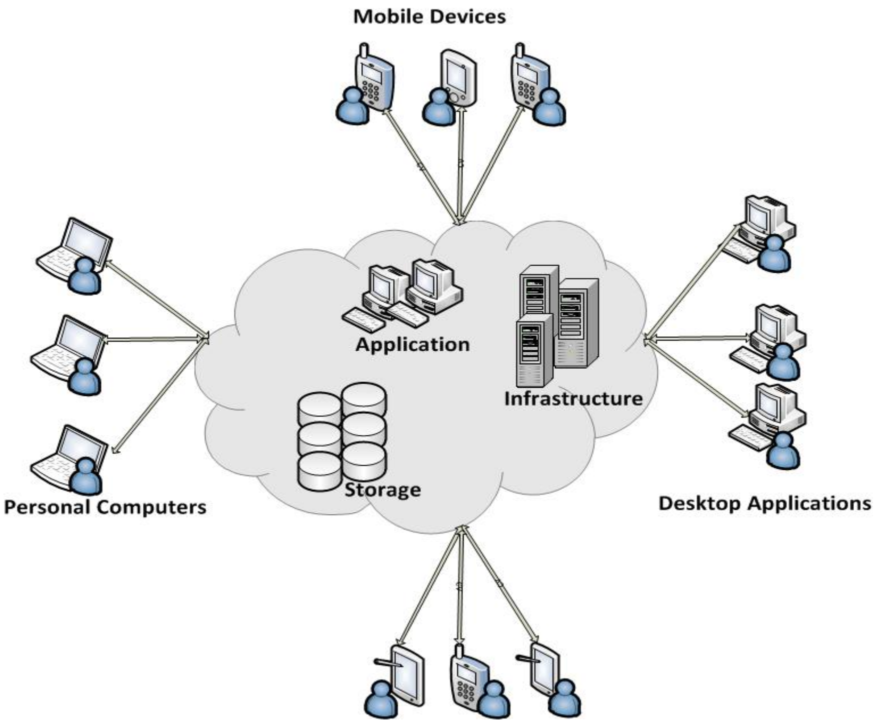

Figure 1.1: The cloud computing architecture is where the users can avail themselves access to the ubiquitous, on-demand virtual computing resources (e.g., infrastructure, storage or applications) via an available Internet connection by using their personal computers or smart mobile devices.

In this thesis, we use three terminologies for describing the tiers on cloud-based architectures, namely *edge clouds* [6], *cloudlets* [7] and *infrastructure clouds* (that by default are designated simply as 'clouds') [8]. Edge clouds can be viewed as, but not limited to, crowdsourcing of mobile devices that cooperate towards providing computation, storage and connectivity. Cloudlets, in turn, are considered to have an utility-like functionality that provides latency sensitive computation, increased 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 uses 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) [9] and second, applications are executed in the real cloud (e.g., Amazon Elastic Cloud Computing (EC2)[3]). 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 [10]. 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 instance, in places where tourists try to avoid a high network access cost). In such situations one major concern is how to gain access to a cloud-based application instead of relying on a fixed infrastructure for communication or suppressed the network unavailability. For instance, users (e.g., a tourist) who do not wish to pay a high Internet roaming charge.

[3]http://aws.amazon.com/ec2/

1.1 Motivation

To explore the motivation of our research we discuss two use case scenarios:

(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[4]). 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 an online account or allow him additional mobile storage so that he can store extra photos there temporarily.

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[5]) 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

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

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 [11] [12] 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. The term 'local user' is a reference to the local people who live near to the current user.

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 [13]. 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 their dynamic and unpredictable behaviours [14]. Also, single points of failure make significant impacts onto 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 [15]. Users store and manage information themselves with the help of their mobile devices and do 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 connection [16]. 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) [17] and Mobile Social Networks (MSNs) [18] 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 peers who share similar interests, activities and backgrounds in real-life connections. 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 [19].

Mobile users however, have been somewhat restricted in the virtual communities of OSNs and many are unaware of the social opportunities available to them [20]. 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 [21] [22]. When the networks grow, more devices with different platforms as well as different application models join in the network. 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)[6] is unable to communicate with the other users who are using a Universal Plug and Play (UPnP)[7] based application.

Therefore, there is a need to develop a platform independent, collaborative mobile cloud application which can adopt the heterogeneity of the

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

networks, applications and devices in a challenged environment. To this end, we envision a more comprehensive and collaborative mobile cloud platform which can deliver a seamless access to cloud-based services with the help of locally available mobile networks.

In such cases the use of a ***mobile opportunistic network*** [23] may help to improve the availability and accessibility of information using co-located users to relay information instead of relying on a fixed infrastructure for communication. Nodes (users in a real-life) in a mobile opportunistic network communicate with each other with the help of other nodes. Human interaction is one of the major parts of such communication as the opportunity of forwarding any message depends on their nature and behaviour of the interaction [24].

In this thesis, we address the following research questions:

- Research Question 1: Is it possible to use a mobile opportunistic network to provide cloud-based services to the user (e.g., a tourist) in a challenged environment that lacks access to network infrastructure?

- Research Question 2: Do the user's mobility and their social interactions help to improve the availability and accessibility of information in a challenged environment?

1.2 Thesis Statement

We make the following thesis statement:

Mobile opportunistic networks can be used to gain access to cloud-based applications in a challenged environment with the help of a user's social collaborations and interactions, instead of relying on a fixed infrastructure for communication.

To support of our thesis statement, we make three contributions. We demonstrate that:

- Using mobile opportunistic networks, local users' mobile networks succeed at integrating tourists' and cloud networks successfully to build an integrated mobile opportunistic cloud-based platform, which can be used to send tourists' information efficiently. We used real-world trace-driven simulations to evaluate two options: storing data at well-situated hubs versus exploiting the mobility of local users, and demonstrated that the latter improves message delivery performance (cf. Chapter 5).

- Mobile opportunistic networks can improve the overall message delivery performance using user's mobility, their interactions and social collaborations even with higher message generation rates and increased message sizes. Our experimental results showed that, the user's active participations and willingness for forwarding messages improves the message delivery performance in a challenged environment (cf. Chapter 6).

- In a challenged environment, a higher communication range can improve the overall message delivery performance but when communicating at a shorter range, users' interactions and social collaborations can make a significant impact on data forwarding. We examined how different wireless networking technologies affect the message forwarding performance within the network. Using Bluetooth and Wi-Fi technologies, we demonstrated that the users' interactions and social collaborations make a significant impact on message forwarding in a shorter communication range (cf. Chapter 7).

1.3 Thesis Outline

This thesis is structured as follows.

- In Chapter 2, we introduce the background of our research. This includes the evolution of mobile opportunistic networks and the fundamentals of mobile ad hoc networks and delay tolerant networking technologies. We indicate the emergence of extending cloud-based application with mobile opportunistic networks in challenged environments.

- In Chapter 3, we present the state of the art research in this field. This includes a detailed up to date survey of the research papers in this field. We discuss the mobile cloud technology, its applications and we then classify the different mobile cloud architectures based on their mode of use, the way they deliver services. Next we discuss the potential for integrating mobile cloud technology with mobile opportunistic networks.

- In Chapter 4, we introduced a new Mobile-Opportunistic Collaborative Cloud (MoCC) architecture for extending mobile cloud platforms using mobile opportunistic networks in challenged environments. The MoCC consists of two different technologies, which are then combined into a single one. These are mobile cloud technology and mobile opportunistic networking technology, by using local users' mobile networks. We also explore the many limitations and challenges in such communications.

- In Chapter 5, we explore different modes of user behaviour for message transferring using mobile opportunistic networks. We examined that, the local users' mobile networks succeed at integrating tourists' and cloud networks successfully to build an integrated mobile opportunistic cloud-based platform, which can be used to send tourists' information efficiently in a challenged environment.

- In Chapter 6, we compare and contrast the impact of the message generation rates and the message size in different opportunistic routing protocols in a challenged environment to determine their performance impact.

- In Chapter 7, we examine how different wireless networking technologies affect the network performance while forwarding messages using mobile opportunistic networks.

- Finally, in Chapter 8, we present our concluding remarks. In this, we summarise the findings, outcomes and limitations of the proposed research as well as outline future research directions.

• **Publications:** While I used the second form of "we" extensively, this thesis has been written entirely by me. I have been primarily responsible for all of the core contributions in the experimental designs, implementation and their analysis of the thesis work. However, I sincerely acknowledge my co-authors to the following publications.

- S. Pal and T. Henderson, "MobOcloud: Extending cloud computing with mobile opportunistic networks," in Proceedings of the 8th ACM MobiCom Workshop on Challenged Networks, ser. CHANTS'13. Miami, Florida, USA: ACM, 2013, pp. 57-62. [Online]. Available: http://doi.acm.org/10.1145/2505494.2505503

Chapter 2

Background

In this chapter we present the background of the research. In the beginning we discuss the evolution of mobile opportunistic networks. Then we discuss the message forwarding in challenged environments that lack an available infrastructure for communication (e.g., rural or sparse areas) or areas with an infrastructure where the network connection is not as accessible (e.g., restricted/full of interference access networks or a high cost roaming zone). Finally we present various routing protocols in mobile opportunistic networks.

2.1 The Evolution of Mobile Opportunistic Networks

There is now one mobile phone for every two people in the world [25]. As such phones become more powerful and sophisticated, users have started to use their phones as personal information processing tools rather than simply for making phone calls. But one large constraint for the mobile cloud is the requirement for Internet connectivity. Commonly, the connectivity between these devices requires a fixed infrastructure of wireless networks (e.g., cellular radio towers or fixed access points). This is a concern in challenged environments where there is limited network availability, but also in areas with network connectivity where the cost of accessing the Internet is simply too high. In such cases it is possible to use mobile devices for communicating directly with one another to improve the availability and accessibility of information using co-located user's to relay information instead of relying on fixed infrastructure for communication [26]. In this section we explore such communications opportunities in scenarios that may not require an infrastructure networks (e.g., mobile ad hoc networking [27]) or an end-to-end connectivity may never be available (e.g., delay tolerant networking [28]).

2.1.1 Mobile Ad Hoc Networks

Mobile Ad Hoc Networks (MANETs) are infrastructure-less, self configuring wireless networks that are formed by the mobile devices without any external interventions. In such networks an end-to-end communication path must exist between the nodes for delivering messages from source to destination. In MANETs, nodes are highly dynamic and random i.e., they move frequently within the networks and change directions often. It is therefore difficult to predict a node's location at any certain time. Message forwarding must take two nodes connected with each other in a physical proximity for sharing information with one another with the same physical layer wireless protocol [29].

Communications over MANETs rely upon the wireless links present in the network, which have a lower capacity of bandwidth utilisation than that of the traditional wire-based communications. It also experiences higher delays and loss rates.

Routing in MANETs are challenging due to the node's arbitrary movements [30]. Routings can be categorised into two classes, they are: *topology-based routing* and *position-based routing* [31]. In the former case (i.e., topology-based routing), nodes forward packets using link-information available within the network. In the latter case (i.e., position-based routing), nodes use additional information for packet forwarding. This may include a node's physical position which can be obtained through a Global Positioning System (GPS) [32].

The topology-based routing can further be divided into three approaches. They are *proactive*, *reactive*, and *hybrid*. The proactive approach uses traditional routing strategies e.g., Destination-Sequenced Distance-Vector (DSDV) routing [33], Optimised Link State Routing (OLSR) Protocol [34]. In DSDV, each mobile node maintains a routing table that lists all the available destinations and updates the table when new information becomes available. The table contains information (e.g., node's IP address, hop count to reach that node) of all the nodes that a node knows directly or through its neighbour. Nodes use broadcasting or multicasting for updating tables when network topology changes. In the OLSR routing protocol, a node generates a regular *Hello* message to discover its immediate neighbours. This is achieved by received replies from their neighbors. In this way a source node can find neighbours located up to two hops away (using the shortest hop forwarding paths). This routing is helpful when constructing a view of global network topology, while keeping the view of optimal routing paths to each neighbouring nodes available locally. The fundamentals of this protocol is that is uses multipoint relays (MPRs), which reduces the message overhead by forwarding broadcast messages during the message flooding process. This routing is appropriate for use in dense and large ad hoc networks.

In the proactive approach, nodes maintain information of the available paths in the network, even the paths that are not currently used. This in turn consumes unnecessary bandwidth of communication. To address such limitations, reactive routing provides an alternative approach. In this type of routing nodes use communication paths that are currently in use. An example of this routing is Ad-hoc On-Demand Distance Vector (AODV) routing [35]. In AODV, a node transmits topological information to other nodes only on demand. When a node transmits traffic to another node, it floods the network with a route request message. The destination is considered to be found if the route request message directly reaches the destination node or to an intermediate node that has a reasonable route entry to the destination node. However, when a route becomes removed or lost, the AODV again generates a new request for the node. This approach however, causes an unnecessary delay in packet forwarding due to the route discovery between the source and destination for message forwarding for the first data packet.

Finally, the hybrid approach leads to an efficient and scalable routing by combining the proactive and reactive approaches. An example of this routing is Zone Routing Protocol (ZRP) [36]. In ZRP, if the packet destination is the same zone as where it originated then, when employing a proactive routing approach, nodes immediately transmit the packets using the available routing table. On the other hand, if the packet destination is outside its originating zone, then the node uses a reactive routing approach to search each neighbouring zone in the route to see if the destination is within that zone. This in turn improves the communication delays within a zone by speeding up the route discovery process.

2.1.2 Delay Tolerant Networks

Delay Tolerant Networks (DTN) are the communications approach in heterogeneous wireless ad hoc network architectures, which help communications in the absence of a continuous network connection. These types of networks are also known as disruption tolerant networks, which leverage communications in 'occasionally-connected' networks that may suffer from infrequent or poor network connections [37]. The fundamental concept of DTN emerges from Inter-Planetary Networks (IPN) [38], which is introduced for communicating between spacecrafts, where communications are greatly delayed due to the vast distance between the Earth and the crafts. In DTN, for a certain period of time in communication, an end-to-end communication path is available between the nodes within the network. However, the end-to-end loss rate is relatively small. This also generates a high delay for communication.

Nodes in DTN have the least knowledge about the networking scenario. Communications in DTN use the store and forward paradigm between the nodes with the absence of a fixed communication infrastructure. A node stores messages and forwards them until it encounters a sporadic contact with another node within the network [26]. An advantage of DTN over MANETs is that, it assures data delivery even in limited network knowledge and high intermittent connectivity.

DTN is practical to use in places where continuous end-to-end connectivity cannot be assumed [39]. For instance, communication to a spacecraft or on an interplanetary scale, military communications networks or even in disaster areas. This may also include areas where the present Internet protocols do not work well (e.g., in rural or sparse areas without a network infrastructure but also in areas with infrastructure with full/restricted interference access networks). Consequently, the connectivity in these places suffer due to the network unavailability.

Routing in DTN can be done in two ways, one is *flooding* and the other is *forwarding* [40]. Both of these routings follow a hop-by-hop communication technique. Nodes select the next hop dynamically, based on the application specific scenario and the employed algorithms. In flooding, a node replicates multiple copies of the same message (to newly-encountered nodes) until the message reaches its destination. This routing focuses on the fact that, there is a good chance of bringing the source to the destination, so that the destination could receive it. On the other hand, in forwarding, nodes have some relevant knowledge about the other nodes within the network and select the best possible path to send messages to the destinations. Unlike the flooding, in forwarding, nodes do not replicate messages for the other nodes.

In DTN, there are a few sporadic links between the nodes. However, the challenge is that when the connection disruption is more obvious between the nodes and all links are sporadic in a network, the use of DTN may not be appropriate. This premise requires the need for mobile opportunistic networks.

2.1.3 Mobile Opportunistic Networks

Mobile opportunistic networks are one kind of MANETs that support the characteristics of DTN. 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 network are fully depends upon the users' interactions, mobility patterns and their willingness in message exchange [41]. The user's mobility patterns are crucial in this kind of communication, since it helps to spread information with user's movements within the network and thereby improve the scope of message delivery. However, such mobility is considered challenging due to the sporadic contact of the users and their unpredictable behaviour [42]. Moreover, these contact opportunities for message forwarding are infrequent in challenged environments.

Nodes in such networks act as the receiver and sender to store, carry and forward messages to the next hope when they are on-the-fly. Unlike the traditional well established network communications, it does not assume the existence of an end-to-end route between the source and the destination nodes [43]. Further, it is possible that the destination node might not even be present within a network when the message is sent (cf. Fig. 2.1).

As illustrated in Fig. 2.1, *node A* (located in area A) wants to send a message to another node, *node E*. *Node E* is located in area B when *node A* sends the message. The message forwarding decisions in mobile opportunistic networks are taken based on locally available information and contact opportunities between the nodes located at a reasonably close distance. Thus,

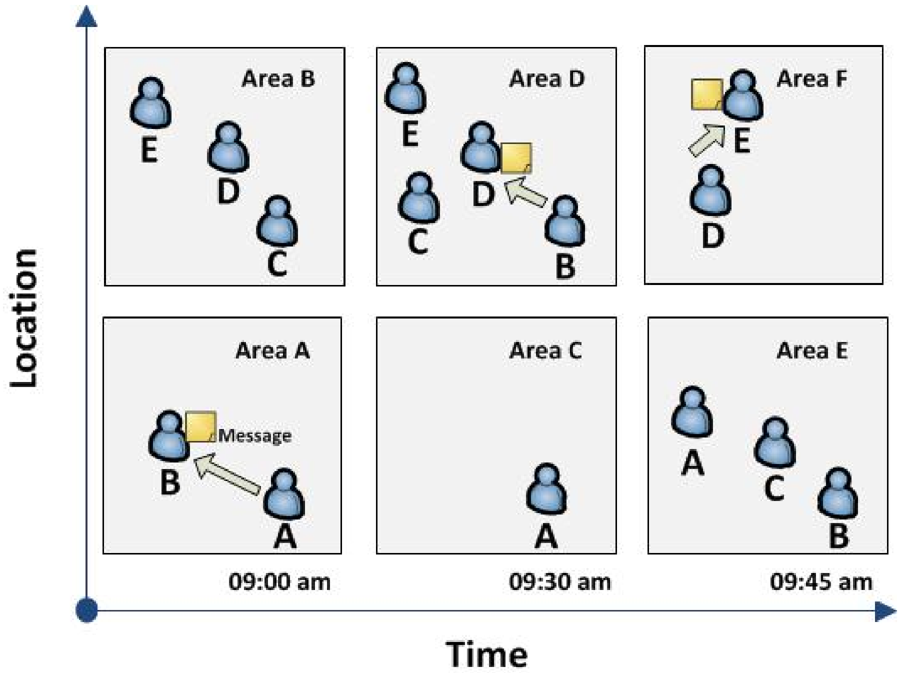

Figure 2.1: Message forwarding with mobile opportunistic networks. In this, nodes forward messages based on the store, carry and forward paradigm to other nodes in a physical proximity when the messages are on-the-fly.

node A forwards this message to another *node B*, located in the same area as *node A*. The typical communication techniques are either Bluetooth or Wi-Fi communications. After a certain period of time, *node B* reaches the area D and forwards the carried message to another *node D*. Depending upon the contact opportunities, the message is then moved closer to its destination, *node E* which has already moved to area F. Then the message is delivered by *node D* to *node E*. This is to note that, when the message finally reaches its destination *node E*, due to the nodes' high mobility, both the source (*node A*) and destination (*node E*) nodes moved from their initial locations.

However, 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. On the other hand, in a social perspective, a user's unpredictable behaviour is a common issue which can degrade the performance of the network through altruism [44]. For instance, users who do not wish to take an active participation in an opportunistic communication and thereby do not forward data packets or a selfish user (i.e., a unhelpful user), who takes an active participation but drops/delays packets that may have a high priority [45]. We further discuss these issues with their possible countermeasures in Chapter 8.2.

2.2 Message Forwarding in Challenged Environments

In this section we present the context from the two points of view related to a challenged environment. One area is without an available network infrastructure and the other has a limited/full network infrastructure for communication or even high network access costs. We further relate these issues to our research motivation for message forwarding in challenged environments.

As illustrated in the motivation (cf. Section 1.1), Bob and Ron require a continuous Internet connection for gaining advantage of the cloud-based applications in a challenged environment. In a challenged environment network infrastructures (i.e. sporadic connectivity etc.) are particularly problematic for cloud-applications, as it requires a continuous Internet connection for communication. This is more likely to occur in places without a network infrastructure or in places where a network infrastructure is available but the access cost is simply too high for the users. Moreover, the current Internet architecture does not support communications in challenged environments that are characterized by high network delays, where frequent network partitions are more obvious. Therefore, the application of pervasive wireless communications between mobile devices and a direct communication to the cloud applications (where available) can be considered as beneficial in terms of data forwarding in such challenged environments.

Most of the recent research advances in this field focus on the more efficient routing protocols for delivering packets with higher delivery performance in these highly dynamic mobile opportunistic networks [46]. For instance, Moon et al. present an architecture for delivering packets by searching possible communication paths using a DTN-based routing mechanism when an end-to-end communication path does not exists [47].

Similar to the Moon et al. architecture, Joe and Kim present an evolution-performance for DTN in a challenged environment [48]. This challenged environment is referenced in an earthquake situation in a city. Using a 'DTN message priority routing', a simulation-based study has been performed in this paper. The authors compare and contrast the routing performance during the disaster time with the normal scenario. In the message communication, a threshold value (i.e., high, medium and low) is used to determine the priority to meet the next node. For each encounter, each node updates their latest meeting time to determine a node's contact histories with the other nodes. For instance, if the meeting time of a node with the destination node is high then it is assumed that the current node is away from the destination node. On the opposite line, if this time difference is very low, it is assumed that this node contacted the destination node recently. This encounter time is referred to as the 'Latest Encounter Time' (LET). This paper shows a routing protocol that is able to provide an efficient message delivery during the disaster situations. This routing protocol is designed to deliver a message with high delivery probability (i.e., low LET value) in the network. But unlike our motivation (cf. Chapter 6), how the network loads and message size make an impact on the routing protocols in such challenged environments is missing in both ([47] and [48]) of the papers.

Ali et al. present a real-time analysis of opportunistic networks in the context of disaster scenarios which includes earthquakes, tsunamis, floods, and storms [49]. A network architecture has been designed that integrates the available network infrastructure and cloud-assisted information processing technology during an intermittent connectivity. The proposed architecture aims to design high bandwidth utilisation for message communication in disaster situations between the victims, by developing a stable broadcasting infrastructure (e.g., radio and wireless system) within a shorter time.

In addition, this architecture overcomes the traffic congestion problem during a disaster by using cloud-assisted information processing techniques. While this architecture addresses the availability and accessibility of a network infrastructure during the disaster, it does not provide the impact of network loads, long-sized messages and different wireless communication techniques over the network (cf. Chapter 6 and Chapter 7). Our present research, finds this specific gap and attempts to address this issue in a challenged environment.

On the other hand, in some cases the *available network communication may be found* but from the accessibility point of view, it is not so convenient to use (e.g., places with high roaming costs). In such cases, proposals [50] [51] [52] [53] based on the locally available infrastructure for communication may help to avail information within a shorter range which may be affected with the user's behaviours and network bandwidth (cf. Chapter 5).

Hung et al. define 'smart cities' architecture, where tourists are able to find cloud-based applications with the help of the nearby user's mobile networks [54]. However, this architecture requires a continuous Internet connection to gain the advantages of such cloud-based applications. Unlike our motivation, this architecture lacks the motivation of using a locally available network connection for gaining access to such applications when there is an absence of an Internet connection (cf. Chapter 4). In addition, Canepa et al. present an architecture to provide information to the tourists through the locally available mobile networks [25]. In this communication, tourists rely upon the local user's mobile communications platforms for sharing information within their mobile communication range. But again, unlike our motivation, what is lacking in this literature is how a tourist gains access to a cloud-based application seamlessly by extending local user's mobile network communications (cf. Chapter 5) and how the architecture handles the increased network loads and varied message sizes (cf. Chapter 6).

Horvitz et al. present an 'opportunistic planning' model by identifying feasible plans and achieving goals for mobile users at the same time he/she is performing other activities [55]. For instance, a user is visiting a town and this 'opportunistic planning' helps him/her to locate the nearest food stores or sightseeing places in this town. The fundamental of this model is to identify one or more goals flexibly adapting to opportunities to a user's trip for a specific destination (e.g., a shopping centre or tourist attraction) with a minimal cost by using the shortest path to the destination. A GPS-based system and a user's mobile device connects through a centralised client-server based system has been used for achieving these results [56].

Sakaguchi et al. further extend the prior 'opportunistic planning' model [55] for a 'tourism navigation system', which navigates tourists to the destination of their preference/choice [57]. This navigation system particularly recommends some 'photographic points' that are situated on the same route to the tourist's destination. Using the General Packet Radio Service (GPRS) [58] technology, this system recommends other nearby sightseeing places by calculating the user's available time for sightseeing or by calculating the time left to reach the destination. Unlike the motivation of our present studies (cf. Chapter 1.1), these two proposals ([55] and [57]) require a continuous Internet connection with the user's mobile devices which may be unavailable is rural places or seem impractical to use if a user is trying to avoid the high cost of Internet roaming.

Along a similar line, Rey-López et al. present a recommendation system for tourists, based on their profiles, interests, locations, schedules and the amount of time used for visiting a place [59]. Unlike the proposed Horvitz et al. model [55] and the Sakaguchi et al. system [57], this recommendation system works independently along with the user's ongoing route. But again this is controlled by a centralised system which requires a continuous Internet connection to establish communications with the user's mobile devices. Using Collaborative Filtering (CF) [60] techniques this system provides content-based recommendations to the users but unlike our proposal, this system does not focus on impact of different wireless communication technologies in the network (cf. Chapter 7).

In our research, we address the challenges (i.e., available network connection for communication, user's behaviour, increased network loads and long-sized messages and different wireless communication technologies) and find solutions where tourists can use mobile opportunistic networks to gain access to cloud-based applications in challenged environments. This in turn supports our research motivation in Chapter 1.1. Returning to the use cases of Bob and Ron, local users who may be interested in sharing information by using their mobile networks with Bob who lacks an Internet connection or with Ron who is trying to avoid the high cost of Internet roaming.

2.3 Routing Techniques

Routing in mobile opportunistic networks is crucial for delivering messages from one node to another. The routers between the nodes create paths dynamically and adjust accordingly when the opportunity arises to bring the messages closer to their intended destinations. The routing decision is taken locally during runtime by the nodes exploiting the ubiquitous wireless communication capabilities of smart mobile devices [61].

Based on the user's behaviour, routing can be made in two ways [62] 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* (e.g., epidemic routing [63]), *single-copy* (e.g., DirectDelivery routing [64]), *simple replication* (e.g., spray and wait routing [65]), *history-based encounters* (e.g., prophet routing [66]) and *prioritisation* (e.g., MaxProp routing [67]).

- **Epidemic Routing:** In the epidemic routing, 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 node buffer constraint.

- **DirectDelivery Routing:** In the DirectDelivery routing, a node generates only one copy of the message during transmission (to avoid flooding in the network) and the node waits until the message reaches it's final destination.

- **Spray and Wait Routing:** In the spray and wait routing, 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 within the network.

- **Prophet Routing:** In prophet routing, 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 encounters occurring between the nodes. The Prophet considers the frequency of the past contacts to maximise the forwarding opportunity to the destination. However, it restricts the communication for sending message to the nodes that have frequent contacts with the destination node. Unlike the Epidemic router, the Prophet router does not replicate the same message to every newly-encountered node. It uses a delivery predictability which is a 'probabilistic metric' for message delivery. This delivery predictability indicates a new node's likelihood to encounter the destination node, based on its previous encounters with the destination node to deliver a message.

- **MaxProp Routing:** In the MaxProp routing, for every new encounter, a router always checks the greater probability of interactions with the newly-encountered node by higher delivery likelihood values. The MaxProp is a history-based routing protocol where each node keeps track of the previous encounters and determines the future message delivery with a higher probability that the message reaches closer to the destination. For the future communication, this routing keeps track of the nodes that have a higher probability to reach nearer to the destination.

2.4 Summary

In this chapter we have discussed the need for mobile opportunistic networking for communication in challenged environments along with its evolution and various routing techniques.

We summarise the chapter as follows:

- Mobile cloud technology requires and constant Internet connection for communication. This is a concern in challenged environments where there is limited network availability, but also in areas with network connectivity where the cost of accessing the Internet is simply too high.

- In such situations it is possible to use mobile devices for communicating directly with one another to improve the availability and accessibility of information using co-located user's to relay information instead of relying on fixed infrastructure for communication.

- Mobile opportunistic networks are one kind of MANETs that support the characteristics of DTN. But unlike MANETs, there is no end-to-end communication path available between the nodes for a message exchange.

- 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 a social perspective, a user's unpredictable behaviour is a common issue which can degrade the performance of the network.

- We find that, the research is promising where we can employ local users' mobile networks to gain advantages for accessing an available cloud-based application in challenged environments.

In the next chapter (Chapter 3), we explore the state of the art research in this field and try to see how recent research advancement addresses several of the points raised in this chapter.

Chapter 3

State of the Art

As the motivation of our research is to enhance users' mobile networks for extending cloud-based applications in challenged environments, in this chapter we study the state of the art in mobile cloud technology and its application scenarios. 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). Next, we explore the integration of mobile cloud technology and mobile opportunistic networks.

3.1 The Mobile Cloud Technology

Mobile cloud technology is the combination of mobile technology and cloud-based applications [68]. It has arisen as a means for improving the capabilities of mobile devices in terms of processing and storage. Mobile cloud technology primarily focuses on the user's mobile devices to access cloud-based services through wireless network communications [69]. This is achieved when mobile applications are deployed (i.e., mobile offloading) to the cloud servers or cloud-based applications running on the user's mobile devices e.g., in terms of 'cloudlets' [70].

Mobile data offloading is the process for delivering data from resource-constraint mobile devices to resource-enhanced cloud servers. Data offloading can be done in two different ways, first, offloading in a *static* environment and second, offloading in a *dynamic* environment [71]. 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. The data offloading can be done using two technologies. One is through Femtocell [72] and another is through Wi-Fi networks [73] (e.g., a Wi-Fi access point). Femtocell, which is an access point base station, is used for data offloading in an indoor environment. The major requirements for this is a small base station that helps gain access to an available Internet connection for data offloading. A femtocell connects to the service provider's network via broadband (e.g., cable) to access an active Internet-based application. The fundamental of a femtocell is that it allows service providers to extend service coverage at the edge of the cell, in particular where access would otherwise be limited or unavailable for the users. But unlike the Femtocell, offloading through a Wi-Fi access point, works in an outdoor environment using the unlicensed frequency bands.

The major components of the mobile cloud architectures are composed of *mobile devices*, *mobile networks*, *Internet access points*, *cloud servers* and the *cloud controllers* (cf. Fig. 3.1). As illustrated in Fig. 3.1, mobile devices connect with the mobile networks via base stations e.g., Base Transceiver Stations (BTS), access points or satellites. BTS facilitate the wireless communications between the users and the network. This mobile network then connects with

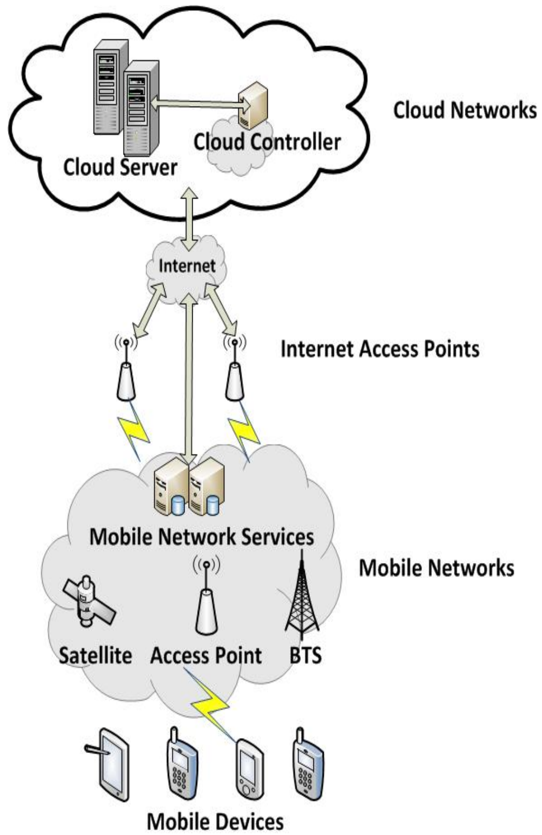

Figure 3.1: Mobile cloud architecture is where user's mobile devices are connected with the mobile network via different access points. The mobile network then communicates with the cloud servers using the Internet access points (e.g., Wi-Fi access points or fixed fibre links). Finally the cloud controllers provide the requested cloud-based service to the users.

the cloud servers via an Internet access point to avail cloud-based services for the users. In the infrastructure clouds, the cloud controllers process these requests to navigate the packets to the corresponding cloud servers for providing the requested services to the users [74].

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 [69]. Traditional infrastructure clouds are built 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 [75].

3.2 Application Scenarios

In this section we explore different applications of mobile cloud technology in various real-life scenarios and the challenges they face. This includes educational sectors, healthcare systems, e-business, mobile gaming, multimedia applications, online television streaming, wildlife monitoring, disaster management and urban traffic controlling systems.

- **Education:** The rapid growth of mobile technology and wireless communication networks has improved the emergence of mobile learning (m-learning) technology [76], as it creates a convenient platform for the users which is easily accessible from virtually anywhere. The fundamental basis of this m-learning technology is the use of mobile devices for learning purposes while users are travelling. This technology is based on the electronic learning (e-learning) technology and the mobility of the devices. Although mobile devices are portable and easily accessible by the users, there are several limitations related to the traditional m-learning technology which includes a weak network bandwidth for communications, low network transmission rates, limited battery power or even the device's small screen size.

The use of cloud-based applications with mobile devices has introduced new ways to solve these limitations [68]. It is now possible to use mobile devices to control cloud-based applications without maintaining a higher amount of infrastructure or resources. Utilising a cloud-based application has several advantages e.g., higher storage capacity, faster processing and the convenient use of resources that provides learners with more scalable services in terms of data accessibility. Thereby improving the m-learning experience for both out-of-classroom and in-classroom education.

The ‘MobiLearn’[1] and the ‘Learning Citizen Cluster’[2] are two projects that are focusing on m-learning technology by exploring the context-sensitive approaches for mobility of the users. This helps visitors (e.g., tourists) to improve their knowledge and helps in cultural information interchange in places e.g., museums, in social communities or to improve the information accessed through updating recent activities and interests online. These projects aim at building a common user centric platform for collaborating information among users, service providers and service developers more easily and the use of cloud-based applications improves the overall m-learning experience through these collaborations and social interactions [77]. Various mobile communication mechanisms can be used for the m-learning process, e.g., voice communications, real-life message exchange (e.g., text messages and emails) and the direct information interchange via document uploading and sharing between the users. Additionally, by employing a learning portal in the Internet, users can manage different activities which also support m-learning management systems.

However, the challenges are to originate the concept of adaptive learning to build instructional strategies and learning content for the user's personal preferences according to their needs as well as providing them with the correct information [78]. The future research goal would be to integrate heterogeneous mobile cloud platforms and various mobile applications seamlessly in order to provide these types of m-learning technologies to users for a better utilisation of resources and to further enhance computational capabilities. To this end, context-aware m-learning technology can be employed to address such issues for improving the m-learning process [79].

[1] http://www.mobilearn.org/
[2] http://www.learningcitizen.net/

These context-aware systems help to determine the user's personal preferences according to their needs through users' collaborations with one another in a heterogeneous mobile cloud platform.

• **Healthcare:** Mobile healthcare (m-healthcare) is a form of electronic healthcare (e-healthcare) technology that manages patients clinical records as well as enabling an ubiquitous and uninterrupted access platform to provide these records to the doctors and caregivers using a mobile-based application [80]. This technology helps with treatments through constant observations without the patient's physical presence being required at the clinic or hospital. Therefore, m-healthcare technology helps reduce the cost of medical treatments. The use of cloud-based applications on mobile devices also enables a greater potential in remote healthcare services with a higher bandwidth utilisation, storage and a more scalable service platform overcoming the device's limitations of storage and processing capabilities.

Hoang et al. propose a middleware based m-healthcare architecture, named 'MoCAsH' [81]. This architecture uses mobile sensing technology with the help of locally available mobile communication infrastructure, and then processes the data to a central cloud server. However, the proposed model relies on intelligent mobile agents and context-aware sensor records for the information processing and storage which requires a continuous network connection that may be affected by the device's limited battery capacity and application scenarios (e.g., in rural areas that lack an Internet connection) .

Tang et al. propose a mobile-based home care management system through the transmission of Multimedia Messaging Services (MMS) [82]. This system is especially configured for hypertension and diabetes patients who can generate their own requirements (e.g., requesting doctor's advice or seeking advice for a particular medical treatment) through text messages using their mobile phones. Similar to 'MoCAsH' [81], in this system a centralised cloud-based service management architecture has been introduced to monitor all these requirements and process them to the appropriate departments or doctors according to the patient's necessity or emergency situations.

However, the exchange of patients' electronic health records among doctors and caregivers, while storing and transmitting that data using resource-constrained mobile devices securely, is still a major challenge [83]. To address this, a security architecture for protecting medical records from unauthorised user access can be employed [84]. The proposed architecture uses cloud-based applications to distribute medical health records and implement a security protocol for efficient cloud-based resource management inside the mobile devices. In addition, to overcome the issue of limited battery power of the mobile devices, the proposed architecture offloads the complex computational services to the cloud and only executes the final process on the mobile devices, which reduces the cost of communication. This architecture improves the overall bandwidth utilisation and reduces the computational complexities to the mobile devices by providing faster data processing between the user's mobile devices.

• **E-Business:** The use of mobile cloud applications in electronic business (e-business) technology is rapidly increasing. These applications allow users to perform their business transactions over the Internet via their mobile devices. This approach is an important aspect towards the development of a faster cloud-assisted e-business technology that enables the adaptability of the device's mobility [85]. Furthermore, mobile cloud technology facilitates these applications e.g., online photo sharing, booking online movie tickets or even online shopping from a favourite book store. These cloud-based mobile applications are more popular at present and users can instantly avail these services even when they are travelling [86]. However, for example, it may happen that the e-commerce web-sites in the cloud may be situated far away from their customers. Therefore, a low latency for communications may cause the company to lose their business revenues.

Research on how to find the online retail businesses more quickly according to the user's choice and demands is promising. To this end, context-aware, collaboration-based technology can be employed [87]. This would help find a collaboration as well as mobile-adaptive local user's communication platform that may help users find the specific answers more quickly rather than relying on a fixed infrastructure for communication.

• **Mobile Gaming:** Mobile entertainment applications are fruitful for generating revenue for the enterprises [88]. The global market of mobile games in 2010 was $66 billion and it is expected to rise to nearly $81 billion by 2016[3]. The concept of mobile gaming is to offload the large scale computing resources into the infrastructure clouds and to use this application via mobile devices as an interface. Research is promising in the areas where multiple mobile users can communicate with each other at runtime in a collaborative platform without any direct physical involvement. Gaming systems using mobile cloud technology attract both the users and game developers in many ways. Users can play the same game over a heterogeneous platform, e.g., a laptop, mobile device or in tablets. This gaming system reduces the cost for both the users as well as the developers. But the challenging task is to develop a cloud-based gaming system over the heterogeneous mobile platforms which will provide high-quality audio and video streaming as well as to reduce response delays at runtime [89]. To this end, an open cloud-based gaming system, named 'GamingAnywhere' can be employed [90]. This system is able to support continuous video streaming and maintains its performance accordingly. The development of this system is based on cloud-assisted client-server models but research is lacking on how the users can play such games using a decentralised mobile cloud platform.

• **Multimedia Applications:** Video, audio and photographs (e.g., multimedia streaming or photo sharing) have different delivery requirements

[3]http://www.dfcint.com/wp/?p=311

in a distributed mobile cloud environment. These applications need to be synchronised to provide coherent information to the mobile users for their requirements. The use of these types of multimedia applications are popular to use or play on the mobile devices because such portable devices are easy to carry and easy to access [91]. The major challenge is an efficient scheduling of multimedia data streaming over different mobile cloud platforms. Over this, an efficient scheduling architecture for massive multimedia data flows with a heterogeneous mobile cloud platform can be used [92]. The proposed scheduling architecture tries to mitigate the delays and energy related issues among the cloud servers. The use of such architecture is promising where users can share their interests with similar users and applications.

• **Online Television Streaming:** Internet Protocol television (IPTV) services like 'Video On Demand' (VoD) and 'Live broadcast TV' are quite popular at present [93]. With the advancement of mobile cloud technology, these services are more in demanded by the users but the concerns are for a continuous need of an Internet connection, network bandwidth or usability of the mobile devices to access these services. The major challenges are how to provide a continuous streaming over these mobile cloud platforms while the devices are changing network frequently, and the use of these devices in places with limited connectivity e.g., sparse areas without an infrastructure for communication or in the urban areas with full interference access networks. To this end, the traditional P2P mobile communications technique [15] can be employed. However, the challenge is how to build a mobile cloud assisted P2P system that is able to provide a high-speed data transfer (i.e., with a high bandwidth) to the users in the areas that are limited to access an IPTV.

Another issue is the 'Instant Channel Change' (ICC) requests in IPTV. Technologies like IPTV and LiveTV typically follow the multicasting mechanism from the servers using IP multicast, with one group per TV channel. For each channel change each user needs to join the multicast group associated with that particular channel and they need to wait for enough data to be buffered before the video is displayed, which is time consuming. To address such issues, the use of a mobile cloud based architecture that provides a faster deployment of IPTV and LiveTV services over wireless networks can be beneficial [94]. The future research is encouraging where users can adopt additional functionalities that are related to improve the latency related issues and connection protocols for a seamless service to the mobile devices.

• **Wildlife Monitoring:** The use of mobile cloud technology is promising in wildlife monitoring and several other related applications, e.g., finding the location of specific animals or to monitor their behaviour. However, the lack of infrastructure (e.g., a fixed network connection) faces major challenges in order to increase the communication opportunities and the throughput in the system. Applications are promising in these areas where the locally available P2P network communications can be integrated in such monitoring systems for an efficient collection of data and access provision of cloud-based services that may require real-time data management [95].

To address this, a mobile cloud based system on outdoor mobility-learning activities with the integration of wireless communication technology can be employed [96]. The proposed system is built on an ad hoc network communication that is formed with the different mobile users. For example, using mobile devices and a Wi-Fi network card the users can share information between each other. This system is based on a centralised service oriented architecture and collaboration between the users participating in this monitoring system.

• **Disaster Management:** Satyanarayanan presents a view to use mobile cloud technology in cases of disaster/emergency situations [97]. The potential use of mobile cloud technology are discussed in situations e.g., finding a lost child or in a natural disaster like an earthquake or tsunami. In such cases, local users can help by sharing the real-time information with one another creating a pool of resources to make further decisions accordingly with the help of the locally available network connections. However, the challenge is the efficient management of the high data traffic in the network during the time of a disaster.

To address such issues, an intelligent transportation system for disaster management with Vehicular Ad Hoc Networks (VANETs) and mobile cloud technology can be employed [98]. The proposed system is able to collect information from multiple sources and locations, including from the point of an incident. It then creates effective strategies to send updated information to the vehicles and other co-located users alternative routes to the destination.

- **Urban Traffic Controlling:** Mobile cloud technology is promising in the use of urban traffic communications and control systems. The cloud-based applications provide the resources required to use traffic strategies and efficient control of massive data transportation. Wang et al. present an agent-based traffic control management system for intelligent vehicular transportation [99]. The system is based on agent-controlled network-enabled technology. The advantage of this system is that it requires less memory and processing power to control the agents than the process that is operated by traditional controlling algorithms. This system deals with a centralised server-based architecture. However, the challenge is how we can build such systems in real-time over a decentralised network that connects to a heterogeneous mobile cloud platform. Moreover, this system requires a continuous network connection between the driver's mobile device and the cloud server that may be unavailable in rural areas that lack a proper infrastructure for communication. Xue et al. present a cloud storage-based traffic video detection system that is capable of processing higher amounts of video streams to generate the present traffic condition in a given area [100]. A large amount of storage-resources are required for deploying such a system which increase the network delays. Research in these areas is promising where we could process the data over the cloud and use the mobile devices for streaming the data at runtime which would reduce the related delays in the network.

To address such issues, a mobile cloud based smart trafficking system can be used [101]. The proposed system is based on a mobile application which runs on each driver's mobile device and a traffic prediction algorithm which is runs inside the cloud server. This system provides real-time guidance to the users and reconstructs the traffic model from the gathered data for the future traffic predictions.

3.3 Classification of Mobile Cloud Architectures

There are several studies carried out showing the classifications of mobile cloud architectures. For instance, 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) [102]. 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) [103]. The IaaS provides storage, hardware and networking components e.g., servers. An example of IaaS is Amazon Simple Storage Service (Amazon S3)[4]. The PaaS provides user with an integrated environment for building, testing and deployment of custom applications. An example of PaaS is Microsoft Azure[5]. Whereas, the SaaS supports a software distribution with the specific requirements that happen remotely via an Internet connection. An example of SaaS is Salesforce[6]. 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

[4]http://aws.amazon.com/s3/
[5]https://www.windowsazure.com/en-us
[6]http://www.salesforce.com/uk/

cloud technology e.g., context-awareness, application related issues, data management and security, privacy and trust's point of view [104].

However, 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. 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, 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:

3.3.1 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.3.2). 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.3.2, 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'[7], 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

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

to a centralised distributed platform where a user can avail such services via a thin client or a Web browser through the Internet.

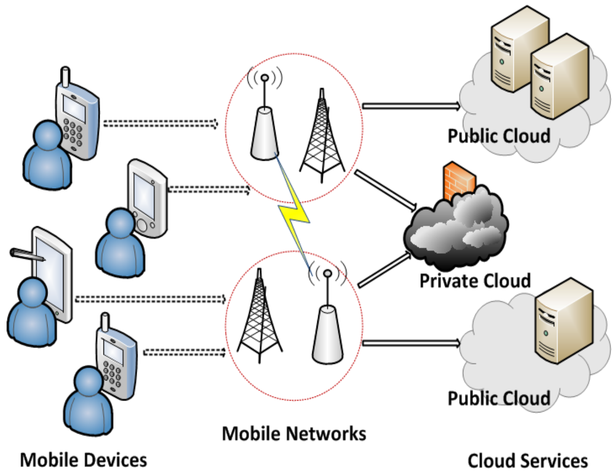

Figure 3.2: The D2C class of mobile cloud architecture is where users connect their mobile devices to the remote cloud servers through mobile networks for accessing cloud-based applications.

For instance, Li et al. propose a D2C class of mobile cloud architecture to deploy mobile computations to the remote cloud servers [105]. In this, mobile agents help to deploy mobile computations to the cloud servers, executing 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 seamless data offloading between the mobile agents and the cloud servers. Over 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 [106]. This is a context-aware offloading architecture that does not require any additional network connectivity and performs equally well for 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 3.3). The gaming service provider instantiates a virtual game-server engine inside a 'in-network' cloud-based platform.

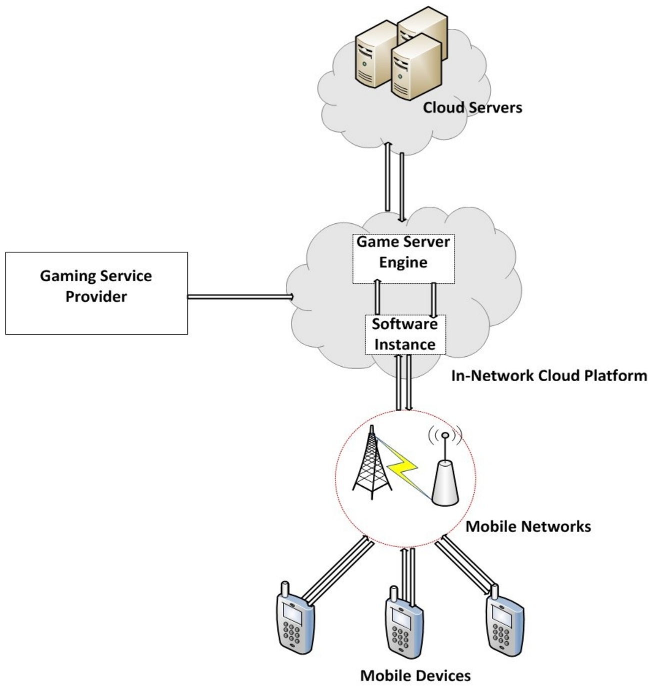

Figure 3.3: The 'MoCa', a D2C class of mobile cloud architecture is where users interact with the virtual game servers (referenced as In-Network Cloud Platform) through the cloud-based mobile networks.

As illustrated in Fig 3.3, 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 the game server engine.

Another D2C class of mobile cloud architecture, called 'volare', is presented in [107]. 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 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' [108]. 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 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 a 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' [106] and 'volare' [107], this architecture explores the service provision during the time of disconnection through techniques such as Forward Error Correction (FEC). 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 [109].

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 [110]. 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 speeding up the resource identification process in the network. The 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' [107], the advantage of this architecture is that, the use of a URI gives the user 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 [111]. 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' [106], this architecture works seamlessly in dynamic heterogeneous networks. But unlike the 'volare' [107], 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) [112]. 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 [108], the major limitation of this architecture is that, it is based on wireless mobile communication networks which may suffer 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 missing. Similar to the Ou et al. architecture [112] 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 [113]. 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 [114], 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 a user's mobility pattern as this changes with location and time [115]. Unlike the Ou et al. architecture [112], 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 [116]. 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 offloads them to the cloud-servers. The proposed architecture is composed of three phases, they are: application structuring phase, partitioning phase and the 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 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 [112] 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 [117]. 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 [112], in this architecture, data offloading improves the energy consumption for both the communication and computation. Similar to the Chun and Maniatis architecture [116], this architecture minimises energy consumption by using partition-based data offloading.

Similar to the Kumar and Lu architecture [117], Ravi et al. propose an energy management architecture for mobile devices [118]. 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 warns 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). 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 3.1, we summarise the various D2C class of mobile cloud architectures discussed in Section 3.3.1 , with their efficiencies. This includes context awareness, bandwidth utilisation, latency used, collaborations, cost efficiency and energy awareness.

Table 3.1: 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***
[105]	L	M	M	No	L	L
'MoCa' [106]	H	L	L	No	M	M
'Volare' [107]	H	L	L	No	H	L
[108]	M	L	M	No	L	L
'IRNA' [110]	M	L	L	No	L	L
'E-Recall' [111]	H	H	H	M	L	L
[112]	L	H	H	L	L	L
[113]	H	L	M	H	M	M
[116]	H	M	M	No	M	H
[117]	H	L	L	No	M	H
[118]	H	L	L	No	M	H

3.3.2 Mobile Cloud "Cloud to Device" (C2D) Architecture

In this class of architecture, cloud-based applications run inside the user's mobile devices (cf. Fig. 3.4). The 'Open Gardens'[8] 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'*.

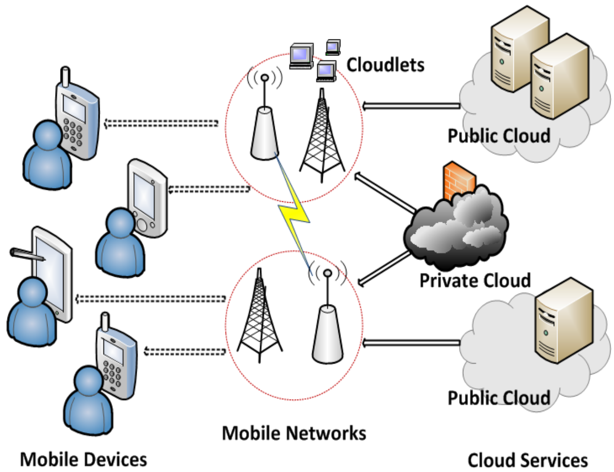

Figure 3.4: The C2D class of mobile cloud architecture is where resourceful cloud-based applications run inside the user's mobile devices with the help of the 'cloudlets'.

As illustrated in Fig. 3.4, cloud-based applications execute in 'cloudelets' that are located to the edge of mobile networks [7]. 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 Wi-Fi technology. A femtocell is used to improve cellular reception inside a building or home (i.e., an indoor network environment) [72], whereas the Wi-Fi technology works better in an outdoor network environment [73]. The 'cloudlets' are executed in the core of the mobile networks. The C2D communication in a cellular network can be observed as a direct communication

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

between the cloud servers and the mobile devices (i.e., the last link is wireless) traversing the Base Station (BS) or core network. However, the local user's mobile networks and their communications are generally non-transparent to the cellular network. This can be achieved in two different ways, first via cellular spectrum (i.e., inband) and second unlicensed spectrum (i.e., outband). Cellular network architecture takes multi-core architecture design for communications, which gives programmers the ability to execute a large number of concurrent threads in a single processor. This in turn accelerates the concurrent execution of applications. In a traditional cellular network, all communications must be done via BS even if the co-located users (i.e., mobile devices) are within a range of direct communication.

The aim of the C2D class of mobile cloud architecture is to use cloud-based mobile augmentation approaches in which resourceful cloud-based applications are leveraged to enhance the computing capabilities (e.g., processing and storage) of the resource-constrained mobile devices [119]. In this, resource-enhanced cloud-based applications are used to increase and optimize the resources inside the resource-intensive mobile devices. A big part of the cloud-based application can be executed in smaller parts as per the user's requirements and available various computing resources (e.g., location of remote cloud servers or nearby mobile nodes).

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 [120]. 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 data offloading using the maximum advantage of each mobile node in the system that uses 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 [121]. 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 parallel data processing and alleviates device's limitations (e.g., CPU, RAM, battery) for executing 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. 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 [121], 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 [122]. 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 motivation, this architecture requires a constant Internet connection for a communication establishment between the mobile devices and 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’ [123]. 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 for 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. Similar to the Verbelen et al. architecture [123], Koukoumidis et al. present a C2D mobile class of mobile cloud architecture to improve data access, latency related issues and efficient energy management procedures for mobile devices [124]. The proposed architecture introduces a ‘pocket cloudlet’ concept, where full or a part of the cloud-based applications is stored inside the mobile device. A major benefit of ‘pocket cloudlet’ is that it reduces the bottleneck of wireless communications and improves latency as well as data access speed at runtime by increasing the device’s memory capacity. Unlike the Verbelen et al. architecture [123], ‘pocket cloudlet’ is able to synchronise resources between edge clouds and mobile devices easily and helps mobile devices with efficient resource selection and management. This architecture requires a memory to store the cloud-data, for instance, data can be stored in the mobile cache.

In table 3.2, we summarise the various C2D class of mobile cloud architectures discussed in Section 3.3.2, with their efficiencies. This includes context awareness, bandwidth utilisation, latency used, collaborations, cost efficiency and energy awareness.

Table 3.2: 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' [120]	H	M	M	No	M	L
'm-cloud' [121]	M	M	M	No	M	L
[122]	H	M	M	L	M	M
'Cloudlets-based approach' [123]	H	L	L	M	L	H
'Pocket-cloudlets' [124]	H	M	L	M	L	H

3.3.3 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. 3.5). 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 [125].

As illustrated in Fig. 3.5, users communicate with each other within a network with the help of locally available mobile network communications.

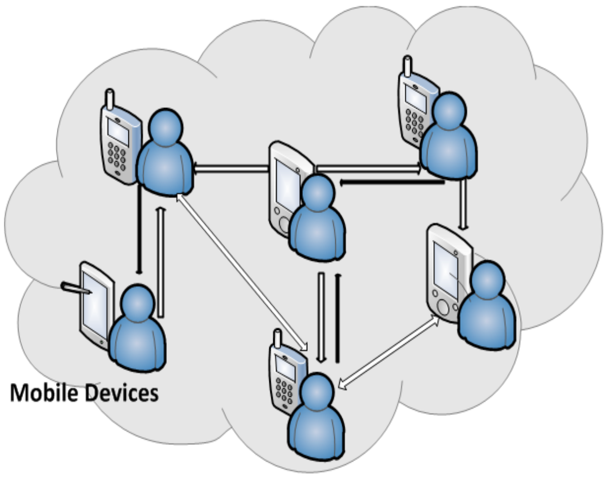

Figure 3.5: The D2D class of mobile cloud architecture is where users create their own ‘cloud environment’ by communicating with one another located in physical proximity.

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 [126].

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 [127]. The social network relations help to avoid unwanted communications by identifying foreign users (i.e., the users, who do not have a social relation to a user in the same network or in successive networks) 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 [128] to secure communication between the users from the attackers/hackers who may steal/hack the user's sensitive information during data offloading. But unlike the motivation of our present research, how to extend user's social relations further to access cloud-based applications during network disconnections is lacking in the proposed architecture.

Pedersen and Fitzek present a D2D class of mobile cloud architecture that explores technical and social aspects [75] in such communication. In this architecture, mobile devices located in physical proximity connect directly and create their own 'networks' for sharing information between each other. There are issues relating to P2P communications or overlay network techniques. However, social aspects deal with cooperation between the users by enforcing incentives in such cooperation [11] [12]. To this end, 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 a 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 the motivation of our present research, 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 [75] architecture, Li et al. present a D2D class of mobile cloud architecture exploring user's mobility patterns and social awareness in data forwarding [129]. The goal of this architecture is to leverage social-aware D2D communication based on social relationships and human mobility on an underlying cellular system. But once again, unlike our motivation, this architecture does not indicate how to enhance these social relationships and human mobility for gaining access to cloud-based applications 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) [130]. This architecture uses limited network bandwidth for search and share 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 a 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 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 [25]. This architecture explores the alternative route by locating users in a physical proximity who may have a stable connection to offer. This connection establishment can be achieved by using the user's mobile networks.

In such a way, a user is able to connect their mobile device with the cloud servers in an ad-hoc manner using another user's stable network connections. Similar to the Jin and Kwok architecture [130], 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 [75], 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 [131]. 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 a 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. [25] model, the data forwarding in 'MobO-Cloud' 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 [132].

In table 3.3, we summarise the various D2D class of mobile cloud architectures discussed in Section 3.3.3, with their efficiencies. This includes context awareness, bandwidth utilisation, latency used, collaborations, cost efficiency and energy awareness.

Table 3.3: 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*
[127]	H	M	M	H	M	M
[75]	H	M	M	H	L	M
[129]	H	L	L	H	L	M
[130]	H	L	M	M	L	H
[25]	M	L	L	H	M	M
'MobOCloud' [131]	H	L	M	H	H	H

3.4 The Integration of Mobile Cloud Technology and Mobile Opportunistic Networks

The state of the art discussions in Chapter 3.3 and Chapter 1.1 indicate that there is a need of a constant Internet connection to gain advantage to a seamless cloud-based application by the users. However, in challenged environments it is not so trivial, since such applications rely on the availability of connectivity. For instance, in sparse or rural areas that lack proper infrastructure, and in high density, urban areas, with restricted/full of interference access networks, connectivity cannot be assumed available. Therefore, we explore the integration of mobile cloud technology and mobile opportunistic networks for a collaborative information sharing platform. In this, users can gain access to cloud-based applications in challenged environments with the help of local users' mobile networks and their social collaborations.

A major operation of mobile cloud technology is data offloading/mobile data augmentation via resource constraint mobile devices. Mobile opportunistic networks help to store, carry and forward data exploring user's physical interactions in a fairly small area. Thus, while integrating mobile cloud technology with mobile opportunistic networks, this data offloading/mobile data augmentation can be done with the help of the co-located users' interactions exploiting their mobility patterns and social behaviours [133].

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 [117]. 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 [134]. 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 [135].

User's mobility, interactions and cooperation and routings for data forwarding are three significant issues when integrating mobile cloud technology with mobile opportunistic networks [24]. User's mobility is important as this exploits their interactions and cooperation between each other for sharing similar social interests. Routing strategies (cf. Chapter 2.3), on the other hand, play an important role for data forwarding between users by selecting the best possible path available [136].

Most of the recent research has been focused on the development model of the mobile cloud platforms and mobile opportunistic networks [102] [137] [138], along with their issues and related challenges in their resources (e.g., battery power, storage) and communications (e.g., user's mobility, data privacy [41] [104] [139] [140], but exactly how a mobile cloud platform can be extended using mobile opportunistic networks in challenged environments is lacking in present research. Our research addresses this specific gap where we can use an mobile opportunistic network to gain access to cloud-based applications 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.

3.5 Summary

In this chapter we present the state of the art survey of mobile cloud technology, their applications, challenges and possible countermeasures. We also discuss the various mobile cloud architectures according to their mode of use. Finally, we discuss the emergence of integrating mobile cloud technology with mobile opportunistic networks to gain access to cloud based applications in challenged environments.

We summarise our findings are as follows:

- The combination of mobile technology and cloud-based applications deliver successful adaptations of services (e.g., processing and storage), which tends toward a mobile cloud technology.

- There is a need for a constant Internet connection to gain advantage to a seamless cloud-based application by the users. However, in challenged environments not so trivial, since such applications rely on the availability of connectivity.

- In addition, heterogeneity of networks, limited bandwidth, context awareness of the device, limited battery power and memory size as well as security and privacy issues to protect user's data are the major constraints to overcome for the continuation of delivering better cloud based applications.

- We find that the use mobile opportunistic networks with the help of local users' mobile networks and their social collaborations can be employed for extending cloud-based applications in challenged environments.

- In our study, we note that how a mobile cloud platform can be extended by using mobile opportunistic networks in challenged environments is lacking in present research.

In the next chapter (Chapter 4), we demonstrate the MoCC architecture, which extends mobile cloud platforms with mobile opportunistic networks. By using this architecture it may be possible to overcome the limitations of high Internet access costs or unavailability of network infrastructure, e.g., for tourists who may wish to gain access to remote cloud-based applications with the help of local users' mobile networks.

Chapter 4

Extending Cloud-Based Applications With Mobile Opportunistic Networks

In this chapter, we devise a new ***'Mobile-Opportunistic Collaborative Cloud'*** architecture (MoCC) to extend mobile cloud platforms using mobile opportunistic networks in challenged environments. 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 Chapter 3.3).

In this chapter, the major contributions are:

- We devise the MoCC architecture which explores a "Device to Device to Cloud" communication that leverages local users' mobile network connections to provide tourists with access to the cloud-based applications in the absence of infrastructure.

- We discuss the issues and challenges associated with the MoCC architecture that need to be improved upon for delivering a more scalable, location-aware and context based service to the tourists in a challenged environment.

4.1 The Scope of the 'MoCC'

In the D2C class of mobile cloud architecture (in Chapter 3.3.1), a mobile device offloads data to the cloud servers. In the C2D class of mobile cloud architecture (in Chapter 3.3.2), cloud-based applications run in mobile devices through mobile data augmentation may be in terms of the 'cloudelets'. Finally, in the D2D class of mobile cloud architecture (in Chapter 3.3.3), devices communicate with one another using locally available network connections within a fairly close distance. Our 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 improve the data offloading/mobile data augmentation with the help of the locally available network connections. Returning to our motivation (in Chapter 1.1), the MoCC architecture aims to gain access to a cloud-based application for Bob and Ron, 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).

The MoCC consists of two different technologies, which are then combined into a single one. These are mobile cloud technology and mobile opportunistic networking technology, by using the local user's P2P communications technology. As illustrated in Fig. 4.1, travellers (e.g., tourists) can connect their mobile devices with the available mobile networks (cf. in Fig. 4.1 this is referenced as 'Local User's Network Communications'). Local users (i.e., local people) play an important role in such communications for information sharing. Unlike the tourists, local users are assumed to 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 ap-

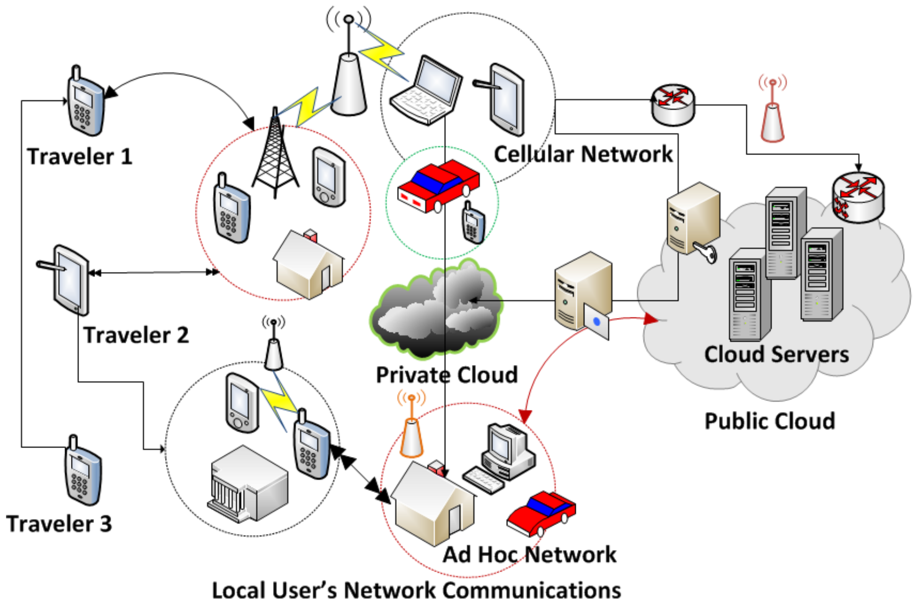

Figure 4.1: The emergence of a 'Mobile-Opportunistic Collaborative Cloud' (MoCC) architecture is where travellers (e.g., tourists) can connect their mobile devices with mobile networks in proximity (referenced as Local User's Network Communications) for information storage and sharing. Travellers can 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 traveller.

plication for mobile P2P networks in an opportunistic way. This network is formed by humans carrying mobile devices that communicate with 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 discuss the MoCC architecture, followed by some potential application scenarios.

4.2 The 'MoCC' Architecture

The MoCC architecture consists of the following five basic components, they are: *users, mobile devices, local users' mobile networks, Internet access points* and *cloud servers*. The functional levels of the envisioned architecture is presented in Fig. 4.2.

As illustrated in Fig. 4.2, the level, named 'user/mobile devices', is composed by the users (both the locals and tourists) and their mobile devices. The level named 'local users' mobile networks' helps the users to communicate with one another in physical proximity. Only the local user's mobile devices are able to connect themselves to cloud servers via an Internet access point (e.g., Wi-Fi access points or fixed fibre links), tourists need to go through this to avail a cloud-based application. Between the levels there is a need of service integration through which services 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. 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., disasters, weather and buildings) can affect this type of communication and user's personal preferences are important in this case [141].

4.2.2 Mobile Devices

Mobile devices are the smart mobile devices carried by the users. Smart phones and tablets are the most popular choices here. Companies are steadily

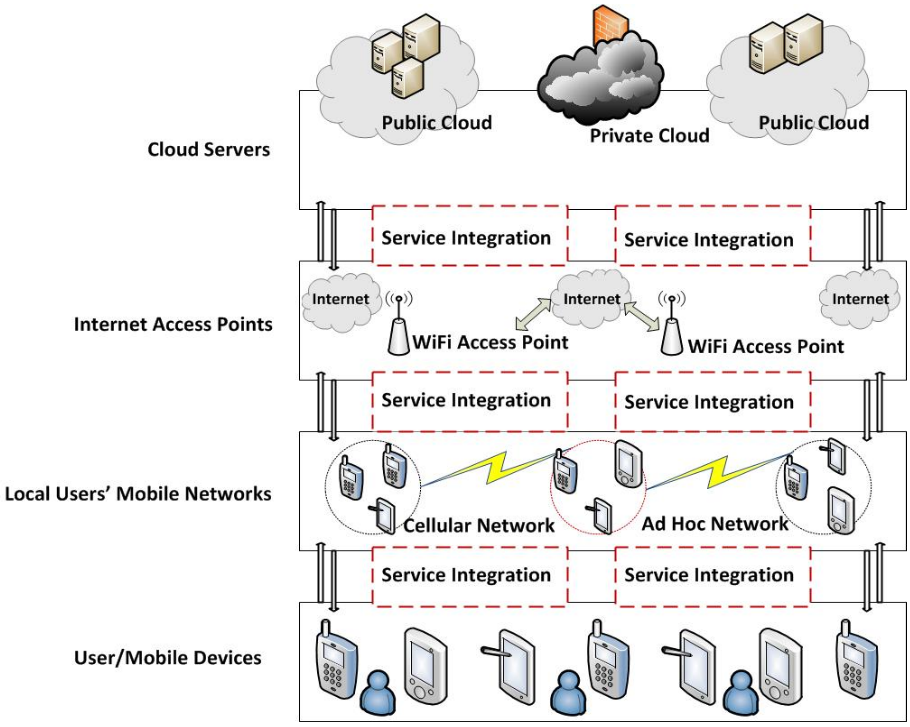

Figure 4.2: The functional levels of the envisioned MoCC architecture. The level named user/mobile devices is composed of users; both the locals and tourists and their mobile devices. Users communicate with each other using the local users' mobile networks. Only the local users can connect their mobile devices to the cloud servers via Internet access points (e.g., Wi-Fi access points or fixed fibre links), tourists need to go through this to avail a cloud-based application. Between each level there is a need for service integration so that components in each level can communicate seamlessly with one another.

trying to build faster and more resource packed 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 totaled 210 million units and declined 21 percent year-over-year"*[1]. Companies like Samsung, Nokia, Huawei, HTC, Sony and Apple are several of the leading companies at present producing smart phones [142]. For instance, sony 'Xperia S'[2]

[1]http://www.gartner.com/newsroom/id/2573415/

[2]http://www.sonymobile.com/gb/products/phones/xperia-s/

comes with 1.5GHz dual core processor, 1GB RAM, 32GB data storage support and 1750mAh battery. Similarly, HTC 'One X'[3] 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 [143] [144].

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. 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. 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 [68] (cf. in Fig. 3.1, in Chapter 3.1).

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 [145]. When a node comes within the communication range of another node, then the opportunity to share information between each other is likely. User mobility and social interactions are important factors in this type of communication.

[3] http://www.htc.com/uk/smartphones/htc-one/

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 [135]. However, 4G connections improve latency and bandwidth capacity. The 4G networks are capable of providing 100 Mbit/s (for the 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 [68]. Moreover, Samsung introduced the 'Yes Buzz'[4] 4G cloud phone which has no SIM card and allows contacts to be saved and synchronised on the Internet.

4.2.5 Cloud Servers

We consider cloud servers here to be 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, the service must have offloading supports to enable user's applications at will [146].

4.3 Potential Applications

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

[4]http://www.yes.my/v3/personal/devices/buzz.do/

4.3.1 Searching for Users in Proximity

As discussed in motivation in Section 1.1, our scenario actor 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 sharing it with the nearby mobile users who may be interested in sharing the meaning of this language so that Ron can understand it.

In this situation, Ron can use a D2C class of mobile cloud architecture e.g., 'volare' [107] (discussed in Section 3.3.1), but this would require a constant Internet connection for communication. Therefore, in such situations the architecture MoCC 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 [147] can be used 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' [111] and the Ou et al. architecture [112] (discussed in Section 3.3.1). However, the concern is that the mobile devices need a continuous Internet connection to avail edge clouds resources [148]. Therefore, this indicates that the MoCC architecture is promising for exploring the locally available mobile networks, instead of relying on a fixed infrastructure for communication is promising. An example would be, using his mobile device; our actor Ron may be able to locate some interested people in the museum who can share the required information to understand the meaning of the ancient script.

4.3.3 Sensor Data Applications

Smart phones are able to connect GPS services for finding a specific location. It is also possible to calculate a device's location and speed with 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' [120] and the 'mCloud' [121] (discussed in Section 3.3.2). Unlike the MoCC architecture, these C2D architectures require a constant Internet connection that may be unavailable in rural or spares 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 [149]. This may be a travel schedule, ticket arrangements or the booking of a hotel which is helpful to the travelling tourist. For instance, Hung et al. define a 'smart cities' [54] approach, where users can interact with each other with their mobile devices for real-time travel searches (e.g., searching for a tourist's attraction or a direction to a particular place). This approach is useful for tourists to find a cloud-based application with the help of the nearby user's P2P network communications. 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., the Pedersen and Fitzek architecture [75] and the Jin and Kwok architecture [130] (discussed in Section 3.3.3), but this is difficult to get information from a global community for which an Internet connection is required. Therefore, the MoCC architecture is promising for combining local and global connectivity when travelling in areas with no Internet connection or in areas with high Internet access costs.

4.4 Issues and Challenges

The emergence of the MoCC architecture is promising for communication in challenged environments. In short, this new networking trend fuses the efficient users' collaborations and interactions with the help of mobile opportunistic networks to avail cloud-based applications. However, it introduces several issues and challenges in the network. As the data forwarding in such a network solely depends upon the user's direct interactions with one another, thus security issues and privacy challenges are major concerns [150]. In this section, we discuss such issues and other associated challenges that are related to the node's mobility, heterogeneity of networks and constraints related to the mobile devices and user behaviour.

4.4.1 High Mobility of the Nodes

A user mobility pattern plays a significant part in transferring information in a real-life scenario [42]. In the MoCC architecture, nodes expect to send and retrieve information while they carry out their usual activities. Thus, nodes are highly dynamic in nature and the devices in the network may rely on sporadic connections with other nearby mobile devices as an opportunity for data forwarding, regardless of the availability of network connectivity and of the surrounding set of neighbouring devices [151] [152].

An important feature of a mobile opportunistic network is that it does not keep track of the current network topology. So, the data forwarding decision is made exclusively based on knowledge available locally [26]. A routing path between the source and destination may not exist and a node forwards packet to intermediate nodes until the intended destination is found. Therefore, it is impractical to establish end-to-end secure routing strategies for this communication. Consequently, the MoCC architecture requires highly dynamic security and privacy solutions that do not depend of a predefined path, and that should take place at every hop. With that in mind, security schemes could exploit mechanisms analogous to the custody transfer found in DTN. In this case, the current node sending the message should guarantee a data delivery to a next hop by employing trust mechanisms which characterise how reliable the next hop may be [153].

As privacy leakage is inherent to this hop-based scenario (i.e., attackers explicitly target an individual or a group of individual's data stored in a cloud database), relational privacy could be employed while storing and sharing data in MoCC. Strong relational privacy (e.g., a friendship or contractual association) can mitigate data leakage by keeping trusted relationship between the users participating in data forwarding [154].

In the context of the MoCC architecture, a node should share data with other nodes following a reliable connection between them. A node should use secure encryption techniques for storing data in a cloud data centre. The information provenance mechanism for cloud-based networks that identifies fault identification and security violations by using the dynamic nature of the network could be an alternative. This solution is able to maintain the integrity of electronic-data in storage and archival services while transferring data from one user to another by dynamic encryption mechanisms [155].

Another alternative to improve hop-based security could be the utilisation of a key management framework that enables the bootstrapping of local security associations between a node and its neighbours along with the discovery of the neighbourhood topology [156]. In MoCC, this framework could prevent 'sybil attacks' [157], where node's reliability is affected by foreign-attacked nodes. It is imperative that, when addressing the privacy and security issues concerning the use of cloud-based applications through different mobile opportunistic contacts, new solutions consider dynamic mechanisms that could mitigate these arising security threats and attacks, resulting from how users move within the network.

4.4.2 Heterogeneity of Networks

Heterogeneity here refers to the use of different connectivity means to access data. In a mobile opportunistic network, mobile devices do not use a unique type of connectivity all the time [158]. This connectivity is limited (e.g., a user's 3G plan) and may vary from place to place (e.g., at home or on the bus). Such a connection can be provided from a wired network, that has high bandwidth; from wireless local (school) and/or wide (municipality) area networks with limited bandwidth; through wireless private area network by means of Bluetooth; or from the user's cellular network [135].

Additionally, communication in mobile opportunistic networks depend upon the node's mobility and their interactions, and the availability of networks to which users connect [159]. In the absence of a global infrastructure, users roam between and/or connect to different types of networks, constantly searching for available connections to share information with one another. Users may still end up victims of malicious users offering 'free' connectivity, but there is strategy to deal with such situations, e.g., the 'IRNA' architecture [110]. This architecture seamlessly integrates the device's dynamics and heterogeneity of the available networks based on the user's application requirements (cf. Chapter 3.3.1).

The lack of a global infrastructure creates the possible threat as users rely on different insecure networks for communication. For instance, an attacker creates vulnerabilities by decrypting a hash which is not strongly protected by encryptions. This adds a new level of complexity for security systems to these kinds of networks on which the mobile users easily rely. Therefore, nodes in MoCC need a seamless integration between the different connectivity means to which they normally resort. Nodes accessing data via different network connections should be provided with trusted connectivity, supported by dynamic routing protocols that follow the node's trusted encounters for controlling data exchange at runtime.

4.4.3 Device Constraints

Mobile devices are limited in various ways, e.g., battery lifetime, available storage or processing power. In mobile opportunistic networks, these limitations are the major constraints for providing a seamless service to users. Due to the limitations of battery lifetime in these devices, it is not possible to run the device all the time in challenged environment, e.g., for a tourist who is travelling in a rural place. Therefore, depending upon the user's choice, the device may be configured to shutdown wireless connections, thus affecting its communication capabilities.

Moreover, keeping track of contact opportunities tends to be more expensive in terms of energy usage than maintaining existing connections. To address this battery related constraint, a context-aware battery management system for mobile devices may be employed [118]. In a challenged environment this system can save battery power by choosing intermediate devices that could aid access to cloud space. However, it is difficult to predict the similar patterns for all the time due to user's mobility, interactions, present locations and various calling patterns (cf. Chapter 3.3.1).

Similarly, storage and device processing power may be already committed locally by the user's own applications, which makes it hard to share with other users at times. As this constant search for the resources can introduce vulnerabilities inside the system (e.g., malicious nodes may offer their resources to get access to user's information), users must be provided with alternatives to get access to different resources that guarantee a secured data exchange [160]. This type of issue can be solved through a cryptography-based security architecture for accessing stored data in a cloud-based infrastructure [161]. With this architecture, users are in exclusive control of their private key. In mobile opportunistic networks, this architecture can secure the unwanted data access from other users in the system. However, it does not support data confidentiality if the system is compromised by the attackers.

Future research needs to focus on the faster discovery of nearby users' devices from the perspective of an external user (e.g., a tourist) locating a safer path which connects to a group of target users with similar interests (e.g., users interested in sports, literature, food, etc.) in a challenged environment. Consequently, such discovery shall help to mitigate the battery related issues in such communications as only relevant intermediate users are selected in the communication path.

Additionally, the present mobile opportunistic networks require a strict security architecture that supports secure/privacy-aware computation offloading mechanisms. Upon this, strong data encryption techniques can be enforced to secure communication between the users from the intruders that may hack the network during data offloading [128].

This mechanism further ensures that the user's privacy remains protected with trust management and private data isolation from unwanted user's access of the device and data loss from the lost or stolen devices. For the former issue (i.e., data isolation from unwanted user's access), a thin client like anti-malware/antivirus or strong system password must be installed and updated frequently to monitor malware. Further, the latter issue (i.e., lost or stolen devices) can be addressed by employing a secure data processing framework [162]. In this framework, the end users have full control over the data stored in a cloud database (i.e., virtual hard drive). Each mobile device is virtualised and processes data using a trust-based mechanism. Therefore, in the context of the MoCC architecture, if a user's mobile device is lost or stolen, the data can easily be retrieved or transferred securely into another system.

4.4.4 Unpredictable User Behaviour

In MoCC, resources are shared among mobile nodes that act as relay entities for this type of communication. However, in a real-life environment the exact behaviour of a user is unpredictable [115]. A node can enter or leave the network at will, they can turn on and off their mobile devices at their preferences. These are situations which contact opportunities to store and forward information at runtime are easily lost. Furthermore, these situations introduce security issues, as users may find themselves in an unknown area (once they turn their devices back on) and the available contact opportunities may be towards malicious nodes.

Altruism can also cause uncertainty in many ways for social-based communication. However, in a real-life application scenario, selfish behaviour is more general and difficult to avoid. Incentive mechanisms can help users to perform and actively participate in the communication. Over this, mechanisms for detecting selfish behaviour and encouraging cooperative behaviour are imperative [163]. By employing social knowledge when detecting selfish nodes in the system, data exchange can easily take place among trusted nodes, mitigating security issues that arise from uncooperative behaviour.

Incentives may be extended in terms of the social reputation, where users gain a higher position in the social community based on their satisfactory behaviour. This helps to encourage other users in engage in the data exchange process [164]. User behaviour inference and incentive mechanisms can help mitigate the effects of unpredictability and lack of cooperative behaviour. Over this, data exchange can be guaranteed, as data can travel only between those who are available at the given moment within the network.

In Table 4.1, we present a quick overview of the various issues, challenges and their potential measures/solutions discussed in Chapter 4.4.

Table 4.1: Highlighting the resulting issues and challenges along with their potential countermeasures in the MoCC architecture.

Issues	*Challenges*	*Measures/solutions*
High mobility of the nodes.	Can cause ‘sybil attacks’, where node’s reliability is affected by the foreign-attacked nodes.	Requires highly dynamic security solutions that do not depend over a predefined path.
Heterogeneity of networks.	Data leakage risks due to in part of the non-trusted data communication in different networks.	Requires strong data encryption mechanisms to protect sensitive information.
Device constraints.	Limited resources may lead users to rely on the ’goodness’ of malicious users.	Requires secure context-aware service management systems.
Unpredictable user behaviour.	User’s selfish behaviour can affect the overall data communication and may damage user’s privacy.	Requires proper incentive mechanisms for users to perform accordingly to reduce altruism in the communication.

In addition, there are several existing social-aware (i.e., utilising levels of social relationships besides the physical contact) and social-oblivious (i.e, focusing solely on the physical contact among users) mechanisms that focus on the importance of the message forwarding in a mobile opportunistic network (cf. Chapter 2.3). These mechanisms establish the baseline for the implementation of novel routing mechanisms that shall be able to forward messages even upon the unpredictable behaviour of users by looking at trust and social similarities between these users.

Consequently, research is needed to investigate local user’s social interactions and group-based community structures for sharing information to improve the message delivery performance (e.g., for the tourists) in a challenged environment. It would be helpful to combine content knowledge (e.g., content type, content interest) with user social proximity within mobile opportunistic network. This would, in turn, bring benefits to the users for a faster and better message delivery performance, overcoming the lack of trust and non-cooperative behaviour that are likely in challenged environments.

4.5 Summary

In this chapter, we introduced an architecture that can be used to extend cloud-based applications in challenged environments. We also explored the many limitations and challenges in such communications.

We summarise our findings are as follows:

- We devise a new 'Mobile-Opportunistic Collaborative Cloud' architecture (MoCC) to extend mobile cloud platforms using mobile opportunistic networks in challenged environments. It consists of the five basic components, they are: users, mobile devices, local users' mobile networks, Internet access points and cloud servers.

- The MoCC combines the D2C, C2D and the D2D class of mobile cloud architectures and explores a "Device to Device to Cloud" communication that leverages local users' mobile network connections to provide tourists with access to the cloud-based applications in the absence of infrastructure.

- We observe that, data forwarding in MoCC is significantly influenced by the user's direct interactions with one another. Issues and challenges related to the user's security and data privacy, node's mobility (i.e., nodes are highly dynamic in nature), heterogeneity of networks (i.e., the use of different connectivity means to access data), constraints related to the mobile devices (e.g., battery power and memory size) and user's unpredictable behaviour (for instance, refusal in data forwarding) are all major concerns for delivering a scalable, location-aware and context based service to the tourists in a challenged environment.

In the next chapter (Chapter 5), we explore different modes of user behaviour for message forwarding when using an MoCC architecture.

Chapter 5

Exploring the Modes of User's Message Forwarding Behaviour

In this Chapter we explore the different modes of user's message transferring behaviour when using the MoCC architecture (cf. Chapter 4.2). As we discussed in the state of the art (in Chapter 3), we examine these behaviours in areas where an ubiquitous network connection is not always available, e.g., in remote areas without infrastructure, but also in areas with infrastructure where the costs of access are too high for users, such as tourists who do not wish to pay high Internet roaming charges.

In this chapter, the major contributions are:

- We use the MoCC, a "Device to Device to Cloud" architecture, for enabling tourists to use cloud-based applications without any Internet connection.
- We devise a new tourist-based mobility model according to user behaviour, their travel interests and activities in different places.
- We evaluate two options for sending tourists' data into the cloud servers: storing data at well-situated hubs and exploiting the mobility of local users.

The goal of this Chapter is two-fold. First, we investigate how to build a mobile opportunistic/cloud-based platform for tourists with the help of the local users' mobile communications that can enable sending or retrieving of data to or from the infrastructure clouds. Second, we use mobile opportunistic cloud-based scenarios to investigate efficient routing algorithms for tourists to access the remote cloud-based applications.

The research aims to address the following research questions:

- Is it possible to use a mobile opportunistic network to provide cloud-based services to tourists that lack access to network infrastructure?
- Does the mobility and social interactions of local users help to send tourists' information efficiently?
- Do local users' mobile networks succeed at integrating tourists' and cloud networks successfully to build an integrated mobile opportunistic/cloud-based platform?

5.1 Background

In this Chapter, our goal is to understand how we can provide cloud-based applications in the absence of dedicated network infrastructure. Much research has investigated how to best integrate mobile applications and cloud infrastructure. These various mobile cloud architectures are characterised as the following classes i.e., D2C (cf. Chapter 3.3.1), C2D (cf. Chapter 3.3.2) and D2D (cf. Chapter 3.3.3) mobile cloud architectures. We find that, the D2C class of mobile cloud architecture does not work well in the absence of Wireless Wide Area Networks (WWANs). Similarly, the C2D class of mobile cloud architecture is not well suited to the absence of WWANs. Finally, the D2D class of mobile cloud architecture requires a constant Internet connection to access remote cloud-based applications via the user's mobile devices.

Most of these architectures study a use case where traditional cloud-based applications are used on mobile devices, or mobile applications are used in a cloud-based platform, in the presence of an available and reliable network infrastructure. Further, unlike our work, most of the architectures either require an expensive Internet connection or they do not focus on how tourists can access remote cloud-based services in the absence of an available network infrastructure.

As illustrated in the MoCC architecture (cf. Chapter 4.2), the tourists' mobile devices cannot directly access cloud servers but can communicate with local users; while local users are able to connect their mobile phones with the Internet to reach cloud severs. Since tourists may be travelling without easy access to mains power, they may be concerned about their mobile devices' limited battery and storage resources, and wish to store data before the power in their devices run out. Therefore, we introduce *information storage hubs* which are static devices, situated in tourist spots, where tourists can store their data without an Internet connection. Tourist spots are places and attractions where tourists often visit. When local people visit the hubs, they can then collect data from the hubs and in turn are able to upload the tourists' messages to the remote cloud servers (cf. Chapter 4.2.5) using *cloud gateways*. We consider that, the cloud gateways are the Internet access points (cf. Chapter 4.2.4), used to send information to the remote cloud servers. Cloud gateways are situated in places like a library, a University building, etc., where local users are able to access Internet connections for their mobile devices to access cloud-based applications to upload tourists' messages into the cloud.

Returning to our motivation (in Chapter 1.1), Bob and Ron have difficulties gaining access to the cloud-based applications. As illustrated in Fig. 5.1, in such situations, Bob could transfer/store some of his photographs into an information storage hub, which then will allow the local user to send his photographs to their intended destinations using cloud-based services. Ron may also be able to use the online cloud translator via his mobile device for translating the meaning of the language, with the help of the mobile devices available locally.

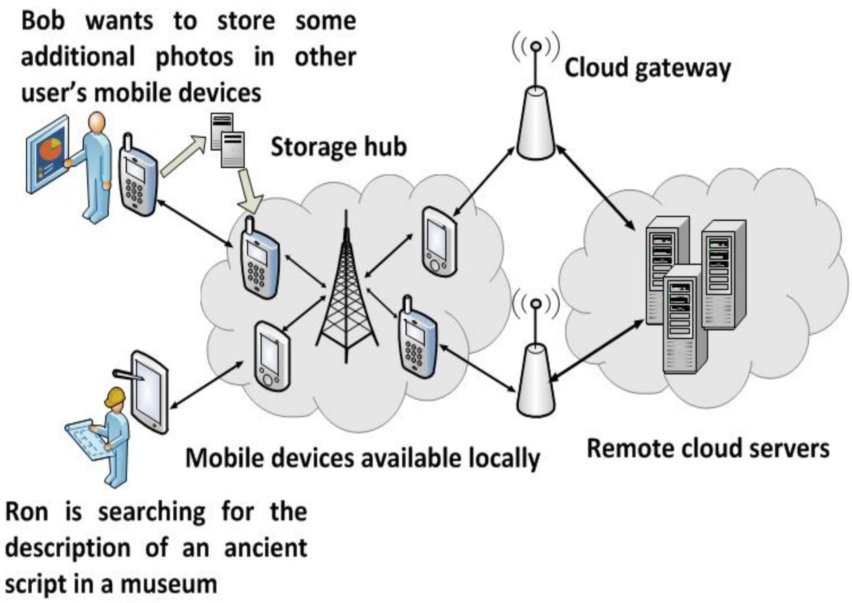

Figure 5.1: A use case of the MoCC architecture (e.g., cf. 4.3.1), is where tourists search for local users who may help to store photographs or perhaps help to understand the meaning of an ancient script. Local users may help tourists by giving storage or information by providing local mobile network infrastructures or with the help of the local users' mobile networks tourists can avail cloud-based applications.

In order to transfer/store additional information for a tourist in an information storage hub the tourist could be charged a nominal one-time only fee, per transaction or a weekly, monthly or yearly subscription for a more frequent visitor, depending on the tourist's choice. This would not only help the tourist to store their extra data to those devices but also benefit the storage facility in order to increase the probability of data forwarding through the local users. The individual organizations, companies or local authorities (e.g., the local council) could be the owners of these storage hubs. The fees paid to those organizations would be used to maintain those storage hubs.

Further, we believe that high roaming costs are issues that need to be overcome. The storage devices (i.e., information storage hubs) could be an alternative and can be beneficial for the tourists in places with a high Internet roaming cost. This may not force a network operator to reduce the high cost roaming charges but the storage devices could be an alternative for a tourist to avoid the high roaming cost, it would be the tourist's choice.

5.2 Experimental Analysis

In this section we analyse our proposed experiment with a real-world trace-driven simulation study. In the beginning, we discuss the evaluation methodology along with the performance metric used for the experiment. Then we explore the simulation setup which includes details for the nodes' characteristics and routing protocols involved in the experiment. Next we discuss and analyse the achieved simulation results.

5.2.1 Evaluation Methodology and Performance Metric

We use the 'ONE' (Opportunistic Network Environment) simulator for the simulation of the proposed experiment [165]. We carry these simulations using real-world human trace-driven data. This can be obtained from the 'crawdad'[1] data archive. We derive a simulation testbed for a simulation time of seven days. We ran each simulation 100 times with different random number generator seeds.

In the experiment, we explore three different modes of message forwarding behaviour for tourists, namely: *Everyone Forwarding* (EF), *Local Forwarding* (LF) and *Pickup and Forwarding* (PF). They are discussed as follows. Note that we assume that all the tourists and local people in the network

[1]http://crawdad.cs.dartmouth.edu/

are trusted, although a reputation framework could easily be incorporated, e.g., [163].

- **Everyone Forwarding (EF):** Everyone in the network is willing to store and forward messages for each other. Suppose a tourist sends message to the network, then every other tourist and local people are able to carry and forward this message until it reaches its final destination using the cloud infrastructure.

- **Local Forwarding (LF):** In this mode of message forwarding, tourists generate messages but unlike in EF mode, tourists do not store and forward messages to their destinations. Only local users store and forward the tourists' messages for them while both are moving within the network.

- **Pickup and Forwarding (PF):** As outlined in Chapter 5.1, tourists might be concerned about their devices' limited battery and storage. In PF mode, tourists use the information storage hubs located in tourist spots to store their messages. These stored messages will then depend upon the local users to carry and forward them until the messages reach their intended destinations using the cloud infrastructure. Unlike the LF mode, in PF mode tourists nodes do not need to interact with local nodes to forward messages. Instead, interaction takes place via the hubs, an appropriate incentive framework [11] can encourage local users to act accordingly.

We choose the commonly-used metrics to evaluate the overall routing performance [166]. They are as follows: (i) **Delivery Ratio:** The proportion of the delivered messages to the total number of messages created in the network. (ii) **Delivery Cost:** The total number of medium accesses, normalised by the total number of messages created. (iii) **Delivery Delay:** The total amount of time to send messages from source to destination.

To test the significant differences among the sample means, we used the ANalysis Of VAriance (ANOVA) in our experimental analysis. The use of ANOVA is aided by the underlying distributions in contrast of more than two means, when the dependent variable is continuous or fragmented in two, and the independent (predictor) variable is a set of discontinuous (i.e., discrete) categories. All simulations are performed in batch mode. This performance analysis has been done on a computer which has the following configurations of 2 GB RAM, 500 GB hard disk and an Intel core i3 processor @2.27 GHz.

5.2.2 Mobility Model and Traces

To illustrate the performance of the employed experiment we simulate our own university town, St Andrews. We design a simulation scenario which consists of four different node-groups i.e., Tourist Nodes (TN), Local Nodes (LN), Cloud Gateways (CG) and Information Storage Hubs (IS). They are discussed as follows:

- **Tourist Nodes (TN):** In our simulation we used tourists (referenced as TN). The tourists are defined as those who are travelling or visiting a place and using their mobile devices and trying to gain access to the cloud-based services with the help of the locally available mobile networks (i.e., mobile devices available locally, cf. Fig. 5.1).

  As we lack traces of tourist activity, we develop a new "TouristActivity-Based" movement model to simulate tourists' behaviour and nature of visits in different places. We assume that tourists visit a place, perform an activity, e.g. taking photos and then move onto another place. Using publicly-available tourist data[2] we prepare the movement model for our simulation. The various tourists' activities include visit time, type of attractions (visit places), average time spent in these places, etc. Based on the tourists' attractions, we choose different probabilities for 10 different

[2]http://www.visitscotland.org/pdf/visitorattraction-monitor2009.pdf

‘Points of Interests’ (POIs) for tourists. We do the same for all tourists nodes in our simulation. POIs include historical sites (e.g., St Andrews Castle, St Andrews Cathedral, etc), entertainment places (e.g., golf club, cinema, etc) or places that they might visit to collect specific information about the town (e.g., the tourist information centre). Tourists generate one message every 9 to 10 minutes while visiting tourist spots. We generate appropriate POIs for tourists using ‘OpenJUMP’[3].

- **Local Nodes (LN):** Local users (referenced as LN) are an important part in such communications as they form a local mobile communication platform for sharing information with their peers within their mobile communication range. When a TN comes close to LN within this network range the opportunity arises for a possible message communication exchange and eventually that happens. To simulate the LN, we use the ‘SASSY’ dataset [167]. This dataset is collected in St Andrews with 27 participants equipped with 802.15.4 Tmote Invent sensors and trackers within a range of 10 metres over a period of 79 days.

- **Cloud Gateways (CG):** The cloud gateways (referenced as CG) are the Internet access points, situated in fixed locations, used to send/retrieve information to/from the remote cloud servers. We situate CG (i.e., static nodes) in different locations throughout the town (e.g., Computer Science building, art gallery, student residences, etc) where local users have Internet connectivity and can forward collected messages to the remote cloud over the Internet.

- **Information Storage Hubs (IS):** In the experiment, we situate different information storage hubs (referenced as IS) in tourist spots throughout the town (e.g., St Andrews Castle, St Andrews Cathedral) where tourists can store their messages without having any Internet connection.

[3] http://www.openjump.org/

As we explore a challenged environment scenario to deploy the proposed simulation, we restrict the tourists from gaining access to these CGs. To this end, in the simulation, the TN cannot directly access the CGs but can reach/communicate with them through the help of the LN, who have full access to these CGs. We assume that if a message reaches to the CG, its status becomes delivered.

5.2.3 Simulation Parameters

Table 5.1 summarises the simulation parameters. The network consists of 100 nodes (27 LN, 60 TN, 6 CG and 7 IS nodes).

Table 5.1: The simulation parameters used in the experiment.

Parameter	***Value***
World Size	4500m X 4500m
Simulation Time	7 days
Movement Model	"TouristActivityBased" Movement Model (cf. Chapter 5.2.2)
Routing Protocols	Epidemic; Prophet; MaxProp
Node Buffer Size	200MB
Transmission Speed	250 KBps
Transmission Range	10m
Transmission Medium	Bluetooth Interface
Message TTL (Time-To-Live)	1 day
Node Movement Speed	Min=0.5 km/h Max=1.5 km/h
Generated Message Size	500 KB to 1 MB

5.3 Results and Performance Evaluation

We now evaluate the routing protocols to determine the performance impact of the different message forwarding behaviours in the MoCC architecture. We use the three performance metrics (cf. Chapter 5.2.1) i.e., delivery ratio, delivery cost and delivery delay. We use Epidemic as a baseline to compare and contrast the routing performance with the other two routers (cf. Chapter 2.3).

5.3.1 Delivery Ratio

Fig. 5.2 shows how MaxProp routing improves the message delivery performance (median delivery ratio 69.04%) compared with Prophet and Epidemic routers while everyone in the network is forwarding messages.

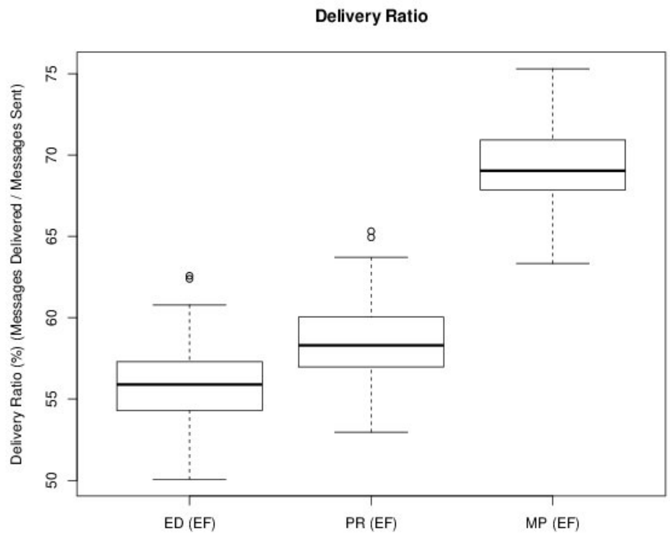

Figure 5.2: In EF, ED routing generates large amounts of messages in the network, although due to the nodes' buffer size and TTL most messages were dropped before they reached their destination. MP and PR routing sends messages by keeping the previous history of delivered messages. This results in a higher delivery ratio for MP(EF) and PR(EF) than ED(EF). (ED=Epidemic router, PR=Prophet router, MP=MaxProp router and EF=Everyone Forwarding).

Fig 5.3 shows the comparison of delivery ratio of Epidemic, Prophet and MaxProp routers when tourists' messages are forwarded by local users, using their mobility patterns and by storing tourists' messages into information storage hubs.

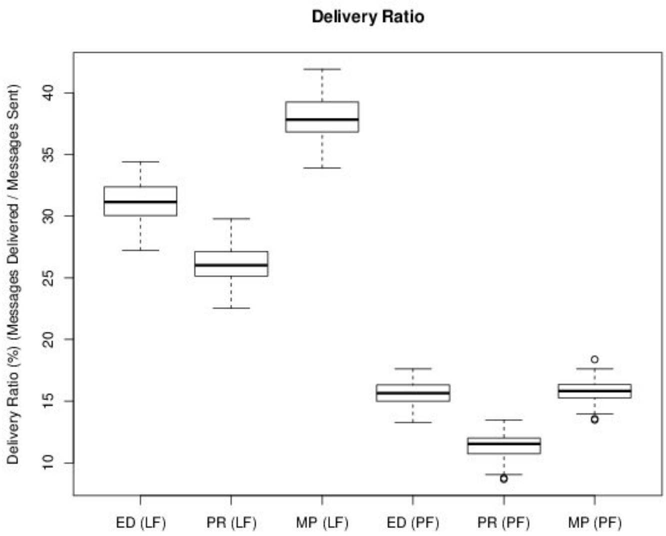

Figure 5.3: In LF, only tourist nodes generate messages and local nodes forward them when ever nodes encounter each other. In PF, tourist nodes deposit messages to the static storage hubs then messages were forwarded depending on the interactions between storage hubs and local users. The result is a higher delivery ratio for LF than PF modes. (ED=Epidemic router, PR=Prophet router, MP=MaxProp router, LF=Local Forwarding and PF=Pickup and Forwarding).

We find that the delivery ratio of MaxProp, Prophet and Epidemic routers increases while using local users' mobility patterns compared with the storing of data into hubs. We see that in the first case, the message delivery ratio of MaxProp router is more than double (median delivery ratio 37.84%) than in the second case (median delivery ratio 15.83%) (cf. Fig. 5.3). We believe the reason for this is that the probability of meeting a tourist and local node is higher when both of them are moving in the network. On the contrary, the delivery ratio of the Epidemic router decreases when everyone in the network is forwarding messages (cf. Fig. 5.2), because a large amount of messages stored by all nodes are dropped, as buffer constraint is a pivotal factor of this routing performance.

We note that exploring local users' mobility patterns, the MoCC architecture gives a better message delivery performance ($\mu = 31.69$, $\sigma = 5.05$) than storing data into hubs ($\mu = 14.29$, $\sigma = 2.23$). But as expected, in the baseline EF, the message delivery performance ($\mu = 61.26$, $\sigma = 6.22$) is higher; a two-way ANOVA shows significant differences in the overall rate of the message delivery ratio [$F(2,891) = 0.00$, $p<0.05$].

5.3.2 Delivery Cost

Fig. 5.4 shows that the delivery cost of Epidemic routing is higher than the delivery cost of MaxProp and Prophet routers. The reason is that by Epidemic routing, a node will generate more copies of a message so that its buffer saves many copies of different messages, and the buffers therefore fills up.

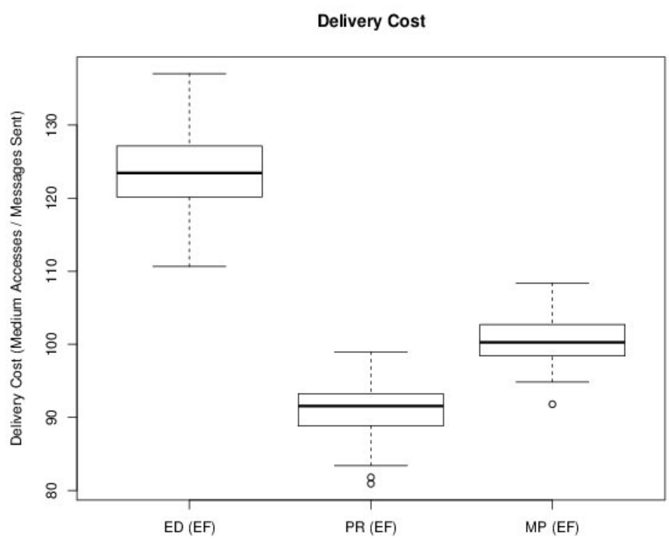

Figure 5.4: MP and PR routers deliver higher amounts of messages to their destinations by using encounter histories. This results in lower delivery costs for MP and PR routers over the ED router in EF mode. (ED=Epidemic router, PR=Prophet router, MP=MaxProp router and EF=Everyone Forwarding).

Fig. 5.5 presents the results of message delivery costs for the Epidemic, Prophet and MaxProp routers when we use LF and PF modes of message forwarding behaviours.

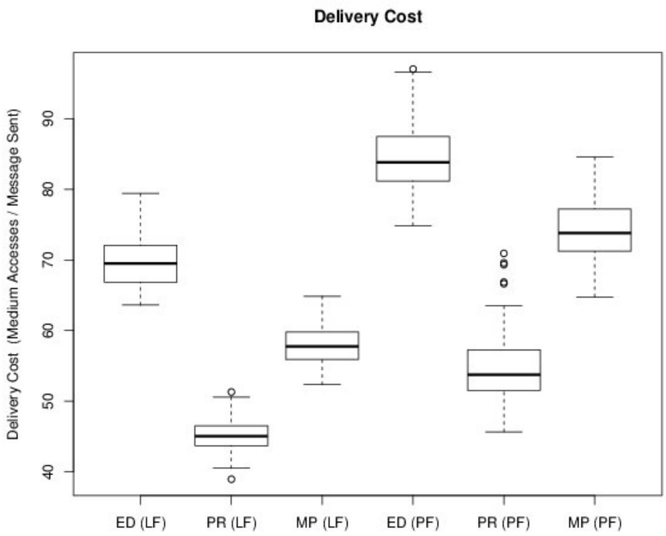

Figure 5.5: Local users' mobility patterns in LF mode helped a higher number of tourists' messages to reach their destinations than in PF mode. This resulted in a lower delivery cost for LF mode than PF mode. (ED=Epidemic router, PR=Prophet router, MP=MaxProp router, LF=Local Forwarding and PF=Pickup and Forwarding).

We find that the message delivery cost, by using LF ($\mu = 57.66$, $\sigma = 10.43$) is lower than message delivery cost of PF ($\mu = 71.21$, $\sigma = 13.12$). As expected message delivery cost is higher when choosing baseline EF ($\mu = 104.99$, $\sigma = 14.28$), a two-way ANOVA shows significant differences in the overall rate of message delivery cost [F (2,891) = 0.00, p<0.05].

5.3.3 Delivery Delay

Fig. 5.6 shows that the delay in Epidemic routing is higher than MaxProp and Prophet routers when everyone forwards messages in the network.

In the EF mode of message forwarding behaviour, a higher number of messages are generated in the network. We observe that due to the nodes buffer constraints, the Epidemic router drops a number of messages in the network before they are delivered to their destinations, which increases the

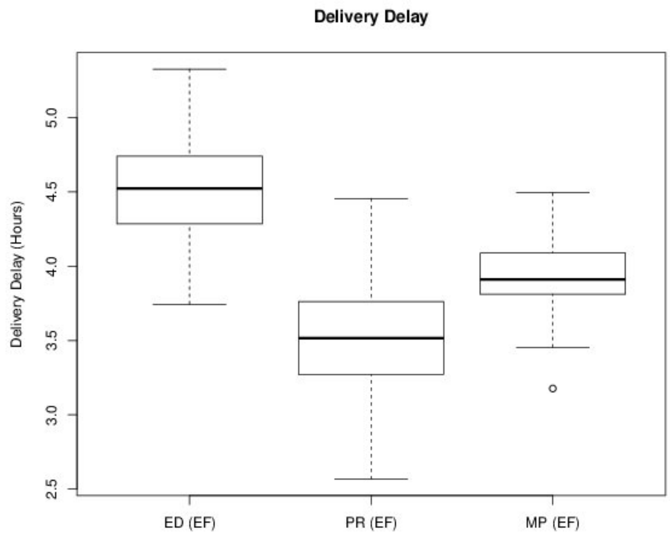

Figure 5.6: In EF, MP and PR routers send messages by keeping an encounter history of delivered messages, whereas the ED router drops a larger amount of messages depending on the nodes' buffer size and TTL. This results in higher delivery delays for ED(EF) than PR(EF) and MP(EF). (ED=Epidemic router, PR=Prophet router, MP=MaxProp router and EF=Everyone Forwarding).

overall message delivery delay in EF.

Fig. 5.7 shows that when tourists store their messages into hubs, the delay of Epidemic, MaxProp and Prophet routers are largely higher than that of forwarding data using local users mobility patterns. This is reasonable because the copies of messages reaching their destinations are faster than in the later case. The reason for the increase of the delay is that by storing data into hubs, each copy of a message has to wait for a longer period of time to reach its destination, as this depends on the encounters between hubs and local nodes. We find that PF has a higher message delivery delay ($\mu = 3.47$, $\sigma = 0.10$) than LF ($\mu = 3.06$, $\sigma = 0.10$). As expected message delivery delay is higher when choosing the baseline EF ($\mu = 3.99$, $\sigma = 0.52$), a two-way ANOVA shows significant differences in the overall rate of message delivery delay [F (2,891) = 0.00, p<0.05].

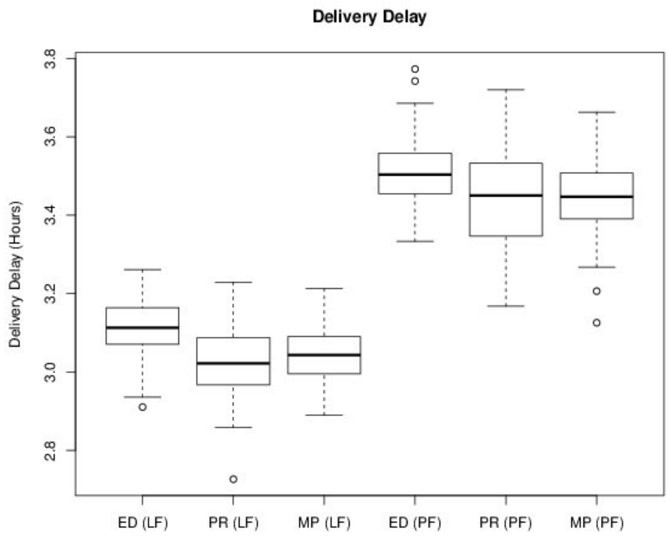

Figure 5.7: In LF, tourists' messages reach their destinations using local users' mobility patterns. In PF, tourists nodes deposit messages into the storage hubs and those messages are forwarded depending on the interactions between the storage hubs and the local users. This resulted in higher delivery delays for PF over LF. (ED=Epidemic router, PR=Prophet router, MP=MaxProp router, LF=Local Forwarding and PF=Pickup and Forwarding).

5.4 Discussions

In this section we have summarised the lessons learned from the above simulation study. We outline our results as follows:

- As a baseline, EF mode of message forwarding behaviour provides the best message delivery performance in the MoCC architecture, but at the same time it increases the message delivery cost and delays.
- By storing data into hubs, the PF mode of message forwarding behaviour may lead to dramatically lower routing performance for our proposed MoCC architecture.
- Exploring local users' mobility patterns, the LF mode of message forward-

ing behaviour provides the optimal message delivery performance when considering message delivery cost and delays.

Further, it is probable that tourists nodes may be unwilling to share their phone memories with other nodes due to the lack of battery power or memory size, e.g., in the PF mode they are storing their messages into well situated information storage hubs and in the LF mode they depend upon local users' mobility patterns to deliver their messages. Our results indicate that the best possible solution is for a tourist to share their messages with any available local node while they are both moving within the network. Designing a protocol that can provide appropriate incentives is therefore needed [164].

Returning to our motivation scenarios (cf. Chapter 1.1), message delivery performance will be higher for Bob in an EF case. Ron however, is interested in getting the information as soon as possible. As we see that the message delivery delay is minimum in the LF mode that would be the best choice for him. Further refinement is needed to find a protocol that can meet the requirements of both applications, or perhaps a QoS-like mechanisms for declaring appropriate forwarding strategies is required.

In general, the null hypothesis for ANOVA indicates that, the sample means are closely similar and obtained by extracting the samples from the same population. In our simulation, we used three different message forwarding behaviours (i.e., Everyone Forwarding (EF), Local Forwarding (LF), and Pickup and Forwarding (PF)) against three different routing protocols (i.e., Epidemic, Phophet and MaxProp). The test allowed us to measure the differences among the various means by examining the ratio of variability among three conditions and variability within each of them, i.e., three message forwarding behaviours provide statistically different results for the three routing protocols [168]. In addition to this, we employed this test to analyse the proposed experimental design because; it can be viewed as an extension of the t-test that is used for comparing more than two groups. Therefore, we used a “two-way ANOVA” to examine the impact of more than two simultaneously independent (predictor) variables in the population, i.e., the sample means of various groups are obtained from the same population, and the factors that are significantly affecting the performance characteristic are also explored [169].

Our work can also be extended to future research to investigate many areas, e.g.,

- While sharing information, tourists and local users may not wish to share some of their personal information with each other. How, by using MoCC will it possible to mitigate users’ privacy concerns while maintaining the same routing performance? In general, mobile opportunistic networks involve reliance on intermediate and unknown nodes, who may attempt to surveil or modify data being sent through the network. Therefore a potential research project is to investigate the privacy requirements for tourist’s information (cf. Chapter 4.4.1).

- Limited battery power for small devices (e.g., cellphones, tablets, PDAs, etc.) can curtail communications. Therefore more research is needed to investigate that how will this affect the message delivery performance in the MoCC infrastructure, when exploring the local users’ mobility patterns (cf. Chapter 4.4.3).

5.5 Summary

In this chapter, we explored the use of mobile opportunistic networking in the MoCC architecture (a “Device to Device to Cloud” architecture) that gives tourists access to cloud-based applications via local users’ network connections. We observed that:

- Firstly, it is possible to use remote cloud-based applications in a situation where there is no Internet connection and by avoiding the high costs of such infrastructure when available.

- Secondly, users' mobility and their interactions/collaborations have greatly influenced the overall message delivery performance within the network.

- Thirdly, by using a "Device to Device to Cloud" architecture, tourists can efficiently send messages to a cloud-assisted destination with the help of the local users' mobile communication networks.

We summarise the chapter as follows:

- We evaluated two potential options for transferring tourists' messages to the cloud services, by storing data at well-situated hubs and exploiting the mobility of local users.

- We demonstrated the potential for using local users' mobility techniques improves the message delivery performance rather than storing data into hubs. We observed however, that minimising delivery costs and delay may not necessarily be an indicator that a routing protocol will perform better than a protocol with a higher delivery cost and delay.

- We evaluated protocol performance with three different proposed modes of message transferring behaviours in three different routing protocols, they are the Epidemic, Prophet and the MaxProp routing protocols. The MaxProp routing protocol consistently perform well across the simulations.

- Our current experiments have only looked at one-way communication, where tourists are offloading messages to their destinations with the help of local users. But in the future we would like to investigate where tourists can also download information using the MoCC architecture.

In the next chapter (Chapter 6), we plan for more comprehensive experiments with real-life traces, to examine how the network performs with the changes of network load (e.g., number of messages) along with the long-sized messages when employing the MoCC architecture. This will in turn help to understand and make improvements in the performance of tourists' message forwarding techniques in challenged environments.

Chapter 6

Exploring the Impact of Network Loads and Message Size in Message Forwarding

In this chapter, we explore how the overall network performs with the changes of network load (e.g., number of messages) along with the long-sized messages when using the MoCC architecture.

In this chapter, the major contributions are:

- We evaluate the performance of the MoCC architecture in different opportunistic routing protocols with the varied (decreasing or increasing) network loads and message sizes generated by the nodes.
- With real-world trace-driven simulations, we compare and contrast the impact of the message generation rates and the message size in a challenged environment to see this performance impact.

The goal of this chapter is twofold. First, we vary message numbers and sizes to explore the overall impact made in message forwarding using the MoCC architecture in a challenged environment (cf. Chapter 2.2). Second, we employ real-world trace-driven data sets to observe the impact of local user's social interactions and collaborations in message forwarding in such cases.

The research aims to address the following research questions:

- How do the routing performances vary with the different network loads and message sizes generated by the nodes within the network?
- Does the network perform accordingly when the number or size of messages changes (decreases or increases) within the network?
- Do the mobility, interactions and social collaborations of local users make an impact on the overall message delivery performance in such scenarios?

6.1 Background

In mobile opportunistic networks, nodes select the next hop of message delivery with the information and contact opportunities available locally [24]. However, in a challenged environment these contact opportunities are more infrequent because of the lack of available users to establish a communication (cf. Chapter 4.4.4), or due to the device related constraint (e.g., battery power and limited memory size) (cf. Chapter 4.4.3).

Returning to our motivation (in Chapter 1.1), Ron searches for a nearby user who may be able to help him understand the meaning of the ancient script or help him to access a cloud-assisted online language translation community. Along with a similar line, suppose Alice is travelling to Chicago. She has a craving for a certain type of food at a very specific food store which she cannot locate. She is trying to find the store by using her mobile device but realises that the cost of Internet roaming in this area is simply too high. In this situation Alice would look for a nearby user who would be able to answer her specific question. This may result with the user passing the information on to Alice based on their local knowledge or on behalf of Alice, they are willing to search for this information on the Internet.

In the first scenario, Ron may take a picture of the manuscript and broadcast it over the network. However, the photo turns out to be a high resolution picture that requires a higher bandwidth to transfer. A nearby user can help Ron to find the meaning of the manuscript or help Ron to send it to his preferable cloud-assisted destination, but from the network bandwidth utilisation point of view this may not be a choice for that user because he/she may not have the capability for a higher bandwidth transfer or the message transfer cost becomes too high for him/her.

In the second scenario, Alice may anxiously be looking for this food store information and re-sends her same queries multiple times within the same network. This results in a nearby user receiving several copies of the same request that may fill his/her buffer capacity that he/she has kept for the other applications. This may also impact the receiving of other user's requests that may be more urgent than Alices.

In both the cases, Ron and Alice do not have any direct access to the Internet instead they fully depend upon the local users' network connections to gain the opportunity to access an Internet connection. The local users can connect their mobile devices with an Internet access point (cf. Chapter 4.2.4) in various places seamlessly (e.g., at home, library etc.).

Therefore, in the context of the availability and accessibility point of view, the previously mentioned situations reflect the same fundamental question: how the various network loads and message size make an impact on the overall message delivery performance when users are communicating in a challenged environment? There are several studies carried out showing the routing performances in different challenged scenarios based on the user's behaviours or different wireless network techniques [170] [171] [172] [173], but how the different network loads and message sizes impact the overall message delivery performance is lacking. Our motivation is therefore to see the overall network performances in such challenged environments with the changes of network loads (e.g., number of messages) and message sizes when using the MoCC architecture.

6.2 Experimental Analysis

In this section we analyse our proposed experiment with a real-world trace-driven simulation study. In the beginning, we discuss the evaluation methodology along with the performance metric used for the experiment. Then we explore the simulation setup which includes details of the nodes' characteristics and routing protocols involved. Next we discuss the achieved simulation results.

6.2.1 Evaluation Methodology and Performance Metric

We use the 'ONE' simulator for the simulation of the proposed experiment [165]. We carry out these simulations using real-world trace-driven data.

In the experiment, we simulate with two different settings of parameters for the generated message sizes and message generation rates. In the first set we used the message sizes of 256kB and 1MB. These particular message sizes were chosen because they are the standard for a text and an image, in varying degrees of message sizes. Messages are originated in randomly chosen nodes with a message size of 256kB and 1MB, and are created throughout the simulation time. In the second set we varied the message generation rate of 1 and 5 messages per 10 minutes (msg./mins.).

We derive a simulation testbed for a simulation time of one day. We ran each simulation 10 times with different random number generator seeds. This is to note that when we varied the message sizes at that point we kept the fixed message generation rates to the node groups. Alternatively, when we varied the message generation rates we fixed the message size. We choose the three commonly-used metrics to evaluate the overall routing performance [166]. They are: Delivery Ratio, Delivery Cost and Delivery Delay (cf. Chapter 5.2.1). All simulations are performed in batch mode. This performance analysis has been done on a computer which has the following configurations of 2 GB RAM, 500 GB hard disk and an Intel core i3 processor @2.27 GHz.

6.2.2 Simulation Setup

In this section we discuss the simulation settings used for the proposed experiment.

We design a simulation scenario which consists of three different node-groups i.e., Tourist Nodes (TN), Local Nodes (LN) and Cloud Gateways (CG) (cf. Chapter 5.2.2).

As we explore a challenged environment scenario to deploy the proposed simulation, we restrict the tourists from gaining access to these CGs. To this end, in the simulation, the TN cannot directly access these CGs but can reach/communicate with them through the help of the LN, who have full access to these CGs. We assume that if a message reaches the CG, its status becomes delivered.

To illustrate the performance of the network, we simulate our own University town of St Andrews, comprised of tourists, students and local users. We choose a world size of 4500mX4500m for the simulation purpose and the network consists of 100 nodes (27 LN, 65 TN and 8 CG). We set the TTL value as half of a day for the message. We use a medium buffer of 200MB for the LN and TN. In the case of the CG we use unlimited buffer space.

When varying the message sizes, we keep a fixed message generation rate. For instance, in both of the following cases for the 256kB and 1MB of message size, the message generation rate is fixed to 1msg./10mins. On the other hand, when we vary the message generation rates for the nodes (i.e., the 1msg./10mins. and 5msg./10mins.), we fix the message sizes to the 512kB. We choose this message size of 512kB rather than the 256kB and 1MB because it will then conflict with the former simulation by repeating it.

The TN are generating messages and the other LN and TN are willing to store, carry and forward these messages to their intended destinations (i.e., CG in this case) while both LN and TN are moving within the network. But as we discussed earlier with regards to the challenged environments, a TN can only forward a message closer to the destination but the message will finally be delivered to a CG with the help of a LN.

To simulate the TN, we use a tourist-based movement model (cf. Chapter 5.2.2). This model is based on the tourist activities throughout St Andrews. In this model, a tourist visits several places of interests (e.g., St Andrews museum, St Andrews castle, St Andrews cathedral, information centres, Golf course, etc.) and performs some activities (e.g., taking photos). On the other hand, to simulate the LN, we use the 'SASSY' dataset [167]. We situate CG (i.e., static nodes) (cf. Chapter 5.2.2) in different locations throughout the town (e.g., Computer Science building, library, student residences, etc.) where local users (LN) have Internet connectivity and can forward collected messages to the remote cloud servers over the Internet.

We assume that the nodes in the network are trusted and forward messages for attractive incentives e.g., social reputation or money [53]. Furthermore, all nodes in the simulation use the Bluetooth broadcast interface for information interchange, given that the availability of the networks for communications might be lacking/restricted in a challenged environment. To see the overall message delivery performance in the network, we employ three relevant opportunistic routing protocols for our simulations. They are the Epidemic, Prophet and the MaxProp (cf. Chapter 2.3). We use the Epidemic routing as a baseline to compare and contrast the routing performance with the Prophet and the MaxProp routings.

6.3 Results and Performance Evaluation

In this section we outline the results achieved from the simulation-based studies.

6.3.1 Delivery Ratio

Fig. 6.1 presents the results of message delivery ratio for the Epidemic, Prophet and MaxProp routers when we vary the message sizes for the nodes.

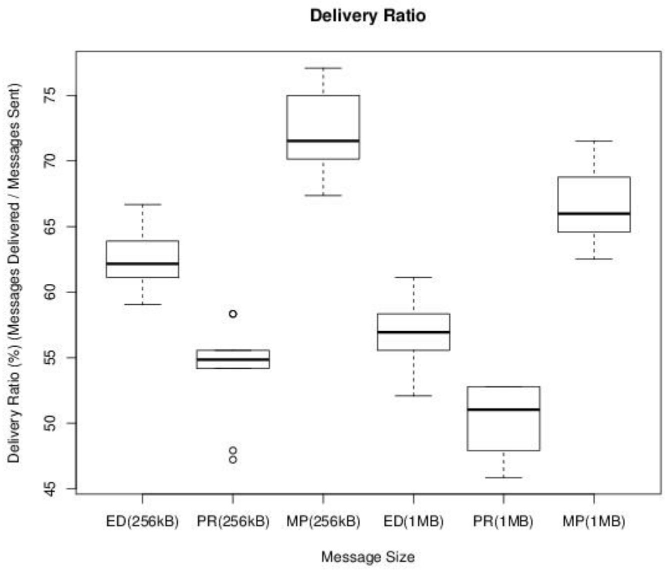

Figure 6.1: The MaxProp router performs consistently with the increased message sizes than the Epidemic and Prophet routers. Results show that for the 256kB of message the median message delivery ratio for the MaxProp router is 71.53% and for the 1MB of message the median message delivery ratio is 65.97%. (ED=Epidemic router, PR=Prophet router and MP=MaxProp router).

With the increased message sizes, we find that the MaxProp router consistently gives the best message delivery performance in the network. For instance, in the case of the 256kB of message size the median message delivery ratio is 71.53%, where in the case of the 1MB message size the median delivery ratio becomes 65.97%. The improvement made in the case of the 256kB message size is 5.53% greater than that of the 1MB message size. The median message delivery ratio for the Epidemic router in the case of the 256kB of message size is 61.81% and for the 1MB of message size it is 56.94%. In addition, with the Prophet router in the case of the 256kB of message size, the median message delivery ratio is 54.86% and for the 1MB of message size it is 51.04%. Compared with the Prophet router, both the Epidemic and MaxProp routers give the better message delivery performance with a higher message delivery ratio. However, when the message size increases, we see that the performance for all three routers decreases. This is due to the node's buffer constraint.

Fig. 6.2 presents the results of message delivery ratio for the Epidemic, Prophet and MaxProp routers with different message generation rates for the nodes.

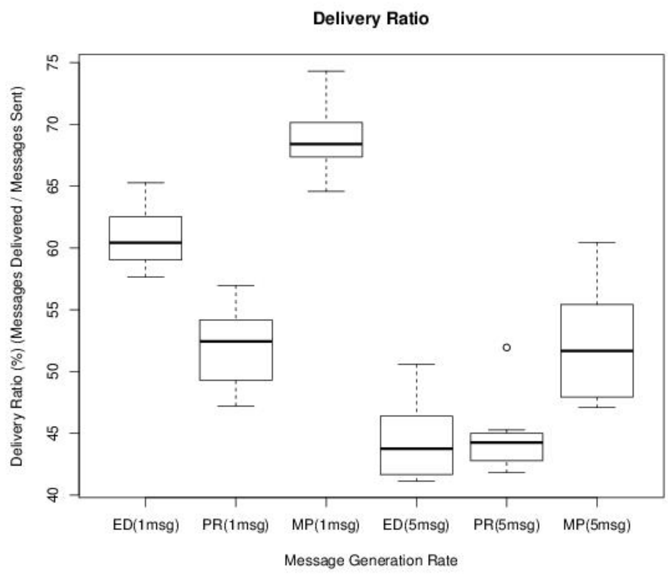

Figure 6.2: The MaxProp router performs better in the message delivery by using node's encounter histories. Results show that for the 1msg./10mins., the median message delivery ratio for the MaxProp router is 68.41% and for the 5msg./10mins. the median message delivery ratio becomes 51.67%. (ED=Epidemic router, PR=Prophet router and MP=MaxProp router).

In this simulation, we take into consideration two possible scenarios (cf. Chapter 6.2.2). First, in a lower message generation rate (1msg./10mins.) and second, in a higher message generation rate (5msg./10mins.). For instance, a user may create/broadcast one message per ten minutes but at certain periods of time it can be increased to five messages per ten minutes (i.e., generating/broadcasting a message every two minutes). This is possible in cases where a user visits a tourist-attraction place and takes photos more often (and save the images) which increases the number of messages.

Back to the results (cf. Fig. 6.2), we see that for the 1msg./10mins., the median message delivery ratio for the MaxProp router is 68.41% and it decreases to 51.67% for 5msg./10mins. Additionally, in the case of the 1msg./10mins., the median message delivery ratio for the Epidemic router is 60.42% and for the 5msg./10mins., it becomes 43.74%.

Interestingly enough, we note that the Prophet router gives the lowest message delivery performance for the first case (i.e., node's generating 1msg./ 10mins.). In such cases, the Prophet router is affected by the node's limited buffer size and their message delivery capability (based on a higher delivery predictability) diminishes with the employed TTL value. But in the second case (i.e., node's generating 5msg./10mins.), the message delivery performance decreases substantially for the Epidemic router compared to other routers. Because the Epidemic router generates a larger amount of messages (as it replicates messages with flooding-based routing mechanisms) due to its buffer constraint, it drops most of the packets before they reach their destination nodes.

Furthermore, we also observe that the MaxProp router consistently gives the better message delivery performance with a high message delivery ratio for both the case of increased message size (1MB) and a higher number of message generation rates (5msg./10mins.). This is because the MaxProp router keeps track the previous encounter histories to interact with the next node that has a higher encounter frequency, which means the newly-encountered node has a greater chance to deliver the message faster to the destination.

In summary, the lower message size (256kB) gives the better performance in the network (μ=63.01, σ=8.19) than the increased (1MB) message sizes (μ=57.89, σ=7.34). With the lower message generation rates (1msg./10mins.), the overall message delivery performance is better (μ=60.63, σ=7.50) than the increased (5msg./10mins.) number of message generation rates (μ=47.16, σ= 5.21). A two-way ANOVA shows significant differences in the overall rate of the message delivery ratios in both the cases [$F(2,81) = 0.00$, $p<0.05$].

We find that, when the network load (i.e., the number of messages in this case) and the message size increases, the overall message delivery performance reduces for the Epidemic router due to the node's buffer constraint. In the case of the Prophet router the message delivery ratio is also affected by the node's limited buffer size and the TTL value, where messages are dropped before they reach their intended destinations. But unlike the Epidemic router, the Prophet router does not replicate the same message to every newly-encountered node. It uses a delivery predictability which is a 'probabilistic metric' for message delivery. This delivery predictability indicates a new node's likelihood to encounter the destination node, based on its previous encounters with the destination node to deliver a message. Thus, in the case of the Prophet router the nodes required a higher delivery predictability to successfully deliver a message, thereby reducing the encountering opportunities with other nodes that have lower delivery predictability. Thus, the low encountering opportunities result in low message delivery performance in the network.

However, in the case of the MaxProp router, using the social strength and storing previous encounter histories, the nodes increase the chances for delivering more packets efficiently (i.e., by using low hop counts) to the destinations which in turn increase the overall message delivery ratio in the communication.

6.3.2 Delivery Cost

Fig. 6.3 shows the results of the message delivery cost for the Epidemic, Prophet and MaxProp routers when we vary the message sizes for the nodes.

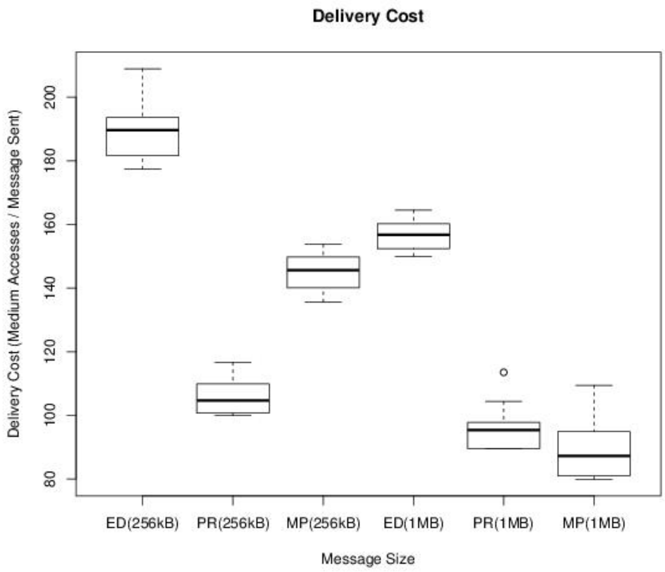

Figure 6.3: The Epidemic router replicates a larger amount of messages which increases the message delivery cost. Results show that for the 256kB of message the median message delivery cost for the Epidemic router is 189.60 and for the 1MB of message the cost is 156.71. (ED=Epidemic router, PR=Prophet router and MP=MaxProp router).

In this case, we use two types of message sizes i.e., the 256kB and the 1MB. The 'cost' is determined by the number of messages replicated to successfully deliver a message from source to destination. We see that, for the 256kB of message size, the median message delivery cost for the Epidemic router is 189.60 and for the 1MB of message it is 156.71. For the MaxProp router, the median message delivery cost for the 256kB of message size is

146.32 and for the 1MB of message size the median message delivery cost is reduced by 26.76 and it then becomes 87.24.

Moreover, in the case of the 256kB of message size, the median message delivery cost for the Prophet router is 105.55. This is the least cost as compared to the median message delivery cost of the Epidemic and MaxProp routers for the same message size (i.e., 256kB). This is due to the fact that the Prophet router follows a high probabilistic-based solution for message delivery. The message only delivers when the probability of a newly-encountered node has a higher chance for a successful encounter with the destination node. This is determined by the previous encounter histories between the nodes. In the context of our present simulation, with fewer contacts for message delivery less replicated messages are generated causing lower message delivery cost for the Prophet router.

We find an interesting fact in the message delivery cost for the 1MB of message size. We notice that the median message delivery cost in the case of the MaxProp router is relatively lower than the Prophet router (with a difference of 10.16). We observe that with the increase in message size and a node's limited buffer constraint, the nodes in the MaxProp router hold fewer messages for delivery. Furthermore, by using the user's social contacts and interactions these messages are successfully delivered to their destinations faster by creating lesser number of replications. Therefore, in this case it reduces the overall message delivery cost.

Fig. 6.4 shows the results of message delivery cost for the Epidemic, Prophet and MaxProp routers with the different numbers of message generation rates for the nodes.

We see that the median message delivery cost for the case of the 1msg./10mins. with the Epidemic router is 170.80 and it reduces to 143.94 for the 5msg./10mins. Upon this, we notice that the Epidemic router gen-

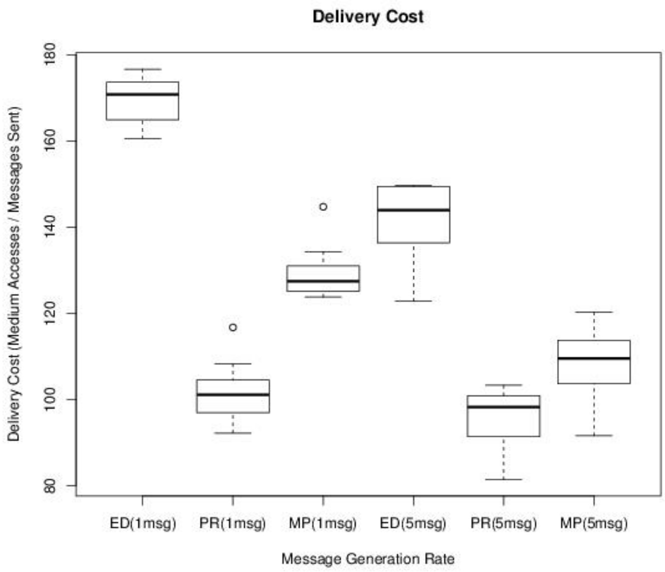

Figure 6.4: The Epidemic router has a higher number of message delivery costs than the MaxProp and Prophet routers. Results show that for the 1msg./10mins., the median message delivery cost for the Epidemic router is 170.80 and for the 5msg./10mins. the cost is 143.94. (ED=Epidemic router, PR=Prophet router and MP=MaxProp router).

erates numerous amounts of messages in the network as it replicates the same copy of the message when it encounters a new node, until the message reaches its destination. Thus, this large amount of message replication increases the message delivery cost in this router.

On the other hand, for the MaxProp router the median message delivery cost for the 1msg./10mins. is 127.46 and in the case for the 5msg./10mins. is 109.53. Both of these results find less cost in the MaxProp router compared with the Epidemic router. We observe that, the MaxProp router increases the message delivery performance by keeping track of the previous encounter histories with the other nodes. In such cases a node that is able to send a message to the destination with low hop counts receives a high priority. Therefore, the results show, the MaxProp router delivered messages with fewer copies of the replications than the Epidemic router.

Finally, the median message delivery cost for the Prophet router is less than the Epidemic and MaxProp routers in both of the simulations. For instance, the median message delivery cost in the case of the 1msg./10mins. is 101.10 and it becomes 98.27 for the 5msg./10mins.

In summary, the smaller message size (256kB) gives the lowest in message delivery cost (μ=146.75, σ=35.41) than the higher (1MB) message sizes (μ=114.32, σ=31.51). Likewise, we find that, with the smaller message generation rate (1msg./10mins.) the overall message delivery cost is higher (μ=133.52, σ=28.72) for the increased (5msg./10mins.) message generation rate (μ=114.73, σ= 21.06). A two-way ANOVA shows significant differences in the overall rate of the message delivery cost in both cases [$F(2,81) = 0.00$, $p<0.05$].

We observe that the nodes using the Epidemic router generates a higher numbers of messages in the network which in turn increases the overall message delivery cost. On the other hand, the MaxProp router can be thought of as an optimisation of the Epidemic router to better cope with non-ideal conditions e.g., in limited buffer size. In such cases, a message should be delivered when the predictability of newly-encountered nodes have a greater probability to reach their destination, than the node currently carrying the message. This is determined by counting the numbers of previous interactions with each other. Moreover, by using social relations along with the node's encountering histories, the MaxProp router delivers messages to the destinations with low hop counts. Thus, with the lesser number of replications the MaxProp router reduces the message delivery cost significantly less than the Epidemic router. But in the case of the Prophet router, nodes not only keep the history of previous encounters but also determine the probability of future encounters between the nodes that have frequent contacts with the destination nodes. Thereby it reduces random encounters and the replication of the messages.

6.3.3 Delivery Delay

In Fig. 6.5 we can see the message delivery delays for the Epidemic, Prophet and MaxProp routers when we vary the message sizes for the nodes.

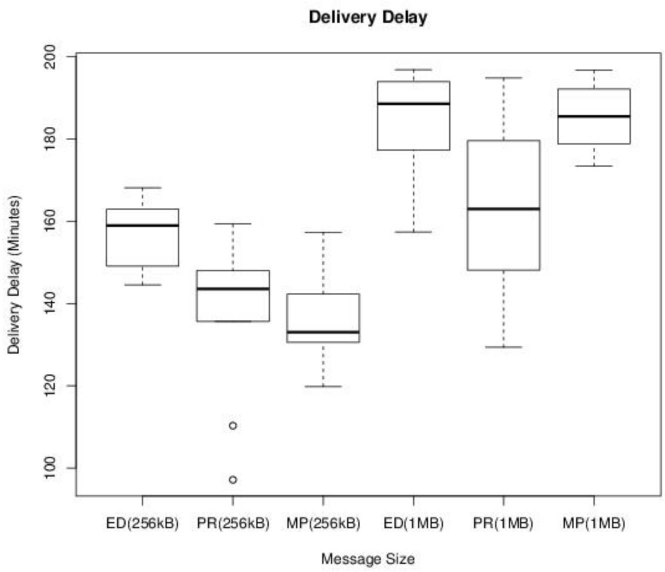

Figure 6.5: The Epidemic router drops a higher amount of messages due to its buffer constraint. Results show that for the 256kB of message size, the median message delivery delay for the Epidemic router is 158.96 (minutes) and for the 1MB of message size, the median message delivery delay is 188.56 (minutes). (ED=Epidemic router, PR=Prophet router and MP=MaxProp router).

We evaluate the performance with two sets of message sizes i.e., 256kB and 1MB. For the 256kB of messages the median message delivery delay for the Epidemic router is 158.96 minutes and for the 1MB of message size it becomes 188.56 minutes. To this end, we find that due to the node's buffer constraints the Epidemic router drops a number of messages in the network before they are delivered to their destinations, which increases the overall message delivery delay in message forwarding. Likewise, in the case of the increased message size (1MB), the node's limited buffer size in the Epidemic router drops more packets which significantly increases the message delivery delay. Along a similar line, due to the buffer constraints, the MaxProp router drops packets in both cases resulting in a median message delivery delay of 136.30 minutes for the 256kB of message size and 185.52 minutes for the 1MB of message size.

However, in the case of the Prophet router the median message delivery delay for the 256kB of message size is 143.58 minutes. Interestingly enough, we notice that in the case of the 1MB of message size, the Prophet router gives the lowest message delivery delay in the network (i.e., 163.02 minutes) compared with the Epidemic and the MaxProp routers. We observe that the Prophet router only selects messages that have higher contact/encounter histories with the destination nodes. Therefore, along with the fewer replications and the possible delivery opportunities closer to the destination, in this case it reduces the overall message delivery delay in the network.

Fig. 6.6 shows the results of the message delivery delays for the Epidemic, Prophet and MaxProp routers with the different message generation rates for the nodes.

When we vary the message generation rates to 1msg./10mins., the median message delivery delay for the Epidemic router is 150.74 minutes and for the 5msg./10mins it is 180.35 minutes. In both the cases we observe similar routing performances. We also observed that due to the node's buffer limitations, the Epidemic router drops a large amount of message which caused high message delivery delays in the network.

We further find that, with the increased network load, the Prophet and MaxProp routers perform in a similar way for both cases. The median message delivery delay is relatively low for the Prophet router as compared to the MaxProp router. For the 1msg./10mins., the median message delivery delay for the Prophet router is 137.10 minutes and it is 148.25 minutes for the MaxProp router. Along the same line, for the 5msg./10mins., the median message delivery delay for the Prophet router is 146.84 minutes and it is

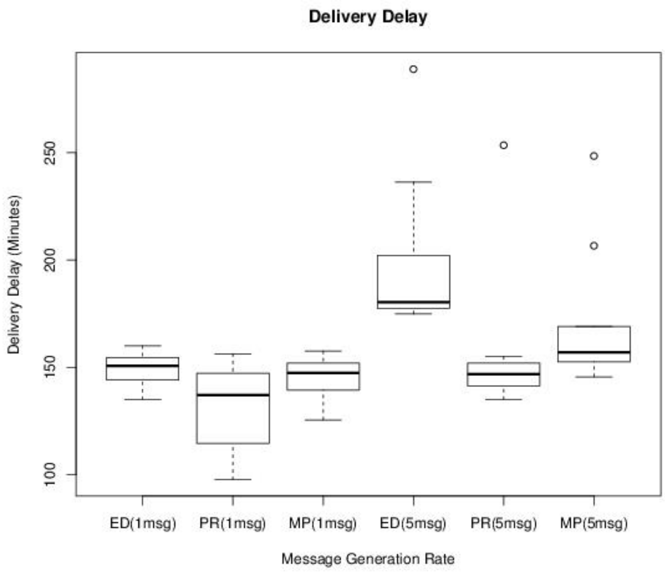

Figure 6.6: The MaxProp and Prophet router have a relatively lower message delivery delay than the Epidemic router. Results show that for the 1msg./10mins., the median message delivery delay for the Epidemic router is 150.74 (minutes) and for the 5msg./10mins., the median message delivery delay is 180.35 (minutes). (ED=Epidemic router, PR=Prophet router and MP=MaxProp router).

157.01 minutes for the MaxProp router.

In summary, the smaller message size (256kB) gives the best performance in message delivery delay (μ=143.73, σ=16.45) than the longer (1MB) of message sizes (μ=178.21, σ=16.85). Likewise, with the lower message generation rates (1msg./10mins.), the overall message delivery delay is lower (μ=142.16, σ=15.30), and it increased for the higher (5msg./10mins.) message generation rates (μ=175.44, σ= 38.09). A two-way ANOVA shows significant differences in the overall rate of the message delivery delay in both cases [$F(2,81) = 0.00$, $p<0.05$].

We observe that, due to the node's buffer constraint in the Epidemic router, nodes drop a higher number of messages which increase the overall message delivery delay for the Epidemic router. This resulted in a number of unsuccessful deliveries as the nodes drop packets before they reach their destinations. For the Prophet router, while selecting the next forwarder, a node reduces the unnecessary message dropping by controlled replications that leads to lower message delivery delays in the employed simulation.

6.4 Discussions

In this section we have summarised the lessons learned from the above simulations study. We outline our results as follows:

- The Epidemic router increases the message delivery ratio, but at the same time it increase the network cost and message delivery delays throughout the simulations.

- We observe that the MaxProp router gives the best message delivery performance by delivering a greater number of messages to the destinations. This increases the message delivery ratio for this router.

- In the Prophet router the message delivery ratio is lower than the MaxProp and Epidemic routers. In addition the message delivery cost and delays in the Prophet router are also low as compared to the other two routers.

- We observe that, *for the increased message size* (1MB), the MaxProp router gives the overall best performance within the network. On the other hand, *for the increased number of network loads* (i.e., number of messages), the message delivery cost and delays are relatively low for the Prophet router compared with the Epidemic and MaxProp routers.

- *Returning to our motivation and problem statement* in Chapter 6.1, Bob may want to have the meaning of the script instantly while he is waiting at the museum, and in such a case the MaxProp router would be the best solution for him. On the other hand, for Alice, who is searching for information about a local food store in a particular region, the Prophet router seems to be the best solution for her in this situation. Alice could also use the MaxProp router but from the message cost and delay point of view Alice may not wish to choose this router because the Prophet router has a lower message delivery cost and delays than the MaxProp router. Furthermore, this ensures conserving the battery power for her mobile device. To sum it up, for getting the best message delivery ratio MaxProp is the best solution for both of them.

- *Based on our findings* in this state-of-the-art research we find that two aspects related to our studies are significant for ***future research***. First, message compression techniques [174] could be used in such communications. This could help Bob to transfer his message more quickly even in a limited bandwidth utilisation for message transfer. Second, further investigation could be made towards the acknowledgement-based broadcast algorithms [175] where Alice would receive an acknowledgement from the other users who receive a copy of Alice's message. This would help Alice to improve message delivery cost and save energy by not re-sending the same message to the others who already have her message. However, what combination of performance metrics would be chosen for optimal results for the best QoS is difficult to predict. It fully depends upon the situations and designer's choice.

- In addition, research must be focused on security and privacy issues [176] related to these communications (cf. Chapter 4.4). The high mobility of nodes [177] [178] and different networking platforms for communications [135] should also be taken into consideration. However, the need for incentive-based framework [163] for the users' participations in such communications needs to be addressed. This would help to motivate others to become active participants in message forwarding.

6.5 Summary

In this chapter, we have examined how the overall network performs with the changes of network load (e.g., number of messages) along with the long-sized messages when using an MoCC architecture. We summarise the chapter as follows:

- To observe the network performance, we used different network loads (e.g., decreasing or increasing message generation rates by the nodes) along with varied message sizes (e.g., shorter and longer) generated by the nodes.

- For the first set of simulations we varied the message sizes while keeping a fixed network load. For the second set of simulations we varied the network load with different message generation rates while keeping a fixed message size. We employed the Epidemic, Prophet and the MaxProp routers to see these performance changes.

- Our experimental results showed that in challenged environments, the MoCC architecture improved the overall message delivery performance using the user's interactions and collaborations even with higher message generation rates and increased message sizes.

- We found that, in the case of the MaxProp router, the local user's mobility and interactions improved the overall routing performance even with the increased message sizes and network loads. This resulted in a high message delivery ratio for the MaxProp router. The Prophet router was useful in cases where the message delivery cost needed to be low. Moreover, in the case of the Epidemic router, while it improved the message delivery ratio, at the same time it significantly increased the message delivery cost and delays in the network.

In the next chapter (Chapter 7), we plan for more comprehensive experiments to examine how different wireless networking technologies make an impact to the message forwarding performances when using the MoCC architecture.

Chapter 7

Exploring the Impact of Different Wireless Communication Techniques in Message Forwarding

In this chapter, employing real-life trace-driven simulations, we examine how different wireless networking technologies make an impact to the user's message forwarding performance when using the MoCC architecture.

In this chapter, the major contributions are:

- We use Bluetooth and Wi-Fi wireless communication techniques to see the impact of different communication ranges to the routing performance in the MoCC architecture.

- We examine how the potential of user's willingness to actively participate in message forwarding makes an impact to the overall message delivery performance with the varied communication's ranges (shorter and longer).

The goal of this chapter is twofold, first, we vary different wireless communications ranges to see the overall impact in routing performances within the network and second, to collate the information to understand how user's social interactions significantly impact over the message forwarding in the MoCC architecture.

The research aims to address the following research questions:

- Is there any significant impact made to the overall message forwarding performance within the network due to the varied communication ranges between the nodes?
- How do the users' collaborations and interactions influence the message forwarding performance in the MoCC architecture, when we vary the communication ranges for the nodes?

7.1 Background

In this chapter we analyse the routing performances in the MoCC with the two different wireless networking technologies. They are Bluetooth and Wi-Fi wireless networking technologies. Bluetooth is a wireless technology standard for communicating in a shorter range, typically 10 metres. On the other hand, Wi-Fi is a local area wireless networking technology for communicating in a range of typically 100 metres.

There are several studies carried out showing the routing performances in different challenged scenarios. For instance, Nakamura et al. presents a model for collecting information during disaster time, by taking into consideration the user's realistic mobility patterns [179]. A simulation-based experimental study has been performed to evaluate the proposed information gathering model during the time of a disaster. In addition with the user's mobility, the authors also introduce an autonomous adaptable protocol combining the geographical routing in MANETs and the store, carry and forward scheme of mobile opportunistic networks. Unlike the motivation of this chapter, the Nakamura et al. model does not indicate the impact of different communication ranges that may affect the network performances in a challenged environment.

Hummel and Hess present a mobility-pattern based approach for message forwarding in mobile opportunistic networks [180]. Using the different users behaviour and characteristics (e.g., daily routines, evening activity, shopping interest, etc.) a simulation-based study has been performed to see the effect of opportunistic forwarding within the network. This study is mainly done with the two different forwarding metrics, namely, 'short connection time' and 'long connection time'. Similar to the Nakamura et al. model [179], this approach takes into consideration the user's mobility patterns for information interchange. But unlike the present scope of our research, how different wireless communication technologies make an impact on the routing performances as well as affect to the overall message forwarding within the network is lacking in this study.

In [181], authors discuss the concept of Pocket Switched Networks (PSN) which connects nearby mobile users for information interchange in a delay tolerant manner. An in-house (an academic working environment) experiment is carried out with the Bluetooth enabled devices for collecting the real-life users' traces of forty one participates in a conference, to monitor their mobility patterns. This research focuses on the environment that may lack an end-to-end network topology for connectivity between the mobile users. In PSN, instead of finding an end-to-end path between the source and destination, nodes forward data with 'hop-by-hop' using user's mobility patterns. Once again, unlike the scope of our present research, PSN does not present the view of how a longer communication range may affect the overall message forwarding performance.

A social-networking based mobility model is described in [182]. In this model, authors explore the idea of social networking for specific node groups according to their higher 'social attractivity'. The 'social attractivity' is defined as the number of friends in a specific area at a certain time. However, this can be changed according to the user's movements (e.g., fast or slow), daily life routine (e.g., going to a specific restaurant or shopping centre), as well as on the time of the day (e.g., office time is good to meet with colleagues but in the evening time a person may want to share his/her time with their friends or family members). While this model focuses on the social connectivity for information interchange, it does not focus on the impact of different wireless networking technologies that can be used by the users for various communications (e.g., indoor and outdoor activities). Returning to our motivation (cf. Chapter 1.1), Bob and Ron are looking for a help from the users available locally. Having said this, in this chapter, we aim to address the gaps in the state of the art research and examine the overall communication performance vary with the different wireless communication ranges for Bob and Ron.

7.2 Experimental Analysis

We examine the employed experiment with a real-world trace-driven simulation study. In the beginning, we discuss the evaluation methodology along with the performance metrics used for the experiment. Then we explore the simulation setup which includes details for the nodes' characteristics and routing protocols involved in the experiment. Next, we discuss the achieved simulation results.

7.2.1 Evaluation Methodology and Performance Metrics

We use the 'ONE' simulator for the experiment [165], over a period of one day. In the first set of experiments we used Bluetooth communication techniques (within a range of 10 metres), and for the second set of experiments we used Wi-Fi communication techniques (within a range of 100 metres), for all the nodes. We ran each simulation 10 times with the different random generator seeds used for the movement model. We use three commonly-used metrics to evaluate the overall routing performance [166]. They are: Delivery Ratio, Delivery Cost and Delivery Delay (cf. Chapter 5.2.1). The performance analysis is done on a computer which has the following configurations of 2 GB RAM, 500 GB hard disk and an Intel core i3 processor @2.27 GHz.

7.2.2 Simulation Setup

In the experiment, we simulate our own University town, St Andrews. For the simulation purpose we use two sets of node groups in the network, they are referred to as the Local Nodes (LN) and Tourist Nodes (TN). The LN represents the local users who are familiar with places (e.g., shopping centre, library, information centre, etc.) in the town. The TN represents the tourists who are travelling to those places.

The LN uses real-life user traces. We use the 'SASSY' traces for this purpose [167]. On the other hand, TN moves with the 'shortest path map-based movement' model in the network. TN generates message into the network and both the TN and LN are willing to share and forward these messages until they reach their indented destinations while both the TN and LN are moving within the network. The network consists of 60 nodes in total (27 LN and 33 TN) and we assume that they all are trusted. We impose specific POIs for the TN (cf. Chapter 5.2.2). These POIs are assigned in some significant spots throughout the town (e.g., St Andrews Cathedral, St Andrews Castle, St Andrews museum, Old Course Golf course, etc.) where tourists visit more frequently. In the case of LN, we do not impose any synthetic characteristics because our intention is to make the LN purely rely upon the real-life mobility traces, to observe the potential impact of users' interactions and social communications in data forwarding. We use three opportunistic routing protocols in the employed simulations, they are, the Epidemic, DirectDelivery and the MaxProp (cf. Chapter 2.3). We use the Epidemic routing as a baseline to compare and contrast the routing performance with the DirectDelivery and MaxProp routings. We choose the DirectDelivery routing to see the communication performance for Bob and Ron with the least cost.

Table 7.1 summarises the list of simulation parameters used in the experiment.

Table 7.1: The simulation parameters used in the experiment.

Parameter	***Value***
World Size	4500m X 4500m
Simulation Time	1 day
Movement Model	'Shortest Path Map-Based Movement'
Routing Protocol	Epidemic; DirectDelivery; MaxProp
Node Buffer Size	200MB
Transmission Speed	250 KBps
Transmission Range	10m & 100m
Transmission Medium	Bluetooth & Wi-Fi
Message TTL	1/2 day
Node Movement Speed	Min=0.5 km/h Max=1.5 km/h
Generated Message Size	500 KB to 1 MB

7.3 Results and Performance Evaluation

In this section we analyse the results achieved from the simulation-based studies. To evaluate the overall message delivery performance, we use the three performance metrics that are described in Chapter 5.2.1, i.e., Delivery Ratio, Delivery Cost and Delivery Delay [166].

7.3.1 Delivery Ratio

Fig. 7.1 shows the message delivery ratio in case of the Bluetooth communication scenario.

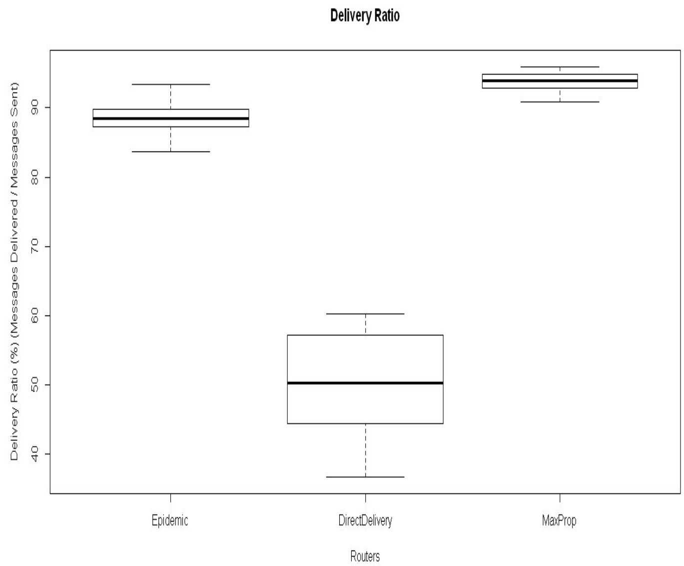

Figure 7.1: The message delivery ratio in the 'Bluetooth' communication scenario. The MaxProp router gives the better performance by using users' interactions and collaborations.

We find that for the Bluetooth communication scenario (cf. Fig. 7.1), the median message delivery ratio for the Epidemic router is 88.53%, whereas in the case of the DirectDelivery router it decreases to 50.21%. We note that, in the Epidemic router, nodes are replicating multiple copies of the same messages to every newly-encountered node. This improves the message delivery ratio for the Epidemic router. But in the case of the DirectDelivery router, a node creates only one copy of the message until it reaches its destination, which reduces its message delivery ratio.

We note that the median message delivery ratio for the MaxProp router is 93.88%. Because the MaxProp router keeps the previous encountered histories and forwards messages to a newly-encountered node that has a higher probability to get closer to the destination node. Therefore, message delivery performance has been improved considerably in this case using users' interactions.

Fig. 7.2 shows the message delivery ratio in case of the Wi-Fi communication scenario.

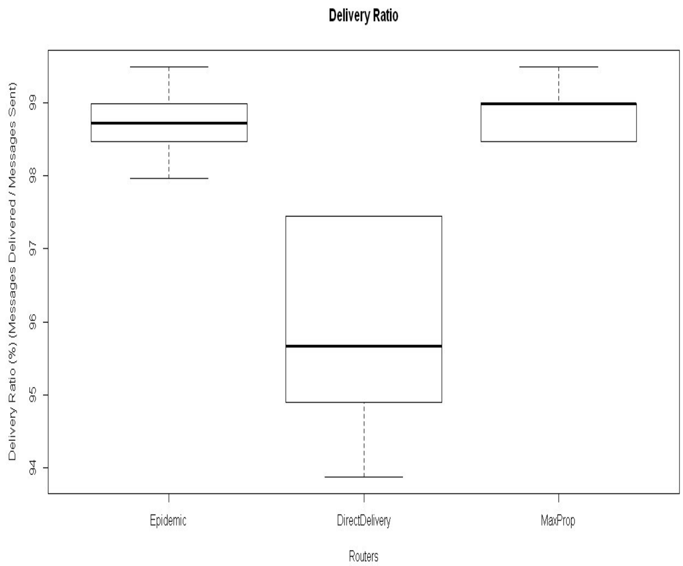

Figure 7.2: The message delivery ratio in the 'Wi-Fi' communication scenario. The median message delivery ratio for the Epidemic and MaxProp routers are almost the same.

For the Wi-Fi communication scenario (cf. Fig. 7.2), the median message delivery ratio for the Epidemic and MaxProp routers are almost the same. They are 98.73% and 98.98% respectively. With the achieved results, we can indicate that the message forwarding with a wider communication range uses the greater contact probability between the nodes. This consequently increases the overall message delivery ratio in the network. It should be noted that, we use real-life trace-driven data for our simulations to see the potential effects of user's interactions and social collaborations within the network. And we observe that these interactions help in message forwarding which in turn increase the message delivery ratio for the Maxprop router.

7.3.2 Delivery Cost

Fig. 7.3 shows the message delivery cost in case of the Bluetooth communication scenario.

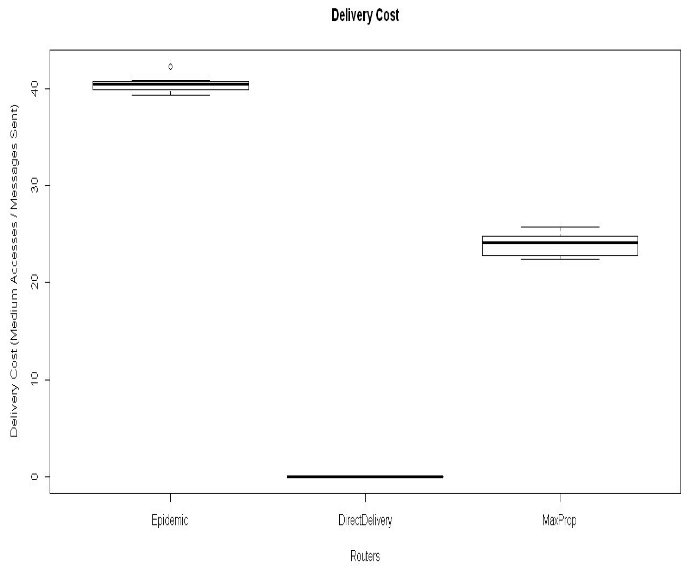

Figure 7.3: The message delivery cost in the 'Bluetooth' communication scenario. The Epidemic router generates a large number of messages, which increase the message delivery cost for this router.

In the case of the Bluetooth communication scenario (cf. Fig. 7.3), the median message delivery cost for the Epidemic router is 40.48 and in the case of the MaxProp router it becomes 24.16. The Epidemic router generates a large number of messages in the network which increase the message delivery cost for this router. The MaxProp router forwards messages based on the previous encounter histories and does not replicate messages. This reduces the median message delivery cost for this router compared to the Epidemic router. The message delivery cost for the DirectDelivery router is zero, because it only generates a single copy of the message in the network.

Fig. 7.4 shows the message delivery cost in case of the Wi-Fi communication scenario.

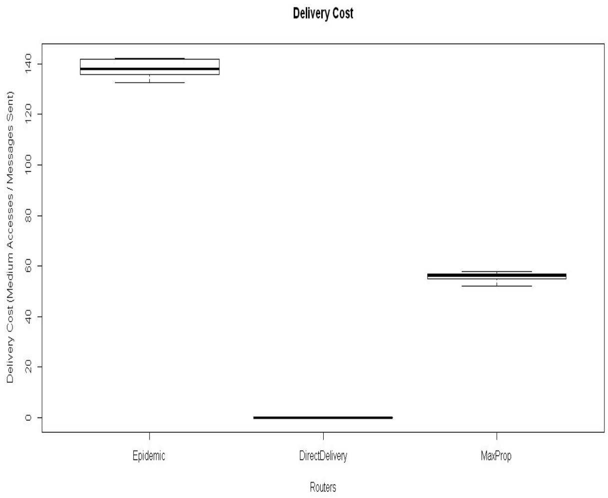

Figure 7.4: The message delivery cost in the 'Wi-Fi' communication scenario. The DirectDelivery router only generates a single copy of the message which results zero message delivery cost for this router.

For the Wi-Fi communication scenario (cf. Fig. 7.4), the median message delivery cost for the Epidemic router is 138.03, and for the MaxProp router it is 56.33. We note that, the Epidemic router replicates a higher amount of messages which increase the message delivery cost compared to the MaxProp router. Same as the Bluetooth scenario above, the median message deliver cost for the DirectDelivery router in the Wi-Fi scenario remains zero.

7.3.3 Delivery Delay

Fig. 7.5 shows the message delivery delay in case of the Bluetooth communication scenario.

We find that the median message delivery delay for the epidemic router, in case of the Bluetooth scenario (cf. Fig. 7.5) is 87.36 minutes, and for the MaxProp router it reduces to 61.47 minutes. By contrast, the median message delivery delay in the case of the DirectDelivery router has increased to 205.5 minutes. We note that due to the node's buffer constraints, the Epidemic router drops a large amount of messages in the network which

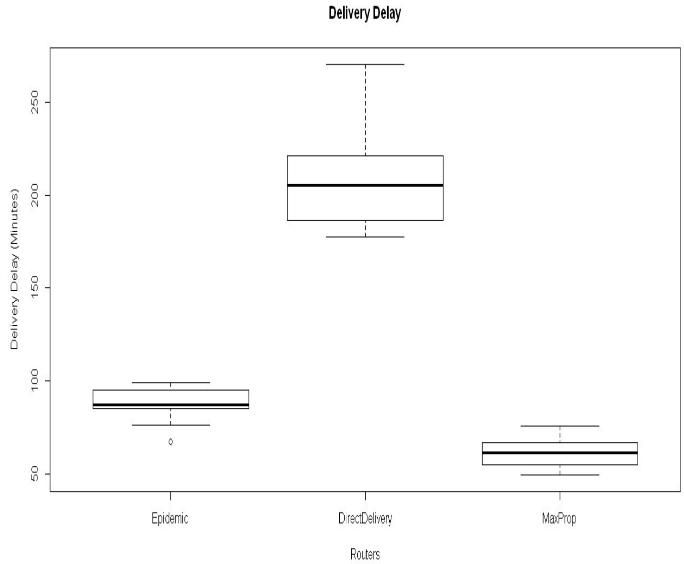

Figure 7.5: The message delivery delay in the 'Bluetooth' communication scenario. The DirectDelivery router only generated single copy of the message in the network and for searching the entire network for the destination node has increased the overall message delivery delay.

results in a higher message delivery delay. The DirectDelivery router generates one copy of the message in the network, but it is unpredictable as to when this message would finally reach to its destination. Therefore, searching the entire network has increased the overall message delivery delay for the DirectDelivery router. However, the user's social collaborations and interactions help the overall message delivery performance in the MaxProp router by finding the destinations faster.

Fig. 7.6 shows the message delivery delay in cases of the Wi-Fi communication scenarios.

For the Wi-Fi communication scenario (cf. Fig. 7.6), the median message delivery delay is low for the MaxProp router (16.22 minutes). Whereas, for the Epidemic router it increases to 21.44 minutes. But the median message delivery delay is high for the DirectDelivery router which is 61.23 minutes. Likewise the Bluetooth scenario, higher amounts of the generated messages

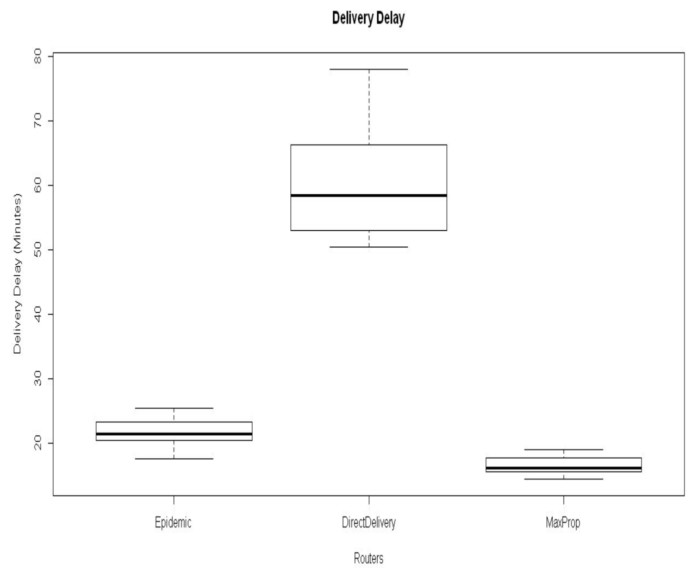

Figure 7.6: The message delivery delay in the 'Wi-Fi' communication scenario. The median message delivery delay is minimum for the MaxProp router as it delivers messages faster by keeping the previous encountered histories and users' interactions.

increases the overall message delivery delay for the Epidemic router compared to the MaxProp router. In the case of the DirectDelivery router, the message delivery delay is higher due the fact that it generated only one copy of the message. Compared to the Bluetooth scenario the wider communication range (i.e., the Wi-Fi scenario) helps to improve the contact opportunities between the nodes which is why Wi-Fi scenarios give better performance in overall message forwarding process.

7.4 Discussions

In this section we have summarised our findings based on the achieved experimental results. We have learned that the message forwarding in the MoCC architecture (cf. Chapter 4) is greatly influenced by the different wireless communication ranges. We outline our results as follows:

- It is feasible for message communication using user's mobility patterns and social interactions by using both of the technologies (i.e., Bluetooth and Wi-Fi in this case) but in the case of a shorter communication range, the user's social interactions greatly influence the message forwarding performance.

- The MaxProp router gives the best message delivery performance compared to the Epidemic and DirectDelivery routing.

- In a wider communication range the overall message delivery ratio is almost similar for the Epidemic and the MaxProp routings. We understand that this is because there is a high probability that the nodes are getting in contact with each other more easily. Returning to our motivation (cf. Chapter 1.1), this type of communications range may improve the message forwarding performance for Bob who is visiting a rural place.

- However, in the case of the MoCC architecture, users' interactions within a shorter range are more promising and therefore users' interactions and willingness for cooperation in message forwarding is important. Returning to our motivation (cf. Chapter 1.1), this type of communications range may improve the networking performance for Ron who is trying to find out the meaning of an ancient script in a museum. Perhaps, attractive incentive mechanisms [11] can be enforced in such communications to encourage user's participation in message forwarding.

7.5 Summary

In this chapter we have discussed the impact of message delivery performance when we vary the wireless communication ranges between the nodes.

We summarise the chapter as follows:

- We evaluated comparisons between various opportunistic routing protocols in different wireless communication technologies (e.g., Bluetooth and Wi-Fi). We used real-life trace-driven simulations to compare and contrast the performance of these routing protocols by exploring user's social collaborations and interactions.

- We used three different routing protocols i.e., Epidemic, DirectDelivery and MaxProp for our simulation. We noticed that the MaxProp router gives the optimum message delivery performance in the network.

- Our results showed that local user's social interactions and collaborations helped to improve the overall message delivery performance in the network. Moreover, we observed that when communicating in a shorter range, users' interactions and collaborations are significant for data forwarding. This in turn supports the need for user's active participations and willingness to share/forward messages within the network.

In the next chapter (Chapter 8), we conclude the thesis by combining the findings we have made in this thesis. We also outline the research directions for the further work .

Chapter 8

Conclusion

Rapid growth in cloud and mobile markets has led to huge demands to access cloud-based applications through smart mobile devices (e.g, smartphones, tablets or PDAs). Several advantages (e.g., portability and the accessibility of using seamless cloud-based services) make these devices a more convenient means for communication in daily life. But major constraints to these devices from the device's point of view are shorter battery power and limited memory size, and from the communication's point of view, the difficulty is accessing a continuous Internet connection, especially in challenged environments. For instance, areas that lack an available infrastructure for communication (e.g., rural or sparse areas) or areas with an infrastructure where the network connection is not as accessible (e.g., urban areas or dense areas with restricted/full of interference access networks) or even areas with high costs of Internet roaming. In such challenged environments, mobile opportunistic networks may help users to gain access to an available network connection for communication via local users' mobile networks. We have therefore examined the following thesis:

Mobile opportunistic networks can be used to gain access to cloud-based applications in a challenged environment with the help of a user's social collaborations and interactions, instead of relying on a fixed infrastructure for communication.

To test the thesis, we have considered the following research questions:

- Research Question 1: Is it possible to use a mobile opportunistic network to provide cloud-based services to the user (e.g., a tourist) in a challenged environment that lacks access to network infrastructure?

- Research Question 2: Do the user's mobility and their social interactions help to improve the availability and accessibility of information in a challenged environment?

To address the first question, in Chapter 3 we surveyed the field of mobile cloud technology. We then explored the possibility of extending mobile cloud platforms using mobile opportunistic networks in challenged environments. We devised a detailed classification of the different 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. In Chapter 4 we proposed a new Mobile-Opportunistic Collaborative Cloud (MoCC) architecture that integrates the D2C, C2D and D2D class of mobile cloud architectures to form a "Device to Device to Cloud" communication that leverages local users' mobile network connections. We found that, it is feasible to use the MoCC architecture to avail a cloud-based application in rural/sparse areas that lack an Internet connection for communication or in urban/dense areas full of interference access networks or even in a high Internet roaming cost zone, instead of relying on a fixed infrastructure for communication.

To address the second question, in Chapter 5 we examined the different modes of user's message transferring behaviour when using the MoCC architecture. We found that the potential for using local users' mobility techniques improves the overall message delivery performance within the network. In Chapter 6 we examined how the overall network performs with the changes of network load (e.g., number of messages) along with the large-sized messages when we employ the MoCC architecture. Once again we found that, in challenged environments, a "Device to Device to Cloud" communication improves the overall message delivery performance using user's interactions and social collaborations even with higher message generation rates and increased message sizes. Finally, in Chapter 7, we examined how different wireless networking technologies affect the message forwarding performance in the MoCC architecture. We found that a higher communication range improves the overall message delivery performance but when communicating in a shorter range, users' interactions and collaborations are significant for message forwarding.

8.1 Contributions

In Chapter 4, we introduced a new Mobile-Opportunistic Collaborative Cloud (MoCC) architecture for extending mobile cloud platforms using mobile opportunistic networks in challenged environments. The MoCC consists of two different technologies, which are then combined into a single one. These are mobile cloud technology and mobile opportunistic networking technology, by using the local user's P2P communications technology.

In Chapter 5, we demonstrated that using the MoCC architecture, local users' mobile networks succeed at integrating tourists' and cloud networks successfully to build an integrated mobile opportunistic cloud-based platform, which can be used to send tourists' information efficiently in a challenged environment. Using publicly-available tourist data, we develop a new "TouristActivityBased" movement model to simulate tourists' behaviour and nature of visits in different places. We used real-world trace-driven simulations to evaluate two options: storing data at well-situated hubs versus exploiting the mobility of local users, and demonstrated that the latter improves message delivery performance.

In Chapter 6, we demonstrated that, the MoCC architecture can improve the overall message delivery performance using a user's mobility, their interactions and social collaborations, even with the higher message generation rates and increased message sizes generated by the nodes. Our experimental results support the need for the user's active participations and willingness to share/forward messages in a challenged environment.

Finally in Chapter 7, we used the MoCC architecture to investigate the impact of various opportunistic routing protocols in different wireless communication technologies in a challenged environment. We employed the Bluetooth and Wi-Fi technologies in this case. We demonstrated that users' interactions and social collaborations can make a significant impact on message forwarding in a shorter communication range.

8.2 Future Research Directions

Throughout the thesis, we have discussed several research issues related to the social and technological domains of the MoCC architecture. However, there are several open research questions and issues which future research would need to address. Therefore, we conclude the thesis by pointing these several potential research questions, open issues and avenues for future work.

• **User's Privacy and Security:** Returning to our motivation (cf. Chapter 1.1), 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 [183]. Due to the absence of a centralised controlled system over the users (cf. Chapter 2.1.3), it is impractical to employ a fixed security solution in such communication [26]. We indicate the open research questions for the 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 issues that need to be addressed for preserving the privacy and confidentiality, and how to monitor them while transferring data through mobile opportunistic networks?

- How can a heterogeneous mobile cloud platform preserve user's relational privacy in data sharing?

Upon this, a dynamic privacy-aware framework can be enforced [154], 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).

• **Heterogeneity of Networks:** Nodes belonging to a heterogeneous network rely on various communication technologies and protocols [159]. In the MoCC, 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 (cf. Chapter 2.2). This raises the requirements for an improved authentication and trust establishment mechanism in data forwarding. In relation to this, we indicate the open research questions for the 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 mechanism that allows detecting dynamic changes of the computing environment according to the user's preferences could be employed [184]. This would enable a resource-constrained mobile devices a unique solution for authentication by identifying non-trusted users and enforces a secure session management between user's mobile devices and cloud servers across heterogeneous mobile cloud platforms.

• **Node Mobility Management:** In mobile 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 [42]. To this end, we indicate the open research questions for the 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 applications?

- How to build a framework which effectively spreads the congestion condition of 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 mobile opportunistic networks, this requires a highly dynamic solution for communication. To address such issues, a 'hop-based' communication mechanism can be employed [185]. This mechanism helps to establish a stable communication using a hop-to-hop message delivery to the neighbouring nodes.

• **Dynamic Resource Management:** Resource management is vital as this helps users offloading data to infrastructure clouds [117]. In a traditional on-premise application deployment model, a user's private data is stored within a secure boundary based on an organisation's policy and fixed security infrastructure. But in the MoCC, users must overcome the inherent uncertainty of an available contact opportunity, making them rely upon locally available infrastructures while hoping for the secure and efficient handling of their data [186]. We indicate the open research questions for the 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, the mechanisms based on privacy-preserving data mining technique can be employed [187]. 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 the user's sensitive data protected during data the mining process. Furthermore, for battery conservation the best approach would be to totally depend on the class of applications [188].

• **Unpredictable User Behaviour:** In the MoCC, unpredictable user behaviour can lead to a higher delay or drop messages during the communication [189]. To this end, we indicate the open research questions for the future research are as follows:

- Do proper incentive mechanisms help users to transfer messages actively within the network?

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

Upon this, incentives for participating in message communication can be employed [12]. Incentives could be social reputations or in terms of money. Moreover, mechanisms for detecting a user's selfish behaviour and encourage them to participate in message forwarding by providing attractive incentives are imperative [163].

Finally, we outlined the open issues and the 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 thesis, which will in turn help to further our understanding towards making improvements in the performance of data-forwarding techniques in real-life scenarios.

Appendix A

List of Acronyms

AODV : Ad-Hoc On-Demand Distance Vector
BTS : Base Transceiver Stations
C2D : Cloud to Device
CF : Collaborative Filtering
CPU : Central Processing Unit
D2C : Device to Cloud
D2D : Device to Device
DSDV : Destination-Sequenced Distance-Vector
DTN : Delay Tolerant Network
E-Business : Electronic Business
EC2 : Amazon Elastic Cloud Computing
E-Healthcare : Electronic Healthcarehhh
GPRS : General Packet Radio Service
GPS : Global Positioning System
ICC : Instant Channel Change
IP : Internet Protocol
IPTV : Internet Protocol Television
IRNA : Intelligent Radio Network Access
JXTA : Juxtapose
LET : Latest Encounter Time
LTE : Long Term Evolution

MANETs : Mobile Ad Hoc Networks
MANs : Metropolitan Area Networks
M-Learning : Mobile Learning
MMS : Multimedia Messaging Services
MoCC : Mobile-Opportunistic Collaborative Cloud
MSNs : Mobile Social Networks
OSNs : Online Social Networks
P2P : Peer-to-Peer
PDA : Personal Digital Assistant
POIs : Point of Interests
PSN : Pocket Switched Networks
QoS : Quality of Service
RAM : Random Access Memory
S3 : Simple Storage Service
SIM : Subscriber Identity Module
UPnP : Universal Plug and Play
URI : Uniform Resource Identifier
VANETs : Vehicular Ad Hoc Networks
VoD : Video On Demand
WAN : Wide Area Network
WWANs : Wireless Wide Area Networks
ZRP : Zone Routing Protocol

Appendix B

Dataset and Data Tables

B.1 Dataset Details

We use the *SASSY* (St Andrews Sensing SYstem) dataset [167] for our simulation-based study. This dataset is collected in St Andrews with 27 participants (22 undergraduate students, 3 postgraduate students, and 2 members of staff of University of St Andrews) equipped with 802.15.4 Tmote Invent sensors and trackers within a range of 10 metres over a period of 79 days. Table B.1 presents the dataset statistics.

Table B.1: The SASSY dataset statistics.

Total Number of Nodes	***Number of Nodes ≥1 Edge***	***Clustering Coefficient***	***Social Links***	***Encounters***
27	27	0.771	254	29,909

Nodes select destinations on a predefined path (e.g., roads) from random POIs to reach them. Each Invent device broadcasts bacon every 6.67 seconds. When this bacon is received by the other devices, they store the related information e.g., the timestamp, the device ID form a Sensor Encounter Record (SER) and the information gets uploaded to the central database located at the Computer Science building in the University. In addition, a

Self-Reported Social Network (SRSN) topology has been generated using the participants 'Facebook'[1]friend lists.

B.2 Movement Model

We develop a new "TouristActivityBased" movement model to simulate tourists' nodes e.g., tourists' behaviour and nature of visits in different places (cf. Chapter 5.2.2). We focus St Andrews town for this purpose. We collect publicly available tourist data[2] (year of 2009) and prepare the movement model for our simulation. When we develop the movement model, we consider various tourists' activities which include visit time, type of attractions (visit places), average time spent in these places, etc. A few of them are discussed as follows (cf. Table B.2):

Table B.2: The issues considered for the "TouristActivityBased" movement model.

Issues	***Remarks***
Types of visitors	National and international.
Admission policy	Free or pay
Visit places	*"The Museum/Art Gallery category demonstrated the strongest presence in terms of concentration of number of attractions, particularly in the free admission sector"*2. This helps us to select the appropriate POIs for the tourists.
Types of visit purposes	School, college, university, business, organizational visit and personal interest.
Average 'dwell' time	This indicates the average time spent in a place. *"Overall visitors spent an average of 1 hour 21 minutes at participating visitor attractions. Visitors spent longest in other category attractions at 2 hours 44 minutes"*2.

We assume that tourists visit a place, perform an activity, e.g. taking photos and then move onto another place. Based on the tourists' attractions

[1]https://www.facebook.com/
[2]http://www.visitscotland.org/

(cf. Table B.3), we choose different probabilities for 10 different 'Points of Interests' (POIs) for tourists. We do the same for all tourists nodes in our simulation. POIs include historical sites (e.g., St Andrews Castle, St Andrews Cathedral, etc), entertainment places (e.g., Golf course) or places that they might visit to collect specific information about the town (e.g., the tourist information centre). We generate appropriate POIs for tourists using 'OpenJUMP'[3].

Table B.3: The tourists' attractions statistics in St Andrews.

Attractions	*Category of the Place*	*Number of Visitors*	*Admission Policy*	*Owner*
St Andrew's Castle	Castle/Fort	55,163	Pay	Historic Scotland
British Golf Museum	Museum/Art Gallery (includes Science/Technology Centre)	43,990	Pay	Charity or Trust
St Andrews Museum	Museum/Art Gallery (includes Science/Technology Centre)	43,556	Free	Local Authority
St Andrew's Cathedral	Historic Monument/Archaeological Site	30,162	Pay	Historic Scotland
MUSA - St Andrews	Museum/Art Gallery (includes Science/Technology Centre)	25,434	Free	University
Gateway Galleries	Museum/Art Gallery (includes Science/Technology Centre)	5,500	Free	University

In the movement model, tourists are moving on the St Andrews roads and they have some POIs. If they are not at those POIs, they will first walk

[3] http://www.openjump.org/

with the ‘shortest path’ to reach these POIs and then stay there until a certain time. A tourist can visit one place at a time.

```
// get path for the next location
@Override
public Path getPath() {
if (mode == WALKING_PLACE_MODE) {
// Trying to find the place
SimMap map = super.getMap();
if (map == null) {
return null;
}
Path p = new Path(generateSpeed());
MapNode to = pois.selectDestination();// select POIs

List<MapNode> nodePath = pathFinder.getShortestPath
(lastMapNode, to);

for (MapNode node : nodePath) {
// create a Path from the shortest path to reach the nearest POIs
p.addWaypoint(node.getLocation());

}
lastMapNode = to;
mode = AT_PLACE_MODE;
return p;

}
else {
Path p =  new Path(1);
MapNode to = pois.selectDestination();
List<MapNode> nodePath = pathFinder.getShortestPath
(lastMapNode, to);
//going towards the POIs
mode = WALKING_PLACE_MODE;
return p;}
}
```

In our simulation, we use the following settings for the POIs for the tourists.

```
# Start scenario settings
# Group and movement model specific settings
# pois: Points Of Interest indexes and probabilities
(poiIndex1, poiProb1, poiIndex2, poiProb2, ... )

...

# Define Group2 (Tourist in St Andrews Town)
Group2.movementModel =  TouristActivityBasedMovement
Group2.groupID = Tourist_NodeNo_

...

Group2.pois = 1,0.2,2,0.2,3,0.2,4,0.1,5,0.1
PointsOfInterest.poiFile1 = data/StACastle.wkt
    PointsOfInterest.poiFile2 = data/StAGolfClub.wkt
    PointsOfInterest.poiFile3 = data/StAMuseum.wkt
    PointsOfInterest.poiFile4 = data/StAMUSA.wkt
    PointsOfInterest.poiFile5 = data/StAGatewayBuilding.wkt
    ...

# wkt = Well-Known Text format
# End scenario settings
```

Nodes (locals and tourists) are moving throughout the town of St Andrews (cf. Chapter 5.2.2). We use the following simulation setting file for them.

```
# Map based movement -movement model specific settings
MapBasedMovement.nrofMapFiles = 1
MapBasedMovement.mapFile1 = data/StAroads.wkt
```

Figure B.1: A map of the St Andrews town along with the various places of attractions.2

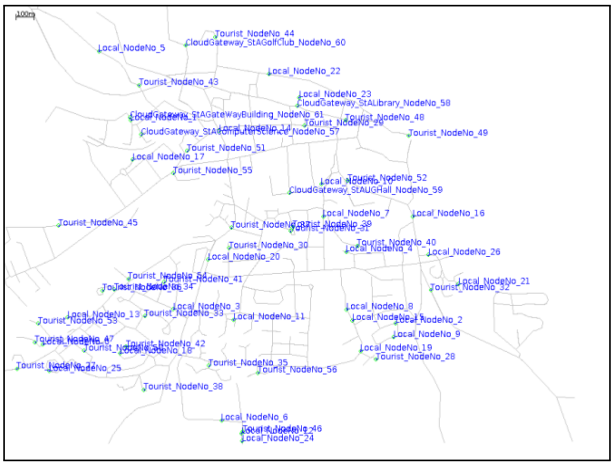

Figure B.2: A screenshot of the employed simulation, where locals and tourists nodes are moving within the St Andrews town (cf. Chapter 5.2.2).

B.3 Data Tables

In this section we present data tables which include the achieved simulations results. Due to the word limitations of the thesis, we present a few of them. They are as follows:

Table B.4: Simulation results for the experiment 5.3.1 (10 runs). The message delivery ratio for the PF, EF and LF modes of message transferring behaviours (cf. Fig. 5.2 and Fig. 5.3).

Epidemic Router			**Prophet Router**			**MaxProp Router**		
PF	**EF**	**LF**	**PF**	**EF**	**LF**	**PF**	**EF**	**LF**
17.34	57.4	27.43	11.69	63.05	27.24	15.17	67.3	39.87
15.36	60.32	29.88	12.72	58.44	25.45	16.31	70.22	40.9
14.99	55.61	30.73	13.38	57.4	29.78	15.55	67.77	39.02
15.65	57.02	30.25	10.27	58.06	26.11	16.02	68.71	36.19
16.68	55.89	31.86	11.78	56.27	26.58	16.59	72.2	36.95
14.8	53.53	32.61	9.52	59.47	25.07	15.65	73.33	34.68
15.08	55.51	32.99	10.37	58.15	27.14	16.78	75.31	37.23
16.12	56.74	30.16	9.99	60.04	24.03	14.61	66.64	38.08
16.78	52.78	31.2	11.78	62.96	27.05	16.12	69.56	36.85
15.83	57.4	29.97	13.1	58.91	25.07	16.59	68.99	34.31

Table B.5: Simulation results for the experiment 6.3.1. The message delivery ratio for the varied message sizes (cf. Fig. 6.1).

Epidemic Router		**Prophet Router**		**MaxProp Router**	
256kB	**1MB**	**256kB**	**1MB**	**256kB**	**1MB**
64.58	56.94	58.33	52.78	70.14	64.58
61.81	61.11	47.22	47.92	76.39	71.53
61.81	56.25	47.92	45.83	71.53	63.89
62.5	56.94	54.86	49.31	75	70.83
59.03	53.47	54.17	47.22	77.08	67.36
59.72	52.08	55.56	52.08	71.53	67.36
66.67	60.42	55.56	52.78	67.36	64.58
61.11	56.94	54.86	50	70.14	62.5
63.89	58.33	54.17	52.08	64.58	64.58
63.89	55.56	58.33	52.78	74.31	68.75

Table B.6: Simulation results for the experiment 6.3.2. The message delivery cost for the varied message sizes (cf. Fig. 6.3).

Epidemic Router		Prophet Router		MaxProp Router	
256kB	**1MB**	**256kB**	**1MB**	**256kB**	**1MB**
195.44	152.40	99.95	89.46	150.19	94.04
177.43	154.38	116.59	113.50	136.43	85.12
193.58	158.85	109.86	104.35	144.83	80.99
186.76	158.21	108.85	97.77	135.62	79.78
193.25	162.98	113.63	96.94	140.05	83.74
208.92	164.48	105.55	94.68	146.32	89.36
179.62	150.95	103.86	94.83	148.01	109.41
192.29	160.17	100.69	89.57	153.70	94.91
181.56	155.21	100.32	95.96	149.81	97.24
186.91	149.96	101.45	89.50	140.99	80.89

Table B.7: Simulation results for the experiment 7.3.1. The message delivery ratio for the Bluetooth and Wi-Fi communications (cf. Fig. 7.1 and Fig. 7.2).

Epidemic Router		DirectDelivery Router		MaxProp Router	
Bluetooth	**Wi-Fi**	**Bluetooth**	**Wi-Fi**	**Bluetooth**	**Wi-Fi**
88.78	98.47	46.94	94.39	94.39	98.47
88.78	97.96	48.47	94.9	92.86	98.98
88.27	98.98	44.39	97.45	94.9	98.98
87.76	98.47	52.04	96.43	91.48	98.47
90.31	98.98	57.14	97.45	94.9	98.98
84.18	98.98	42.35	96.43	90.82	98.98
89.8	98.47	58.16	97.45	94.39	98.47
93.37	99.49	60.2	94.9	95.92	99.49
83.67	98.98	36.73	93.88	93.37	98.98
87.24	97.96	52.55	94.9	93.37	98.47

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