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Mobile Edge Computing: A Survey

architecture, applications, approaches and challenges

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Abstract

Mobile edge computing (MEC) is an emergent architecture where cloud computing services are extended to the edge of networks into the mobile base stations. As a promising edge technology, it can be applied to mobile, wireless and wireline scenarios, using software and hardware platforms, located at the network edge in the vicinity of end users. MEC provides seamless integration of multiple application service providers and vendors towards mobile subscribers, enterprises and other vertical segments. It is an important component in the proposed 5G architecture that supports variety of innovative applications and services where ultra low latency is required. However, there are some challenges exists in the MEC eco system. To address these challenges, first off need to understand the network infrastructure of MEC, cloud and cellular network.

Some questions and problems are addressed in this thesis that outlines the importance and challenges of MEC deployment. Impact of MEC integration with the traditional mobile and cloud network appears in this paper. A survey has been presented that contributes in general understanding of mobile edge computing (MEC). Readers will have an overview of MEC, such as definition, advantages, architectures and applications. Moreover, related research and future directions are pointed out in this thesis. Finally, security and privacy issues and their possible solutions are also discussed.

This thesis is dedicated to my

late **Parents**

who were my first teachers. Without their support, guidance, and infinite wisdom, I would not have made it this far. My fervor towards professionalism is all colored by them.

Also I would like to dedicate with my heart-felt and deepest gratitude to my **siblings**, I am blessed beyond belief. Their love and support means more to me than they will ever know.

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Contents

List of Figures

Acronyms/Abbreviations

1G	First Generation
2G	Second Generation
3G	Third Generation
4G	Fourth Generation
5G	Fifth Generation
API	Application Program Interface
AR	Augmented Reality
ASP	Application Service Provider
BS	Base Station
BSC	base station controller
COTS	Commercial-Off-The-Shelf
nDCs	Nano Data Centers
DNS	Domain Name Server
DOS	Denial of Service
EAB	Edge Accelerated Web Browsing
EEG	Electroencephalogram
eNodeB	Evolved Node B
ETSI	European Telecommunications Standards Institute
FC	Fog Computing
FN	Fog Node
GPRS	General Packet Radio Service
GPS	Global Positioning System
IaaS	infrastructure-as-a-Service
IDS	Intrusion Detection System
IoT	Internet of Things
ISG	Industry Specification Group
LBS	Location Based Service
LTE	Long Term Evolution
M2M	Machine-to-machine
MCC	Mobile Cloud Computing
MNO	Mobile Network Operator
MU	Mobile Users
NFC	Near field communication
NFV	Network Functions Virtualization
NILL	Non-Intrusive Load Leveling
NP-hardness	non-deterministic polynomial-time hard
OTT	Over-the-top
QoE	Quality of Experience

RAN	Radio Access Network
SRAN	Service-Aware RAN
SAE	System Architecture Evolution
SCADA	Surpervisory Control Data Acquisition
SDCompute	Software Defined Compute
SDN	Software Defined Network
SDSec	Software Defined Security
SDStorage	Software Defined Storage
SRAN	Service-Aware RAN
TDMA	Time Division Multiple Access
UE	User Equipment
UMTS	Universal Mobile Telecommunication System
UTRAN	UMTS radio access network
VDTNs	Vehicular Delay-Tolerant Networks
WAN	Wide Area Network
WSAN	Wireless Sensor Actuator Network

Chapter 1

Introduction

The prevalence of mobile terminals, such as a smartphones or tablet computers, has an uttermost effect on mobile and wireless networks that has triggered challenges for mobile networks worldwide [20] [92]. Cellular networks has to endure low storage capacity, high energy consumption, low bandwidth and high latency [68]. Moreover, exponential growth of an emerging technology, i.e., Internet-of-Things (IoT), is foreseen to further stumble cellular and wireless networks [14]. Mobile cloud computing (MCC) that is an integration of cloud computing to mobile environment has provided considerable capabilities to the mobile devices that empowers them with storage, computation and energy by proffering the centralized cloud resources [59] [25]. However, popping up a myriad of mobile devices, MCC is encountering noticeable challenges, such as high latency, security vulnerability, low coverage and lagged data transmission that could become cumbersome, especially for next generation mobile networks (e.g., 5G) [42]. Moreover, MCC is less suitable for scenarios involving real-time applications and high quality of service (Qos) According to the recent report presented by Cisco Visual Networking Index, 11.6 billion mobile-connected devices will be used by 2020 [92]. The trend of increase in mobile usage is fundamentally driven by the augmentation of mobile users and mobile application development (e.g., iPhone apps, Google apps etc.) [45] [13].

In the era of computing paradigm, edge computing also recognized as fog computing [43], has begun to be of paramount significance, especially mobile edge computing (MEC) in cellular networks. The prime purpose of mobile edge computing is to address the challenges that are stressing mobile cloud computing. MEC offers MCC capabilities by deploying cloud resources, e.g., storage and processing capacity, to the edge within the radio access network that leverage end user with swift and powerful computing, energy efficiency, storage capacity, mobility, location and context awareness support [100] [41]. Previously, the technology at the edge of the Internet known as cloudlet has been introduced to deploy mobile cloud services but was inadequate due to its limited Wi-Fi coverage. In a high computational environment, cloudlets have become inefficient to offload end devices working load [41]. Alternatively, MEC is equipped with better offloading techniques that characterize network with low-latency and high-bandwidth.

1.1 Problem Statement

In the light of aforementioned concern, the problem statements are:

1. Why do we need mobile edge computing?
2. Where can we use mobile edge computing?
3. What are the main challenges in using mobile edge computing and what are the solutions related to these challenges.

1.2 Thesis Outline

This thesis presents a survey on mobile edge computing that is organized in the following way:

Chapter 1 (Introduction) gives a brief introduction of mobile edge computing and its value in the mobile operator networks. Problem statements addressing the surveyed technology also appears in this chapter.

Chapter 2 (Background and Related Surveys) describes an overview of mobile edge computing that mainly encompass; definition, architecture, mobile edge computing advantages key enablers and related surveys that are presented recently. Most importantly, the related concepts and technologies also appears in this chapter

Chapter 3 (Applications and Emerging Scenarios) illustrate edge computing applications and mobile edge computing use cases. Some recent research efforts are also presented in this chapter

Chapter 4 (Research Infrastructures) display mobile edge computing server infrastructure and services. Mobile edge computing deployment scenarios and testbeds also appears in this chapter.

Chapter 5 (Security and Privacy Issues) identify security and privacy issues that are under consideration prior to the mobile edge computing implementation .

Chapter 6 (Open Research Problems) discuss the possible solutions to the issues identified in previous chapter. In this chapter, security, resource optimization, tranparent application migration, pricing, web interface and other issues are briefly discussed.

Chapter 7 (Discussions and Future Works) reiterate problem statement that are presented in this thesis and the limitations faced during the project.

Some of the future works are also stated. Furthermore, this chapter has presented a timeline for understanding how the amount of plan was carried to complete the project.

Chapter 8 (Conclusion) Finally, this chapter comes up with the conclusion of this project.

Chapter 2

Background and Related Surveys

2.1 Mobile Edge Computing

The term 'mobile edge computing' was first introduced in 2013 when Nokia Siemens Networks and IBM developed MEC platform that enable applications to run directly. This platform accelerates only the local scope that does not support application migration, interoperability etc. [77]. Later, in 2014, MEC was standardized by European Telecommunications Standards Institute (ETSI) Industry Specification Group (ISG), the group includes Nokia Networks, Intel, Vodafone, IBM, Huawei and NTT DOCOMO. MEC is also acknowledged by European 5G PPP (5G Infrastructure Public Private Partnership) as a prime emerging technology for 5G networks [36].

2.1.1 Definition of Mobile Edge Computing

According to European Telecommunications Standards Institute (ETSI), mobile edge computing is defined as [36]:

"Mobile Edge Computing provides an IT service environment and cloud-computing capabilities at the edge of the mobile network, within the Radio Access Network (RAN) and in close proximity to mobile subscribers."

Mobile edge computing offers cloud computing capabilities within the radio access network. Allowing direct mobile traffic between core network to end user, instead, MEC connects user directly to the nearest cloud service enabled edge network. Deploying MEC at the base station enhance computation, avoid bottlenecks and system failure [80] [42].

According to the white paper published by ETSI, mobile edge computing can be characterized by [72]:

1. On-Premises: Mobile edge computing performs in segregates that enhance its performance in machine-to-machine environment. MEC property of segregation from other network also makes it less vulnerable.

2. Proximity: Being deployed at a nearest location, mobile edge computing has an advantage to analyze and materialize big data. It is also beneficial for compute-hungry devices, such as augmented reality, video analytics etc.

3. Lower latency: Mobile edge computing services are deployed at nearest location to user devices that isolates network data movement from the core network. Hence, user experience is accounted high quality with an ultra-low latency and high bandwidth.

4. Location awareness: Edge distributed devices utilize low-level signaling for information sharing. MEC receives information from edge devices within the local access network to discover device location.

5. Network context information: Applications providing network information and services of real-time network data can benefit businesses and events by implementing MEC in their business model. On the basis of RAN real-time information, these applications can judge the congestion of the radio cell and network bandwidth that in future help them to make smart decision for better customer deliverance.

2.1.2 Related Concepts and Technologies

There are some terms similar to mobile edge computing, such as mobile cloud computing, local cloud, cloudlet and fog computing [102].

- *Mobile Cloud Computing (MCC)* generally integrates all the advantages of mobile computing, cloud computing and mobile internet [9]. The main focus of cloud computing is to enable isolated virtualized computing, storage and communication resources that leverages end users [37]. Some examples of cloud computing infrastructures and platforms are Amazon EC2, Microsoft Azure, Google, and Aneka. Mobile cloud computing enable resources on demand, such as network, server, application, storage and computing resources in a mobile environment [61]. MCC also focuses on resource management that could easily be manageable [37]. In a MCC infrastructure the centralised cloud servers are located far off from end devices, therefore are less productive in computation intense environment. For example, mobile applications connected to the cloud may face network latency or disconnections while mobile applications are used.

- *Local Cloud* is administered by internal or external sources explicitly intended for a group or institution [17]. Local cloud is deployed in a local network that coordinates with its remote cloud server to promote data privacy. It is enabled by installing a software on the local server that is integrated with the cloud server. However, local cloud is favorable in terms of communication delay but it is subject to some computational limitations due to its sparse resources [106].

- *Cloudlet* is a small-box data center that is normally deployed at one wireless hop away from mobile devices, such as public places like hospital, shopping center, office building etc. to facilitate a convenient approach as shown in figure 2.1 [54]. Several units of multi-core computers forms a cloudlet that is connected to remotely located cloud servers. Cloudlet is brought as a promising solution as concerns distant wide area networks (WAN) latency and cellular energy consumption by utilizing cellular data connectivity to the cloud server [11]. The prime focus of cloudlet is to bring cloud technologies closer to the end user that provide support to resource and latency sensitive applications [95]. Cloudlet utilizes technology, such as Wi-Fi that is located at one hop or multiple hops at the edge of internet and therefore it is dependent on robust internet connection. Moreover, there are some security and privacy issues that involves user reluctance of accessing privacy relevant services, such as e-commerce websites [69].

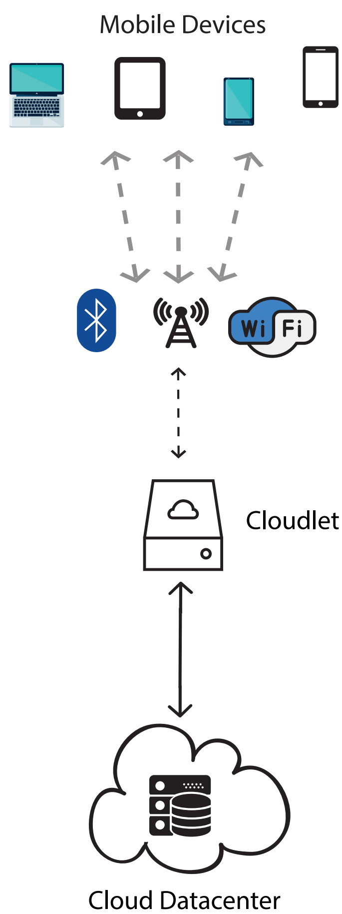

Figure 2.1: Cloudlet

- *Fog Computing* is also known as edge computing that supports ubiquitous connected devices. Fog computing term was created by CISCO systems that bring cloud services to the edge of an enterprise network as MEC. In fog computing, the processing is mainly carried out in the local area network end at IoT gateway or a fog node. Fog computing has a benefit to allow single processing device to gather data from different sensors and act accordingly. For example, a smart robotic vacuum cleaner receiving data from multiple sensors installed in a house that are capable to detect any dirt and send any command to vacuum cleaner to react accordingly. Fog computing offers much low latency as compared to cloud computing that is located far from end user. However, fog computing has some limitation due to its dependency over wireless connection that has to be live in order to perform complex actions. Fog computing and MEC terms are widely used interchangeably but they differs in some ways, for example, in fog computing environment, intelligence is at local area network level that is processed at the fog node or IoT gateway, therefore is a rising trend in wireless networks for IoT and machine-to-machine (M2M) communication whereas, in mobile edge computing environment intelligence, communication capability and processing power is pushed with in the RAN, therefore it is popular for 4G and future 5G networks

2.1.3 Architectures of Mobile Edge Computing

Mobile edge computing functions mostly within the radio access network (RAN), prior to MEC architecture we first retrospect the evolution and general cellular network communication architecture in a RAN perspective.

History and Role of RAN in Cellular Networks

Back in early 1980s, first commercial cellular network (1G generation) was introduced with the compliance of analog modulation and mobility support, which later was eventually replaced by 2G because of its digital radio signaling capability using time division multiple access (TDMA). 2G networks were known for better voice quality that was achieved by leveraging digital technology for better voice quality. Later, 3G released better data transfer rate and multimedia application coherence using RAN with limited data support [70]. With an accustomed support of mobile internet using RAN Long-Term Evolution (LTE), 4G got an edge over other wireless mobile telecommunications technology providing best user experience [44].

The radio access network (RAN) is a part of cellular network communication system infrastructure that facilitates the connection between mobile phone or any wireless controlled machine with the mobile core network [22]. In traditional cellular radio system, wireless user equipments connects through RAN to the mobile operator networks. User equipment includes mobile stations, laptops etc. RAN covers the wide geographical area that is divided into several cells and each cell is integrated with its base station. Base stations are typically connected with each other via microwave or landlines to radio network controller (RNC) also known as base station controller (BSC). RNC is responsible to control node base station (node BS) and also carry out some mobile management functions. Most of the encryption is done before sending user data to the core network. The RNCs are connected with one or two back haul networks. Cellular networks have become more efficient then before, because LTE technology provides high-speed wireless communication radio access networks with low-latency and high-bandwidth. System architecture evolution (SAE) of RAN LTE core conforms heterogeneous networks and legacy systems, such as air interfaces of general packet radio service (GPRS) or universal mobile telecommunications (UMTS) [13]. The UMTS is a third generation system that may depend on global system for mobile communication (GSM) that has been developed in Europe.

A generic view of cellular network is illustrated in figure 2.2, where the core network is wire-connected (e.g IP/Ethernet) with RAN and RAN wireless-connected with user devices. RAN connects base station with backhaul network through Ethernet interface that support high data transfer rate [71].

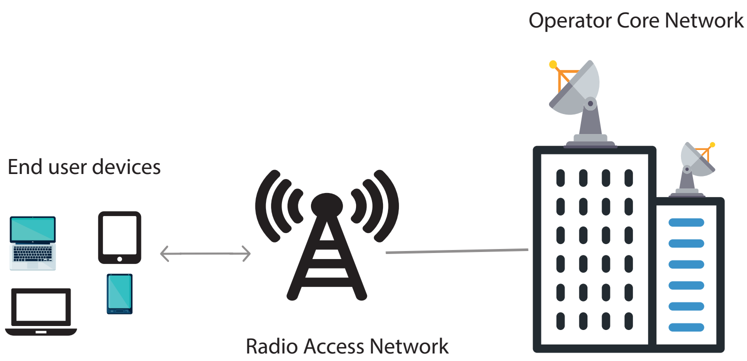

Figure 2.2: Cellular Architecture

In the past, IP has grown from the internet, to organization networks and increasingly adopted by LTE network. The IP traffic between RAN and core is encapsulated with GPRS tunneling protocol with an IPsec encryption [16]. This has prohibited IT services to be inserted at nearest location to the end users. Moreover, mobile operators are reluctant to deploy applications, having risk of denial of mobile services or performance decrease.

Three-Layer Architecture

MEC is a layer that resides between cloud and mobile devices. Therefore, the infrastructure is derived as a three-layer hierarchy; cloud, MEC and mobile devices [56]. Mobile edge computing mostly complies with cloud computing to support and enhance performance of the end devices. The formation of a three-layer service model, is depicted in figure 2.3.

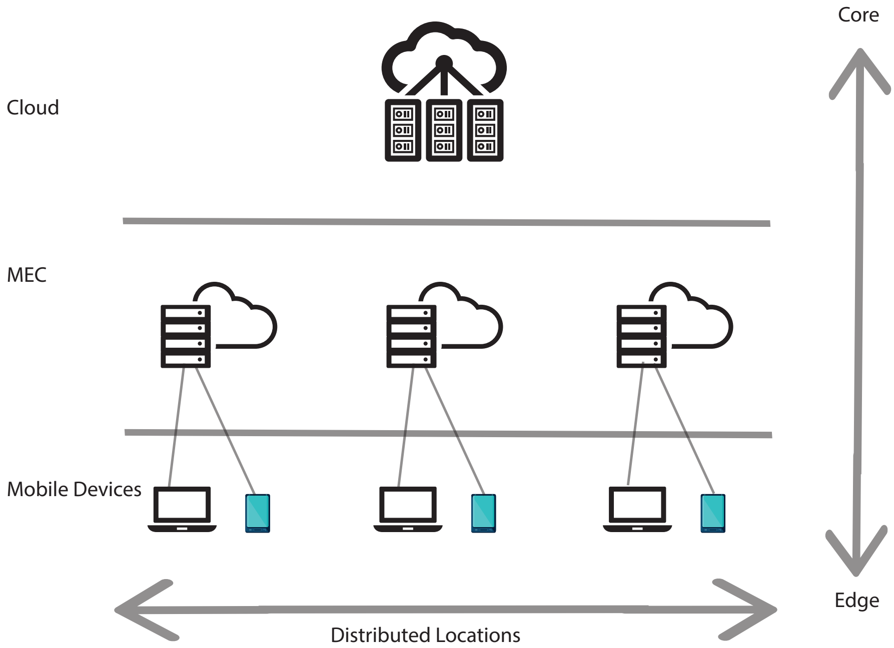

Figure 2.3: Three-layer architecture [90]

The general architecture of mobile edge computing is depicted in figure 2.4. As shown, mobile devices are connected to core network through the edge network i.e., radio access network and MEC, and core network is connected with the cloud network. With the evolution of LTE based RAN, it has become more feasible to deploy MEC that bring cloud services near to the mobile subscribers.

MEC constitutes geo-distributed servers or virtual servers with built-in IT services. These servers are implemented locally at mobile user premises, e.g., parks, bus terminals, shopping centers, etc. [56]. MEC may utilize cellular network elements, such as base station, Wi-Fi access point, or femto access point (i.e, low power cellular base station). MEC may be deployed at a fixed location, for example, in a shopping center or mobile device located in any moving object, e.g, car, bus etc. MEC can be deployed at LTE base station (eNodeB) or multi-technology (3G/LTE) cell aggregation site. The multi-technology cell aggregation site can be both indoor or outdoor location. To push intelligence at the base stations and to effectively optimise RAN services, mobile edge computing technology develops an energetic ecosystem and a new value chain that allows intelligent and smart services at nearby location to the mobile subscribers.

To sum up, MEC key value proposition is that it offers cloud computing by pushing cloud resources, such as compute, network and storage to edge of the mobile network in order to fulfil application requirement that are compute hungry (e.g. Games applications), latency-sensitive (e.g. Augmented Reality applications) and high-bandwidth demanding (e.g. Mobile Big data Analytics).

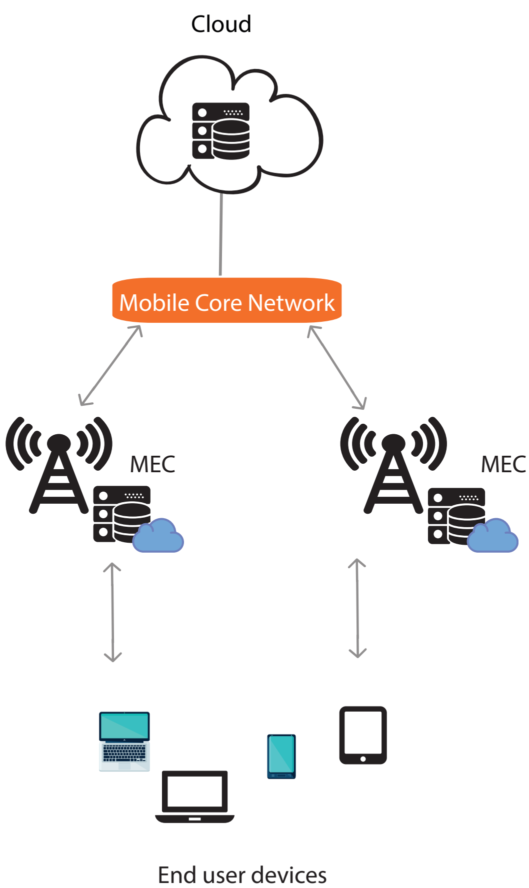

Figure 2.4: Mobile edge computing architecture

Adaptive Computation Offloading

In computer science, computation offloading is a process of migrating computing tasks to external sources, such as cloud, grid or cluster [57]. Computation offloading is a solution to enhance the capacity of mobile devices by transferring computation to higher resourceful servers that are located at the external location [50]. Emergence of resource-demanding applications, such as 3D games will continue to demand more mobile resources. Improvement of mobile hardware and network will still not be able to cope up with the trend in demand. Therefore, mobile devices will always have to compromise with its limited resources, such as resource-poor hardware, insecure connection and energy driven computing tasks [47]. For example, editing video clips on mobile phone requires a large amount of energy and computation that is obtained with some limitation as compared to desktop or laptop. To deal with these constraints, many researchers have managed computation offloading to computational power resources [33] [82] [49] , such as cloud.

2.1.4 Advantages of Mobile Edge Computing

As already discussed in previous sections, there are several benefits associated with mobile edge computing that is turning out to be promising for both mobile network operators (MNOs), and application service provider (ASP), in addition also befitting content providers, Over-the-top (OTT) players, network equipment vendors, IT and middleware providers [107] [13]. MEC concept focuses on important metrics, such as delay and high-bandwidth that is accomplished by limiting data movement to MEC servers then to centralised servers that has a severe latency cost. Moreover, power consumption is also one of the main concerns. Computational tasks are referred to external resource-rich systems to increase user equipment (UE) battery life. In addition, distributed virtual servers provision scalability and reliability.

In regards to the actors (MNOs, ASPs and end users), MEC benefits include [83] [13]:

- *Mobile network operators* could enable RAN access to third party vendors to deploy their applications and services in more flexible and agile manner. These enabling services could generate revenue by charging based on the services used, such as storage, bandwidth, and other IT resources. OTT services and DVR services offered by cable operators may likely be faster since their services could reside in MEC servers.

- *Application service providers* could gain profit by MEC enabled infrastructure-as-a-service (IaaS) platform at the network edge that make ASPs services scalable along with high bandwidth and low latency. ASPs could also get a real time access to the radio activity that may develop more capable applications. RAN is revamped into Service-Aware RAN (SRAN) that provides information of subscriber location, cell load, network congestion etc.

- *End users* could experience fast computational applications through offloading technique that is handled by MEC servers within RAN. In addition, tight RAN assimilation and physical close servers could improve user quality of experience (QoE), such as high throughput browsing, video caching, better DNS etc.

2.2 Mobile Edge Computing Key Enablers

The emerging MEC trends introduces several possibilities for network functions virtualization (NFV), software defined networks and fifth generation wireless networks.

2.2.1 Network Functions Virtualization

Network functions virtualization enables the virtualize environment of network services that are launched by the dedicated hardware. The goal of NFV is to move network functions from dedicated hardware devices to generic servers. NFV comes with several beneficial attributes, such as flexibility, cost effectiveness, scalability and security. According to the change in demands, NFV enables a flexible access to the operators and service providers to scale there services. Virtualize network devices installed at the network edge will be beneficial to end users by integrating MEC in the virtualize environment.

2.2.2 Software-Defined Network (SDN)

Software-defined network (SDN) is an innovation to computer networking that separates control layer and the data layer [84]. Data layer contains user generated messages and is responsible to forward them using the forwarding tables prepared by the control layer [39]. This is managed by a centralized control system. MEC concept along with SDN can make centralized control more efficient and reliable, e.g., in vehicle to vehicle connectivity the ratio of packet loss can be resolved.

2.2.3 Fifth Generation Wireless Networks

The 5th generation wireless system to be the next communication standards that are likely to be more faster and more reliable then 4G networks. 5G together with MEC can possess better user experience. MEC at the edge of the network will be providing services for complex traffic handling and routing. The main architecture of 5G will be relying on the edge technologies.

2.3 Other MEC Key Enablers

Other enabling opportunities includes live video streaming and internet of things.

2.3.1 Live Video Streaming

Live video streaming, such as live TV or live conferencing on mobiles devices requires high bandwidth and ultra low latency. This data stream creates a huge traffic that stresses the mobile network. Moreover, heavy data movement over the network refers to service interruption or service denial. Since live video streaming is one of the main goal of 5G networks, MEC will play a major role for video streaming by pushing intelligence at the network edge near to the end user.

2.3.2 Internet of Things (IoT)

IoT is an emerging technology in which physical objects communicate with each other mainly through internet. These physical object requires fast data transmission and high computational power in order to keep there data integrity. IoT can largely benefit from MEC technology and deliver better services.

2.4 Related Surveys

There are several surveys written on edge paradigms (e.g. Fog Computing and Cloudlet). These surveys are mainly focused with in their specific area of technology, for example, the survey papers have not covered other edge technologies, such as mobile edge computing.

The paper [100] has depicted a survey report on fog computing. The main focus of the paper is on fog computing and its deployment scenarios. Since, in FC the processing is mostly in the local area network depending on wireless connection, there is a lack of explanation on the deployment of the presented edge paradigm in RAN. Readers of the paper can have a limited overview on FC technology and its implementation.

A survey on cloudlet [69] has been studied that is based on mobile computing. The paper has presented a cloudlet base survey that is beneficial for technology experts who are relevant to the proposed technology but might not gain a substantial knowledge about other edge technologies.

Finally, there is only one survey paper [2], written on mobile edge computing that explains MEC applications, state-of-the-art research efforts and MEC challenges. The presented paper is not much comprehensive and does not cover a wide scope of MEC. For example, in the paper, other similar concepts and technologies are not mentioned and the applications utilizing these technologies are also not been discussed. The differences between different edge paradigms are not stated either. Moreover, security and privacy issues with possible security mechanisms are not been identified. There are not enough references given in the paper that may limit the quality of is content.

The given thesis has targeted the detail approach of MEC, MEC use cases and MEC challenges. Security issues and security mechanisms are targeted in this thesis that was missing in previous survey report, as discussed. The differences between related concept and technologies, their approach and limitations are also explained in this thesis. Several papers were studied and are referenced in order to maintain the soundness of the presented thesis.

Chapter 3

Applications and Emerging Scenarios

3.1 Applications

MEC architecture is a new revenue stream for mobile operators that yet had to get mature but on the other hand we see quite a few areas adopting Edge Computing (e.g Fog Computing) as it is been compassed in recent articles [36] [23]. Some recognized applications include Augmented Reality, Content Delivery, Healthcare relevant applications (e.g U-Fall) etc. appears in this section.

3.1.1 Augmented Reality (AR)

In the era of mobile technology, augmented reality applications have recently adapted mobile technology, such as Layar, Junaio, Google Goggles, and Wikitude [67]. AR enables real environment user-experience by combining real and virtual objects that exists simultaneously [76] [10]. Recently AR applications, are also being adaptive in sound and visual components, such as news, TV programs, sports, object recognition, games etc. [103]. However, AR systems usually demand high computing power; to perform computational offloading, low latency for better quality of experience (QoE) and high bandwidth that is conducive to sustain interminable IT services.

Edge computing infrastructure has recognized to be a niche for latency-sensitive applications in AR domain [18] that empowers AR systems, for example, it maximize throughput by pushing intelligence to the edge of the network instead relying on the core network. Therefore, offloading computation-intensive operations at the nearest cloudlet is more optimized and efficient that could enhance user experience.

One example of AR application is Brain Computer Interaction that works by detecting human brainwaves [104]. The application serves by integrating wireless electroencephalogram (EEG) headsets, smart phones and edge server. The data is received by EEG Bio-sensors in real-time acquiring large signal processing tasks handled by edge technology and cloud computing. Edge server captures the data coming from the sensors and process them on user device as shown in figure 3.1. Data can also be processed at cloud server for archiving purpose.

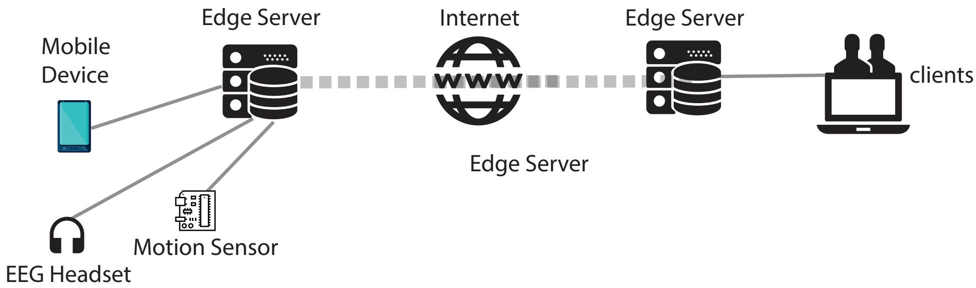

Figure 3.1: Architecture of Pervasive Neuroimaging System[104]

3.1.2 Content Delivery and Caching

The edge computing technology plays a comprehensive role in Web site performance optimization, such as caching HTML content, reorganizing web layout and resizing web components. User makes HTTP requests that passes through the edge server. This server handles user requests by performing number of tasks to load web page on user device interface. These requests and response are time efficient as the edge server is deployed close to the edge devices. The edge computing infrastructure is time efficient as compared to the traditional internet infrastructure where user requests are handled at the servers that are distantly placed at the service provider. In addition, edge computing also analyse network performance during on and off peak hours. For example, under congested network conditions where several users are streaming video at the same time, the graphics resolution is decreased to minimal to accommodate every user averting any denial of service or jitter.

MEC incorporated with internet infrastructure can bring intelligence, such as website optimization within the RAN. Like other edge paradigms, MEC can take advantages of the mobile networks especially it can efficiently utilize 5G wireless networks to enhance web site performance.

3.2 Emerging Scenarios

It is very crucial to stay ahead of the curve to apprehend mobile technology trend. In this section, emerging scenarios of MEC are demonstrated that are recently considered in the ETSI white paper [36], such as video analytics and mobile big data. Several papers [102] [97] [43] [74] have referred MEC scenarios in connected vehicle, smart grid and wireless sensor and actuator networks (WSAN). Further more, [90] expanded the scenario on smart building control and software-defined network (SDN), later followed by ocean monitoring [3].

3.2.1 Healthcare

Science and technology in health domain is a substantial research area for many researchers [19]. Like other industries, healthcare department can also be aided from edge computing, e.g, patients suffering from strokes fall. According to the stroke statistics, after every 40 seconds on average, someone is having stroke in United States [30]. Falls are common among stroke patients who suffers mostly due to hypoglycemia, hypotension, muscle weakness, etc. According to recent research, one third of the strokes could possibly be averted by early mitigating the fall incidents [34]. In order to detect and prevent fall, many research has been done, for example, by enabling human computer interaction devices, such as smartphone, smart watch and google glass, but certain limitations exists.

Recently, researchers have proposed smart healthcare infrastructure called U-Fall, that exploit smartphones by engaging edge computing technology. U-Fall is based on fall detection algorithm that is designed by using acceleration magnitude values and non-linear time series analysis [19] [23]. U-fall sense motion detection with the help of smart device sensors, such as gyroscopes and accelerometers. U-Fall intelligently maintain integrity between the smartphone and the cloud server to ensure real time detection. In addition, the proposed infrastructure is capable to deliver accurate results that makes it more reliable and dependable.

Furthermore, the three-tier architecture that includes role model, layered-cloud architecture and mobile edge computing can help health advisers to assist their patients, independent of their geographical location. MEC enabled smartphone collects patient physiological information, e.g, pulse rate, body temperature etc, from smart sensors and sends it to cloud server for storage, data sync and sharing. Health advisers having access to the cloud server can immediately diagnose patient condition and assist them accordingly [89].

3.2.2 Mobile Big Data Analytics

Mobile phone technology is valued a growth-engine for small, medium and large enterprises, and also have widespread social connotation. The ubiquity of mobile phones and its big data coming from applications and sensors, such as GPS, accelerometer, gyroscope, microphone, camera and bluetooth are stressing the network bandwidth [52]. Big data consists of large and complex data sets that is generated by data processing applications, sensors, devices, video and audio channels, web and social media [62] . These data sets may be structured or non structured and may not be possible to process by a single machine [94]. Big data is of paramount importance to businesses because it extract analytics and useful information that may benefit to different business segments [27]. Big data analytics is a process of extracting meaningful information from raw data that could be helpful for marketing and targeted advertising, customer relations, business intelligence, context-aware computing, health care etc. [8][78].

Implementing MEC near to the mobile devices can elevate big data analytics with the help of network high bandwidth and low latency. For example, instead of using typical path from edge device to the core network, big data can be collected and analyzed at the nearest MEC location. The result of big data analytics can then be passed to the core network for further processing. This scenario will perhaps also accommodate data coming from several IoT devices for big data analytics.

3.2.3 Connected Vehicle

Vehicles are facilitated with an internet access that allows them to connect with other vehicles on the road. The connection scenario can either be vehicle-to-vehicle, vehicle to access point or access point to access point. By deploying MEC environment along side the road can enable two-way communication between the moving vehicles. One vehicle can communicate with the other approaching vehicles and inform them with any expected risk or traffic jam, presence of any pedestrian and bikers. In addition, MEC enables scalable, reliable and distributed environment that is synced with the local sensors [24].

3.2.4 Video Analytics

Surveillance cameras in old times use to stream data back to the main server and then the server decides how to perform data-management. Due to the growing ubiquity of surveillance cameras, old client-server architecture might not be able to stream video that may be coming from million of devices and therefore, it will stress the network. In this scenario, MEC will be beneficial by implementing intelligence at the device itself which is programmed to send data to the network, when there is any motion detection. In addition, MEC enabled surveillance cameras can be effective for several applications, such as traffic management application on the basis of traffic patterns can detect traffic jam or an accident. The application can also be helpful for face recognition, for example, if someone commits a crime then his photo can be transferred to these intelligent cameras to trace the culprit [35] [38] [35]. As illustrated in figure 3.2, the surveillance cameras connected at different locations, transmits data to MEC server for processing and analytics. Perhaps, the management server make decisions as per the defined rules.

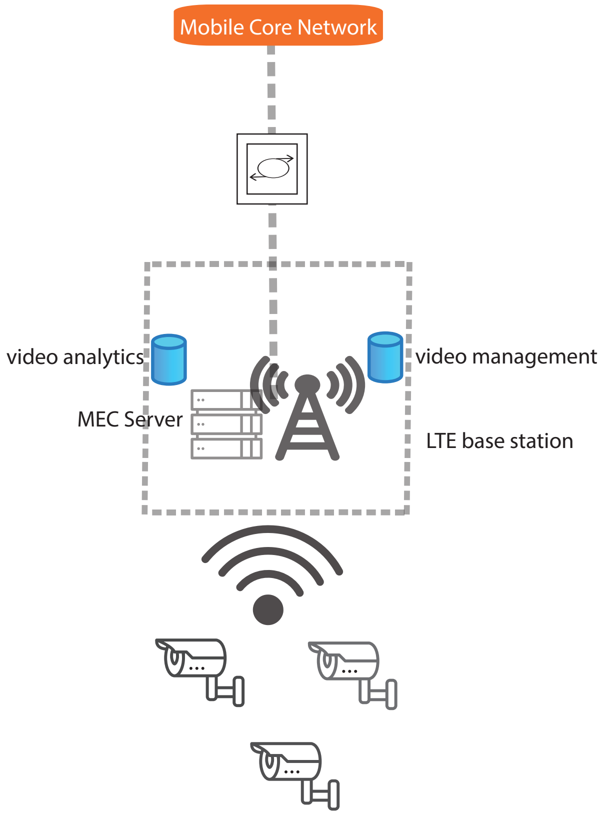

Figure 3.2: Video Analytics

3.2.5 Smart Grid

Smart grid infrastructure is an electrical grid that consists several components, such as smart appliances, renewable energy resources, and energy efficiency resources. Smart meters that are distributed over the network are used to receive and transmit measurements of the energy consumption [58]. All the information collected by smart meter is supervised in supervisory control and data acquisition (SCADA) systems that maintain and stabilise the power grid. Moreover, MEC integrated with distributed smart meters and micro grids can support SCADA systems. For example, in this scenario, MEC will balance and scale the load according to the information shared by other micro grids and smart meters.

3.2.6 Wireless Sensor and Actuator Networks (WSAN)

Wireless sensors and actuator networks(WSAN) are sensors that is used for surveillance, tracking, and monitoring of physical or environment situation, e.g., light intensity, air pressure, temperature etc. [48]. MEC enabled actuators autonomously manage measurement process by developing an active feedback loop system. For example, air vent sensors manages air pressure flowing in and out of the mine to save miners from any emergency. These sensors consume very less energy and bandwidth with the help of MEC.

3.2.7 Smart Building Control

Smart building control system consists of wireless sensors that are deployed in different parts of the building. Sensors are responsible for monitoring and controlling building environment, such as temperature, gas level or humidity. In smart building environment, sensors installed with MEC becomes capable of sharing information and become reactive to any abnormal situation. These sensors can maintain building atmosphere on the basis of collective information received from other wireless nodes. For example, if humidity detected in the building then MEC can react and perform actions to increase air in the building and blow out the moisture.

3.2.8 Ocean Monitoring

Scientists are researching to cope with any ocean cataclysmic incidents and know the climate changes in advance. This can help to react quickly and mitigate to prevent from any disastrous situation. Sensors deployed at some location in the ocean transmits data in great quantity that require large computational resources [3]. The data handled by cloud may occur delays in the transmission of live forecast. In this scenario, MEC can play a vital role to prevent for any data loss or delay in sensor data.

3.3 Miscellaneous Research Efforts

In this section, several research efforts are presented that are recently described.

3.3.1 Low Latency

MEC is one of the promising edge technologies that improves user experience by providing high bandwidth and low latency.

In 2016, Abdelwahab et al [1] proposed REPLISOM that is the edge cloud architecture and LTE enhance memory replication protocol to avoid latency issues. LTE bottleneck occurs due to large number of IoT devices memory allocation to the backend cloud servers. These devices offloads computational tasks by replicating and transmitting tiny memory objects to central cloud, that makes IoT to be scalable and elastic. The LTE-integrated edge cloud provide its compute and storage resources at the edge to resource-intensive services. Thus, the proposed REPLISOM reduces the stress of LTE by intelligently scheduling memory replication events at the LTE-edge to resolve any conflicts during memory replication process for the radio resources.

In 2015, Nunna et al [66] proposed real time context-aware collaboration system by combining MEC with 5G networks. By integrating MEC and 5G, it empowers real time collaboration systems by leveraging with context-aware application platform. These systems require context information combined with geographical information and low latency communications. The 4G networks might not be capable to fulfill such requirements, instead 5G networks and MEC are proficient to utilize contextual information to provide real-time collaboration. The above suggested model is beneficial for scenarios life Remote Robotic Tele-surgery and Road Accident that demand high bandwidth and ultra low latency.

In 2016, Kumar et al [51] proposed vehicular delay-tolerant network-based smart grid data management scheme. The authors investigated the use of VDTNs to transmit data to multiple smart grid devices exploring MEC environment. With the use of store-and-carry forward mechanism for message transmission, the possible network bottleneck and data latency is avoided. Due to the high mobility of vehicles, smart grid environment supported by MEC use to monitor large data sets transmitted by several smart devices. According to the data movement, these devices makes computation charging and discharging decisions with respect to message transmission delay, response time and high throughput network for movable vehicles.

3.3.2 Computational Offloading

Computational offloading is one of the main advantage of MEC to improve application performance, energy consumption and response time.

In 2015, Takahashi et al. [93] proposed edge accelerated web (EAB) browsing prototype that is designed for web application execution by a better offloading technique. The purpose of EAB is to improve user experience by pushing application offloading to the edge server that is implemented within the RAN. EAB-frontend at client-side retrieves the rendered web content that is processed at EAB server, whereas, audio and video streaming travels through EAB-backend and are decoded depending on client hardware capability. As shown in figure 3.3, web content, contents determination and rendering is done at MEC server, whereas video and audio is processed at client if client device has decoding harwdware.

In 2016, Chen et al. [21] designed an efficient computation offloading model using a game theoretic approach in a distributed manner. Game theory is a persuasive tool that help simultaneously connected users in making correct decision to connect what wireless channel based on the strategic interactions. If all user devices offloads computation activity using the same wireless channel that might cause signal interference

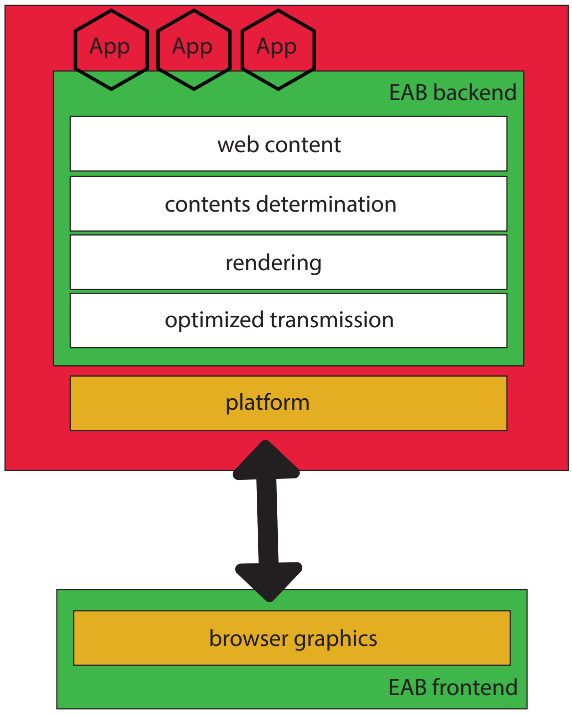

Figure 3.3: Components Arrangements in EAB

with each other and decrease wireless quality. Specifically, game theory targets the NP-hard problem of computation offloading incurred by multi-user computation offloading and provides a solution by attaining Nash equilibrium of multi-user computation offloading game.

In 2015, Sardellitti et al [79] proposed an algorithm based design, successive convex approximation (SCA). This algorithm optimizes computational offloading across densely deployed multiple radio access points. The authors considered MIMO multicell communication system where several mobile users (MUs) requests for their computational tasks to be carried at the central cloud server. They first tested a single user offloading computational task at cloud server where resulting problem is non-convex optimization. In multiuser scenario, the SCA-based algorithm attained local optimal solution of the original non-convex problem. According to the formulation results, authors claimed their algorithms to be surpassed disjoint optimization schemes. Moreover, they added the proposed SCA design is more suitable for applications acquiring high computational tasks and minimizes energy consumption.

In 2016, Zhang et al [105] proposed contract-based computation resource allocation scheme. This scheme improves the utility of vehicular terminals by intelligently using services offered by MEC service providers under low computational conditions. MEC provider receives the payment from vehicles on the basis of the amount of computational task they offloaded at MEC servers. Using a wireless communication service, information of the contract and payment information is broadcast to the vehicles on the road. Vehicular network architecture is plotted in figure 3.4 that show vehicles connected with MEC deployed at RAN location. MEC shares an associated contract information with the service provider that keeps a control over billing system. Later, the bill is sent to the user according to the computation service they have utilized.

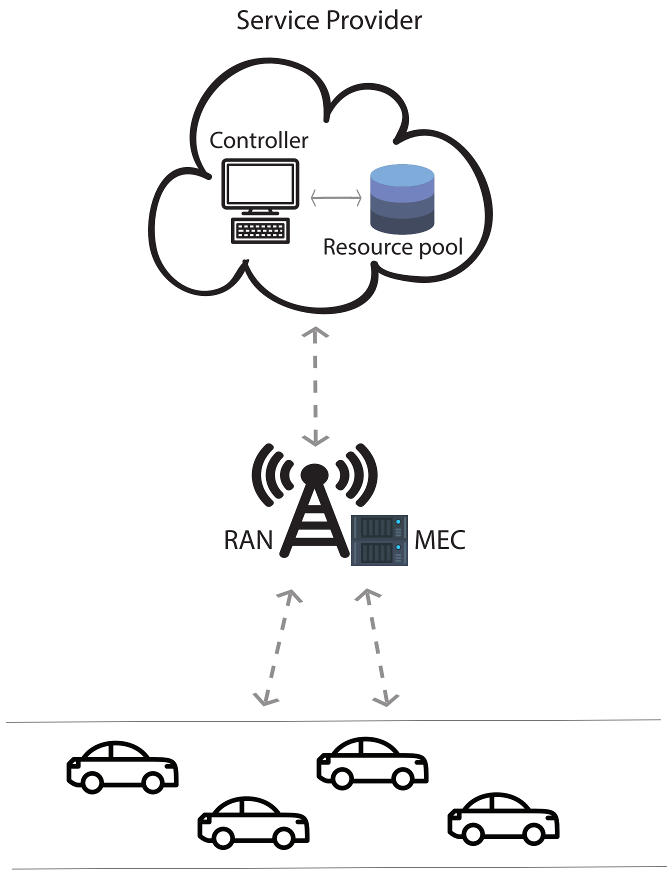

Figure 3.4: Vehicular Network Architecture

In 2015, Habak et al. [31] proposed FemtoCloud system that forms a cloud of orchestrated co-located mobile devices that are self-configurable into a correlative mobile cloud system. FemtoCloud client computing service is installed on each mobile device to calculate device computing capability, energy information and capacity for sharing with other mobile devices. Each mobile properties are built and maintained inside a user profile which is shared in mobile cluster that is connected with cloudlet or a control device and also available in a Wi-Fi network. Intensive computational tasks in the form of codes are sent to cloudlet to leverage the computational capacity of other connected mobile devices. The tasks associated with the mobile are completed and results are shared with the control device until the mobile device dissociate the cluster. FemtoCloud model is designed to reduce the computational load from the centralised location and bring it to the edge of mobile network. As shown in figure 3.5, there are several modules working together to form FemtoCloud system. The user interface module stores user profile that define the resources of the user device. Capability estimation module is responsible to calculate device computational capacity. Profile module stores the user behavior and femto system usage in different scenarios. Execution prediction module is responsible to share tasks among different processing nodes. Time prediction module develops a generic user profile on the basis of presence time the user is connected to the FemtoCloud system. Task and scheduling module assigns user devices on the basis of the information collected fomr previous modules. Local connectivity estimation module measures the bandwidth between the devices (i.e. control device and mobile device). Discovery module search for the mobile devices that have FemtoCloud client installed in it. After the device is located, this module registers mobile device to the cluster. All the stated modules work together to develop FemtoCloud eco system.

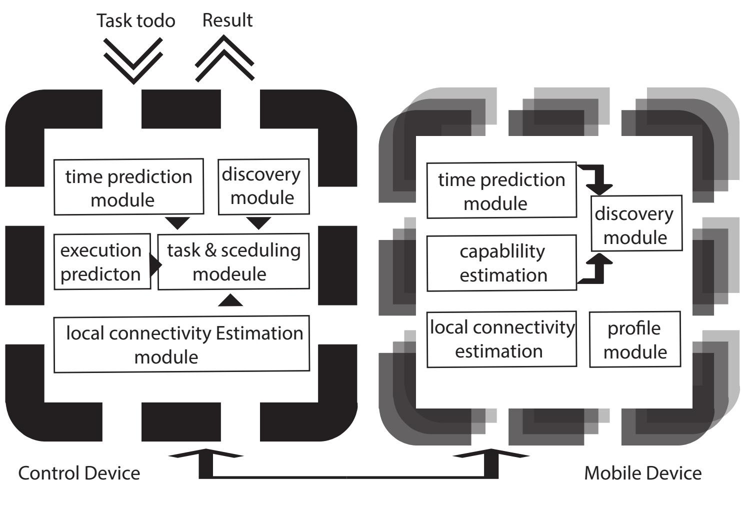

Figure 3.5: Femto Architecture [31]

3.3.3 Storage

User end devices with limited storage capacity may leave negative impact of user experience. End users can utilize MEC storage resources to overcome their device storage limitation.

In 2016, Jararweh et al [41] proposed Software Defined System (SDsys) for Mobile Edge Computing. The proposed framework connects software defined system components with MEC to further extend MCC capabilities. The components jointly works cohesively to enhance MCC into the MEC services. Working with Software Defined Networking (SDN), Software Defined Compute (SDCompute), Software Defined Storage (SDStorage), and Software Defined Security (SDSec) are the prime focus of the proposed framework that enable applications require compute and storage resources. Application like traffic monitoring, content sharing and mobile gaming will benefit from SDMEC. In figure 3.6, SDsys layered hierarchical framework is displayed.

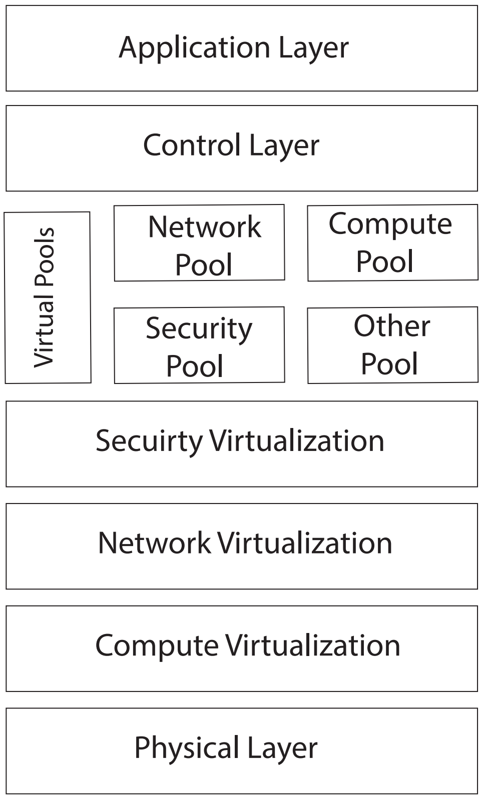

Figure 3.6: Layers of SDsys [41]

3.3.4 Energy Efficiency

As previously mentioned, MEC architecture is designed to improve energy consumption of user devices by migrating compute intensive tasks to the edge of network.

In 2015, El-Barbary et al [11] proposed DroidCloudlet that is based on commodity mobile devices. DroidCloudlet is legitimized with resource-rich mobile devices that takes the load of resource-constraint mobile devices. The purpose of the proposed architecture is to enhance mobile battery life by migrating data-intensive and compute-intensive tasks to rich-media. DroidCloulet works as a client device or as a server device running an application that supplements resource-poor devices by offering its available resources. One of the devices takes the role of an agent that is responsible for sharing resources with other group of devices. DroidCloud has several modules that are shown in figure 3.7. As stated, any mobile device can be client that require resources or any mobile device can be server that serves its resources to other devices, this is performed by server profiler, offloading agent and class loader. Server profile decides on the basis of its resources that whether it should act as a server or a client. Offloading agent follows its predefined offloading policy to process offloading either at the server or at the local operating system. Class loader main task is to execute classes and their parameters of offloading agent on operating system server. Other modules depicted in the picture performs auxiliary roles to support DroidCloud functionality.

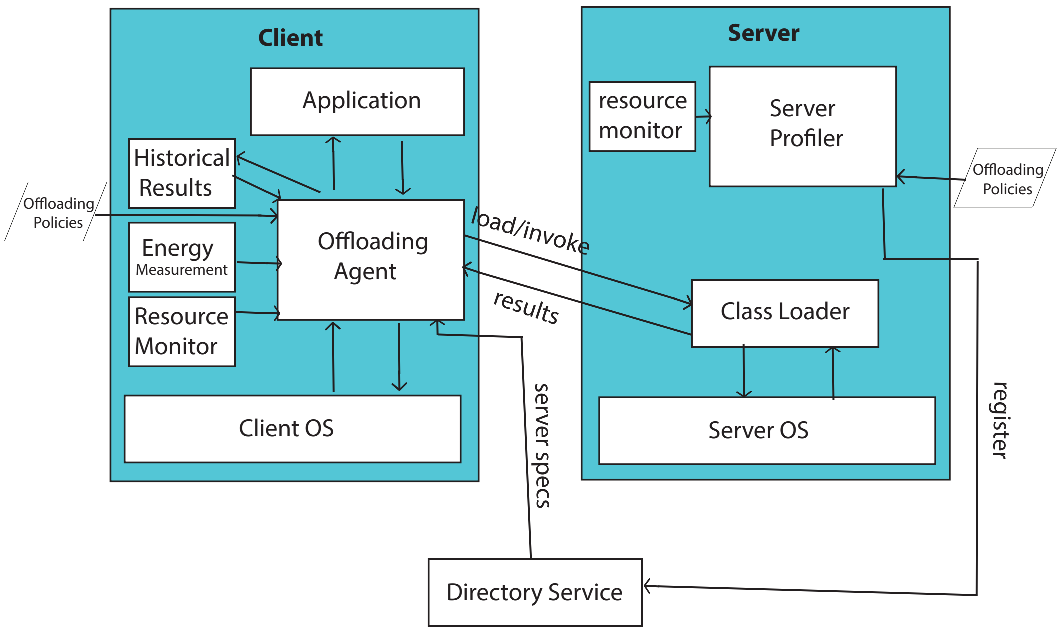

Figure 3.7: DroidCloud Architecture [11]

In 2014, Wei Goa [28] proposed opportunistic peer-to-peer mobile cloud computing framework. The probabilistic framework is comprised of peer mobile devices connected with in their short-range radios. These mobile devices are enable to share both the energy and computational resources depending on their available capacity. He proposed the probabilistic method to estimate opportunistic network transmission status and to ensure the resultant computation is timely delivered to its initiator. The purpose of the proposed framework is to facilitate warfighters at the tactical edge in a war zone. This framework is beneficial for situational awareness or surrounded ground environment understanding, with the help of data processed by in-situ (on site) sensors. The preambled novel framework, is thus efficiently share computational tasks by migrating workloads among warfighters mobile hand held devices, perhaps taking an account of timeliness of computational workload for successive resultant migration.

In 2015, Beck et al [12] proposed ME-VoLTE that is an architecture which integrates MEC to voice over LTE. Video calls multimedia encoding is offloaded at MEC server that is located at the base station (eNodeB). Video encoding offloading at external services helps in escalating battery life of a user equipment. Encoding is high compute-intensive and hence is very power consuming. In the proposed system, encoding techniques are wisely used to stream video on MEC server. MEC transcodes video by using special codec program before responding to user device request. This phenomenon significantly increase data transmission and enhance power management.

In 2016 Jalali et al [40] proposed flow-based and time-based energy consumption model. They conducted number of experiments for efficient energy consumption using centralized nano data centers (nDCs) in a cloud computing environment. The authors claim that nDCs energy consumption is not yet been investigated. Therefore, several models were presented to preform energy consumption tests on both shared and unshared network equipments. In the paper, it concludes that nDCs may lead to energy savings if the applications, especially IoT applications that generate and process data with in user premises.

Chapter 4

Research Infrastructures

There are a few papers depicting MEC infrastructure that has been described in this chapter [36] [72] [26].

4.1 MEC Platform

The main services of MEC application server is Commercial-Off-The-Shelf (COTS) products that is available for general mobile users. As shown in figure 4.1, MEC server is comprised of an application platform and hosting environment which is further divided into virtualization and hardware resources.

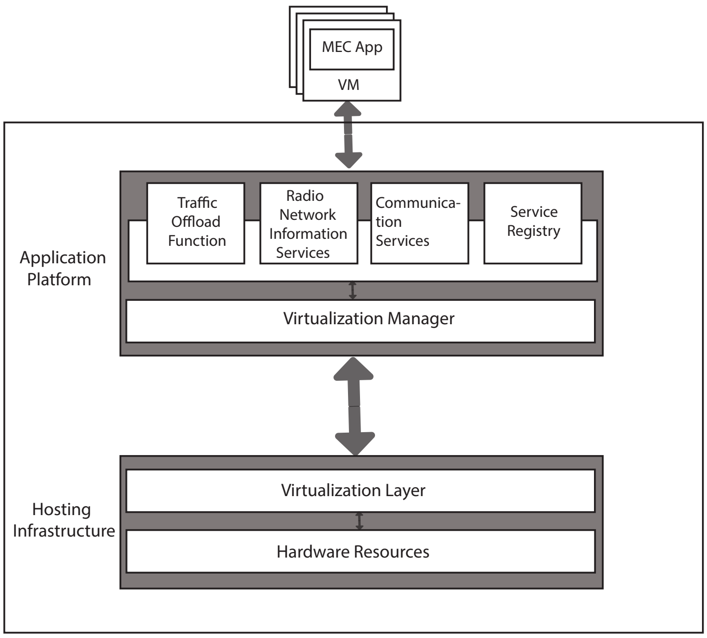

Figure 4.1: MEC Server Platform [26]

Application platform enables application hosting from ASPs, vendors and third parties. The application platform is comprised of virtualization manager and services that includes traffic offload function (TOF), radio network information services (RNIS), communication services and service registry. These services are managed by application platform management.

- *Traffic offload function (TOF)* is responsible for traffic offloading on the basis of the policy that is defined. It has the pass-through mode and end-point mode, the application is passed through application in pass-through mode whereas end-point mode terminates the traffic.

- *Radio network information services (RNIS)* enable cloud application services that serves the mobile users with in the radio access network. RNIS is responsible of delivering information of user and cell relevant that is accessible to the authorized application.

- *Infrastructure services* consists of communication services and service registry that performs intermediary role to MEC hosted applications. Communication services facilitate a communication stream between the hosted application on MEC and application-platform services. Service registry provides application service visibility of the end-points to applications that want to deploy their own services.

4.2 Deployment Scenario

As mentioned earlier, mobile edge computing can be deployed flexibly and intelligently at different sites that includes UMTS radio access network (UTRAN), LTE E-UTRAN Node B, 3G Radio Network Controller (RNC) and multi-Radio Access Technology (RAT), as illustrated in figure 4.2. MEC deployment will use network functions virtualization (NFV) architecture or NFV platform may be dedicated for MEC, otherwise will be shared with MEC architecture.

According to the first release of information services group (ISG) MEC, the implement scenarios can either be at outdoor environment, such as LTE site, 3G site etc. or indoor environment, such as shopping malls, hospitals, etc.

1. MEC in outdoor scenario: Several ways are possible to implement MEC in outdoor scenario, for example, macro cells vendors insert virtualization environment into a radio access network . This scenario helps operators to deliver network features with high value services. Moreover, it improves quality of experience (QoE) by providing low latency, pushes more intelligence to the edge and provide better computation offloading. The infrastructure where MEC is closely integrated with RAN, gives a better network traffic analysis, radio network status, device location services etc.

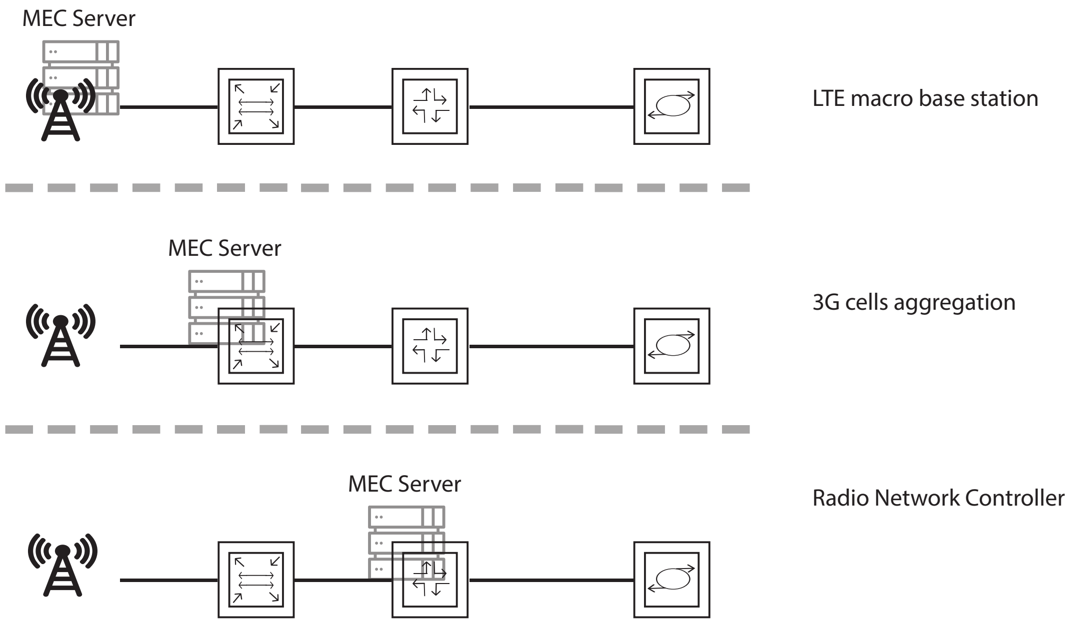

Figure 4.2: Edge Computing Deployment Scenarios [26]

2. MEC in indoor scenario: In Wi-Fi or 3G/4G access points, MEC can be deployed through light weight virtualization. Its deployment in machine-to-machine environment can monitor temperature, humidity, air conditioning, etc. with the help of connected sensors at various indoor locations. MEC can also be beneficial in case of any emergency situation, such as in any hazardous situation in a residential building environment it can help people to evacuate the building with the help of AR services etc.

4.3 MEC Testbed

This section lists some recent testbeds that are developed and tested by implementing mobile edge computing platform.

4.3.1 5th generation test network

The 5th generation test network (5GTN) architecture was developed and successfully tested at Oulu, Finland, that is based on LTE and LTE-Advanced (LTE-A) technology [75]. It opens an opportunity for application developers to develop their application in a test environment before they are brought to the market. The introduced testbed is composed of different environments, one is located at Technical Research Centre of Finland (VTT's) 5G laboratory and other is at the University of Oulu's Centre for wireless communications (CWC). CWC network is opened for public users, whereas VTT's network is in more secured and private environment. Both networks are integrated with the help of carrier-grade technology that offers a real-time environment. The private network is connected to 5G test laboratories that are in different parts of Europe. The purpose is to stretch 5G network functionality. CWC network was targeted for any mobile user of any mobile operator. The key purpose is to give an access to the university students and visitors with high-nature 5G experience .MEC functionality is based on Nokia provided solution that is operative in an AirFrame cloud environment can be tested in 5GTN architecture. It will allow the third-parties service providers to test their application in an MEC-5G.

4.3.2 Industrial Testbeds

Nokia and China mobile successfully tested advance mobile solutions for utmost mobile data capacity and real-time video [64]. The testbed was deployed in a car race stadium where 11707 active users were simultaneously connected with small cells and 6195 users with macro cells. In total, 95 LTE small cells were installed having 2.6 TDD, 2.3 TDD and 1.8 FDD specifications at the ultra-dense distance of 10-15m. Platform built for MEC with airframe Radio Cloud platform for MEC and Airscale Wi-Fi with flexi zone controllers. The system successfully delivered high performance HD videos on user mobile panels offering multi-screen view. Similarly, other testbed application was created by Nokia and Chunghwa Telecom (CHT) implemented at a baseball stadium that gives a live TV coverage like view and live experience of match atmosphere simultaneous at the same time [65]. MEC environment was created with the help of Nokia Flexi Zone base stations that uses 30 MHz of LTE spectrum. Spectators are able to see four video feeds at the same time that are on a split mobile screen. MEC offers ultra-low latency that is required for live video streaming by moving compute power to process the videos at the nearest place to the subscribers.

Nokia and its partners delivered an intelligent car-to-car infrastructure communication system using operator's live LTE network [63]. Vehicles connection is facilitated by different cloudlets deployed at Nokia MEC platform at mobile base stations as shown in figure 4.3. These cloudlets were able to deliver end-to-end latency below to 20ms. First use case tested was emergency brake or slowing down car prior to any upcoming emergency. Vehicles can communicate almost a real time with the vehicles that are even beyond sight. The second use test case is cooperative passing assistant that also utilizes cloudlets deployed at LTE base stations. Vehicles changing lanes are alarmed with the critical distance between them. On the basis of distance and car velocity the situation is computed by the cloudlets and later signaled to vehicles with guidance of possible actions to prevent from any risk.

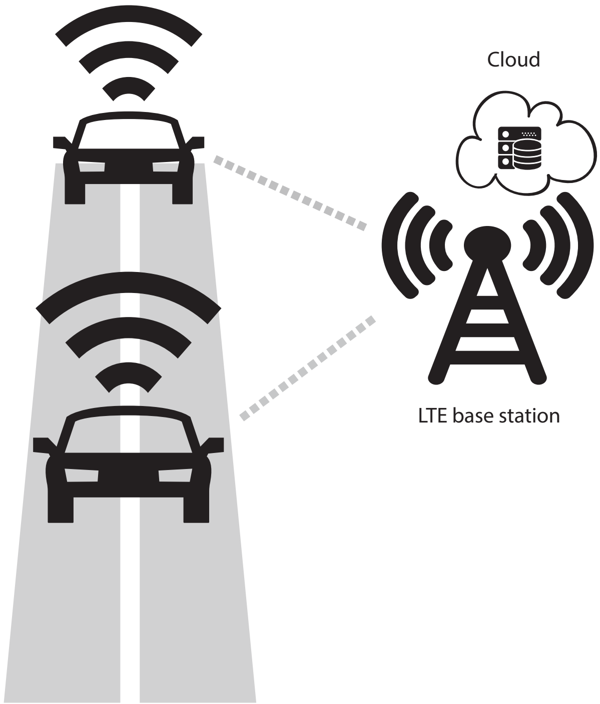

Figure 4.3: Vehicular Communication System

Chapter 5

Security and Privacy Issues

5.1 Security

Despite its benefits, mobile edge computing is not a panacea. There are some challenges that need extensive research studies of every layer of MEC infrastructure. This section explains MEC research issues that are mentioned in several papers, in context of different architectural designs [77] [101] [91] [53].

5.1.1 CIA Triad

The components of CIA triad, confidentiality, integrity, and availability makeup a model design for information security. There are several aspects of trust that need considerations in MEC infrastructure.

1. Confidentiality: There are several applications hosted at the edge of network providing there services to the mobile users, e.g location-awareness. In spite of the fact that these applications are beneficial but they also posses confidential risks. For example, at application layer there is no rule defined to separate user identity from its geo-location [87]. Therefore, new protocol is required to be preambled. The user information is vulnerable between MEC and cloud communications channel. Intercepting the communication stream, such as packet sniffing, will exploit location-based attacks on end devices.

2. Integrity: The MEC ecosystem incorporates multiple actors, such as end users, service providers, infrastructure providers etc. that causes several security challenges. Cloud servers efficiently enable compute nodes to authenticate them to administrative servers in data center due to its isolated environment but is less suitable in an open environment. For example, MEC nodes under multi-management domain will be difficult to share there identification with cloud servers. This scenario can invite several attacks, such as man-in-the-middle attack in which the attacker can authenticate themselves to the central cloud systems and later with end devices to steal there secret information.

3. Availability: Due to less isolated environment, MEC system may suffer denial of service (DOS) attacks that could be application or packet-based. On single node, these attacks might not be much hazardous but if the correlative attacks occur simultaneously at multiple geo-locations, it can lead to serious implication. For example, compromised sensors in industrial sector will make a ripple effect globally. Such attacks are difficult to mitigate, as MEC systems are directly connected with the end devices and there is no way of detecting malicious network activity.

5.1.2 Network Security

The preponderance of various communication networks, such as mobile core networks or wireless networks, network security is a very important element in MEC environment. In traditional network security environment, network administrator defines network security policy that isolates network traffic, whereas, the deployment of MEC at the internet edge, stresses the network management policy that may be vulnerable to various attacks, such as denial of service (DOS) that may damage MEC and cause useless heavy network traffic. This kind of attack is limited to MEC nodes and not much effective to back-haul network, since the back-haul network is more secured. Attackers can also launch traffic injection or eavesdropping attacks that can takeover the network or a quantum of a network. Hacker hijacking the network stream can launch attacks to effect MEC system performance. For example, gateway located in public places can be deceit public private communication. Man-in-the-middle attack is likely to be effective before compromising gateway and later intercepts data communication. Attacker can successfully manipulate data traveling from cloud to user and vice versa. It is difficult to mitigate such attacks because, one of the reason is deploying and dropping virtual machines that makes it cumbersome to maintain blacklist. Han et at [32] proposed measurement-based approach that prevents user connection with rogue gateway by observing round-trip time between user and the DNS server.

5.1.3 Core Network Security

It has to be noted that all edge paradigms may be supported by core network. And most of the core network security is enable by mobile core networks or central cloud. Cloud service security are mostly managed by third party suppliers, such as Amazon, Microsoft, Google etc. However, it is not possible to completely rely on their security mechanism and has to be more protected. In addition, there is a high risk of user's personal and sensitive information that can be stolen by malicious entities. Edge paradigm equipments existing at the edge, exchange information with each other and may bypass central system security mechanism. Thus, makes privacy vulnerable and hackable. This type of security issue will not effect the whole ecosystem and will be limited due to its decenrtalised nature. There is also a possibility of the system data that can be changed and provide false information, if the services are hijacked. The level of this effect will be limited but may cause denial of services. If the core infrastructure is compromised then it can sabotage some elements of the core systems. Core network elements that are compromised can disrupt lower level infrastructure. Attackers may have all the access to the information and may tamper the network data flow.

5.1.4 MEC Server Security

MEC at the edge, comprises of several virtualized servers that provide IT intelligent services. However, these services are liable to external security threats, for example, physical access to the data centre is less protected or guarded. Attacker breaching security channels can physically damage IT resources. This particular attack is limited to a specific geographical location and may not be very critical. Moreover, stream of information to and fro the local scope of data centre can be stolen from malicious actors, such as users, ASPs etc. Or the design flaws, configuration errors, insufficient security training or abusing one's own privileges may be alarming risk to the data center system security. Being newly preambled in the technology world, MEC lacks some security expertise for adequate system security. Once the login has been accessed to the MEC system resources, attacker can abuse system integrity or can execute denial of service attacks, man-in-the-middle attacks etc. The services are discontinued or interrupted as a result of such security breach. Another security issue is the compromise of an entire data centre. In this type of attach, the whole data center is hijacked through single or a combination of different attacks. The attacks might be privilege escalation or a fake infrastructure. A compromised data center has a large impact over geographical location that refers to high scale damage.

5.1.5 Virtualization Security

In core mobile edge data center, several network instances co-exist sharing network instances. If one resources is compromised, it can effect the whole virtualized infrastructure. Attacker may misuse and exploit system resources that has been conceded. Denial of Service (DOS) attacks are most likely to happen. MEC virtualized systems can completely drain the resources that are serving computational, storage and network tasks. User connecting MEC virtual servers may result to denial of request and services. Furthermore, malicious antagonist can misuse virtual resources and not only effect the system itself but also IoT devices that are connected to it. For instance, any IoT that is in the range of radio network and is vulnerable can be hacked and sabotaged. One of the common security concern is a privacy leakage. Several APIs implemented in MEC environment are responsible to deliver information of physical and logical infrastructure. However, these APIs are most likely to be less protected against any malevolent activity. Several attacks can be escalate, e.g malicious virtual machines hosted in a data center can advance to other virtual machines or to other data centers. Users moving across different geographical location can escalate such attacks to other MEC virtualized servers. Virtual machine itself that is effected by an attacker can become a hostile and launch attacks on other VM's hosted on the same system.

5.1.6 End Devices Security

End user devices can potentially be harmful to effect some elements of ecosystem. However, the impact could be narrow due to limited user device surroundings. User devices act as a carrier in a distributed environment. In addition, there could be rogue users that can intrude the system and do some malicious activities. For example, they can inject false values or information in the system. Device can be reconfigured and set to send fake information, such as wrong surveillance camera information or incorrect data announcements by vehicles etc. Moreover, there are some scenarios where devices can participate in service manipulation. For example, any compromised device connected in a cluster environment can change and control services in that cluster.

5.2 Privacy Issues

Due to the close proximity to end user, privacy security, such as data, usage and location may be challenging in mobile edge computing. User privacy breach may get worse if the attacker gains personal information, such as credit card information, personal emails etc. Data privacy or information privacy of the user have a risk of being accessed. Even it could be worse if the attacker gets user sensitive information. Aggregation scheme, such as homomorphic encryption can enable privacy-preserving aggregation at gateways to secure user information [55]. Attacker may retrieve user information by learning usage pattern of user device while accessing MEC. For example, in a home smart-grid environment, meter reading, such as the presence and absence of user at home, user in-house behaviour can help attacker to perform any malicious or criminal activity. Non-Intrusive Load Leveling (NILL) has been introduced to encounter these kind of issues [60]. But it cannot be implemented in MEC environment due to untrusted third party, e.g no duplicate of battery to perform NILL. One possible way to counter this kind of privacy is by creating dummy tasks and perform multiple offloading to different locations, and thus can hide the original tasks by hiding behind these fake ones. Another privacy issue is user location. The Global Positioning System (GPS) that is very useful for users to benefit from geo-location services. Mobile users use location based services (LBS) for GPS navigation. However, LBS endures certain privacy issues, for example, user sharing their location information with LBS. User device connected to the nearest MEC will give an indication to the attacker that the compute device is near to which MEC location, as shown in figure 5.1. In order to secure location information, there are several ways to confuse the attacker. For example, MobiShare system is flexible and secure for sharing information of geo-location and has a good support for location-base applications [98].

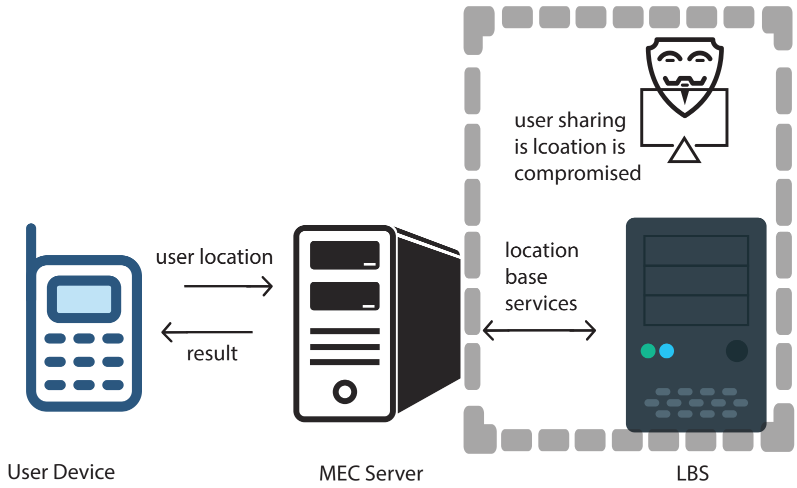

Figure 5.1: Archtecture of Location Sharing

5.3 Security Mechanisms

Security breach may cause potential harmful problems within the system. Therefore, it is very important to implement security mechanism and safeguard the MEC resources from any intrusion. Some of the security mechanisms are listed in this section.

5.3.1 Identification and Authentication

In a cloud computing environment, data centers are mostly hosted by cloud service providers, whereas in all edge paradigms, providers may be hosted by several providers depending on their choices. For example, Cloud service provider may extend there IT services to the edge using there existing infrastructure, MEC resource providers may differ with the extended cloud infrastructure and end user may want to use limited cloud resources depending on their budget and want to lease their resources on the local cloud. In order to integrate all these services, proper identification and authentication is required. Every entity in the ecosystem, such as end devices, virtual machine services, Cloud and MEC infrastructure service providers, and application service providers should be able to identify and mutually authenticate each other.

A user-friendly solution has been introduced that provides a secure authentication in a local ad-hoc wireless network [86]. The connected devices shares only limited public information that enables them to exchange authenticated key protocol. Similarly, NFC also enables a secure authentication method in a cloudlet scenario [15]. NFC applications based on cloudlets enables authentication by NFC capable end devices. Moreover, is is also of prime importance to have a continuous connectivity of user devices with their respected cloud servers. A Stand-Alone authentication is introduced for a scenario if there is temporary disconnection between MEC and the cloud server [91]. If the connection is fragile then Stand-Alone authentication would be able to authenticate users with the cloud servers.

With the evolution biometric authentication, such as face recognition, eye recognition, touch based, finger print etc., it will be very helpful to introduce biometric authentication system in mobile edge computing.

5.3.2 Access Control

With the deployment of authorization design, it is also important to confirm credentials of requested entities to perform certain actions. Without any proper access control mechanism it is difficult to prevent MEC infrastructure from any malicious activity. For example, MEC service providers deploying VMs, these VMs connecting to the APIs available at the edge of network etc., all these resources need an access control to execute their services.

In the context of mobile edge paradigm, where there are many actors involved, it is very important to have an authorization mechanism that authenticate these actors to enforce there own security policy. If there will be a trust relationship developed, then it will able to authorize all entities to communicate with each other abiding by the security policies.

5.3.3 Network Security Mechanism

Network security is one of the prime concern for MEC concept, due to the predominance network infrastructure. Attackers are more into launching attacks, such as man-in-the-middle, DOS etc. to sabotage mobile network environment, it is very essential to deploy a comprehensive security mechanisms. Intrusion detection and prevention mechanism is an important prerequisite before the deployment of MEC infrastructure. Several network entities could be vulnerable to any threat that need to be monitored from internal or external threat. In such cases, the edge infrastructure should be in-charge of monitoring their network and equally coordinate with surrounded and core networks. Intrusion detection system (IDS) can be employed in MEC data center to monitor and analyze system logs for any unauthorized access. It can also be employed at MEC network side to detect and prevent network from any attack, such as man-in-the-middle attack, DOS and port scanning etc. A Cloudlet that is located at one hop away from mobile devices can efficiently be meshed to form a security framework to detect any intrusion [81]. Cloudlet can serve as a proxy for distant cloud servers in-case of any unavailability issue caused by certain attacks. Moreover, by implementing software-defined network (SDN), it will be easy to reduce network cost and to scale network resources. SDN can isolate network traffic and segregate malicious data. The proposed access control scheme based on OpenFlow is useful for multiple security

[46]. For example, having direct access to the network components will make easy to monitor and detect any abnormal activity in network traffic.

5.3.4 Virtualization Security Mechanism

Virtualization technology is one of the foundation for edge paradigm and thus its security is of paramount importance. Malicious element getting an access to the virtual servers may hijack the whole edge data center. Virtualized servers and their hosted physical servers can be protected through hypervisor hardening, network abstractions, isolation policies etc. [73].

5.3.5 Data Security

In an edge paradigm, user data is outsourced to MEC server that gives an access control to mobile user. This invites some challenges, such as data integrity and authorization, for example, outsourced data can be modified or disappeared, moreover, the uploaded data can easily be accessed by malicious activists. Moreover, data owners and data servers posses dissimilar identities and business interests that makes MEC architecture more vulnerable. Good auditing methods can be used to audit the data storage in order to confirm that data is properly stored in the cloud [99].

5.3.6 Data Computation Security

Secure data computation is another important issue that has to be addressed carefully. There are two major aspects to secure any computation task that is outsourced which includes computation verification and data encryption. Verifiable computing allows the computing node to offload some functions to other servers that could not be trusted, but it enables the maintenance of the results that are verifiable. Other servers performs a check on the given function and confirms the correctness of computation. There should be a mechanism in which the user is enable to verify computational accuracy. A verifiable computing protocol is proposed that returns computational-sound, non-interactive proof that enables client server to verify [29]. Data encryption is another security mechanism. The data that is sent from user device need to be protected and encrypted before it is outsourced to the MEC server. One of the popular security services is a keyword search that means to search keywords from the encrypted data files. A statistical measure approach is proposed that search through a secured searchable index [96]. The index is secured through one-to-many order-preserving mapping approach.

Chapter 6

Open Research Problems

As a recent technology approach, no sufficient research study has been specifically designed for mobile edge computing. Therefore, there are some security issues in MEC that need to be addressed before its commercial deployment. This chapter illustrates and identifies the open issues that investigated by different researchers in the development of MEC.

6.1 Security

It is one of the main concern for technology advisers to secure MEC deployment. There are some security mechanisms that are applicable in MEC, as discussed in previous chapter. However, there are still some issues that need proper research study. For example, compute intensive applications outsource their computation on MEC servers, these tasks are performed through wireless medium that opens up the risk of intrusion. Moreover, different users connected to common physical server also raise some security issues [88]. The application data movement is possible through encryption and decryption strategy but it effects application performance.

6.2 Resource Optimization

Promoting cloud infrastructure to the network edge, MEC incorporate less resources then the traditional cloud infrastructure. Computational offloading is performed at the MEC virtualized servers. However, computational tasks carry extra overload due to heterogeneous processor architecture, for example, smart phones and cloud has mostly ARM and x86 architecture, therefore they need to perform translation or emulation [85]. Thus, an optimized solution for enhancing performance of intrinsic limited resources is required [4].

6.3 Transparent Application Migration

As mentioned previously, user applications tasks are moved to MEC server for computation etc.. It is very challenging to transparently migrate these applications for the usability of delay-sensitive mobile applications, such as real-time applications [7]. Poor Compute resources and service delay, deteriorates the performance of mobile applications [5]. Application migration is a software level solution that can be achieved by doing more research study to find solutions that optimize cloud services at the edge [6].

6.4 Pricing

Mobile edge computing environment involves several actors that quote different prices for their services. These actors have different payment methods, different customer management and different business policies. Therefore, it gives a rise to several questions; 1- what will be the mutually agreed price, 2- what will be the mode of payment, 3- who will process customer payment etc. For example, game application on user device have to utilize cloud resource, mobile network and game services. The user has to pay for the game that has to be divided equally or as per mutual contract to all the entities involved. This can be argued that agreeing to the pricing may be difficult among different entities.

6.5 Web Interface

Currently, the interface available to access MEC and cloud is the web interface that is not sufficient due to its overhead problem. The web interface is generally not designed for mobiles and hence have compatibility issues. Therefore, the standard protocol is required for smooth communication between the user, MEC and cloud. The latest version of HTML5 is designed specifically for advanced devices, such as mobile or smart phones. However, a performance and test based research is required to accept HTML5 in MEC environment.

6.6 Other Issues

Many issues that are already discussed in previous sections, in addition, there are also some other issues that are imperative to strengthen the MEC framework. A comprehensive scientific research study is required to avoid any security issue that can damage the system.

- *Openness of the Network*: Mobile core network has a sound authority over the mobile network but in MEC architecture it will be very challenging to open network for third party vendors due to the possible security risks.

- *Multi – service and Operations*: ASPs, OTT, network vendors and content providers require an access to MEC data centers. This scenario causes complexity for seamless third party services.

- *Robustness and Resilience*: Deploying resources at MEC is very important to enable robustness of the MEC server.

- *Security and Privacy*: User privacy and its data security may be exposed while integrating mobile services with MEC. Prior to MEC deployment, there should be an assurance that the network infrastructure is well protected.

Chapter 7

Discussions and Future Works

This chapter reflects the project findings and discussions about the different phases of this study. In Addition, research problems are reiterated for the reader convenience.

7.1 The problem statement

The prime objective of this project is to address the research problems, as defined earlier in section 1.1. Throughout the research study, MEC architecture, applications, approaches and challenges are studied with reference to the problem statements that are listed below:

- Why do we need mobile edge computing?
- Where can we use mobile edge computing?
- What are the main challenges in using mobile edge computing and what are the solutions related to these challenges.

To adequately address the problem statement, MEC approaches and implementation is thoroughly studied in this thesis. The importance of MEC and its potential to current and future mobile networks has been interpreted. Available edge paradigms are extensively studied and their differences are also depicted in this project. Furthermore, this project has analysed the challenges that may arrive during the technology implementation. In order to address these challenges some possible solutions are identified. During the research study, it has been learnt and discussed the far-reaching influence of MEC eco system and its instrumentation.

7.2 Challenges during the project

During the project period there has been a lot of challenges in finding the relevant research study. One obvious reason is that there is very few research study that specifically explain MEC concept and its implementation. MEC is a recent technology approach that is a bit immature. Therefore, there is not much scientific research conducted as yet.

7.2.1 Available testbeds

It was very challenging to refer any test scenario that is associated with MEC, except the testbeds mentioned in Section 4.2. Those which are mentioned, does not specify the sufficient detail of the system environment, such as the system specification and components that are used during the test. Moreover, there

7.2.2 Benchmark

No specific test were found during the research study that establishes a benchmark. Therefore, there is not much study available on MEC that may evaluate its performance.

7.2.3 Available applications

Since, MEC is not practically deployed in the industry, thus its a challenge to find MEC applications that are tested and analyzed. Instead, applications that belongs to other similar edge computing technology were mentioned in this project.

7.3 Thesis Contributions

This project demonstrates a detail survey on MEC. Even though there are some vulnerabilities in the proposed technology but however, some security solutions are presented for future research study. The findings of this thesis indicates the importance of MEC for computational intensive applications that require high bandwidth and highly latency-intolerant. In the context of mobile live streaming that is to be one of the key use case of 5G networks is illustrated. Furthermore, MEC longer-term role in evolved mobile networks is also indicated in this thesis. The difference between the similar technologies, such as cloudlet, local cloud, fog computing and mobile cloud computing, are also demonstrated.

7.4 Future Works

Edge paradigms are introduced recently so these technology infrastructure is not properly defined. Therefore, some security risks exists in the infrastructure that need future study. Alternatively, MCC has been studied for longer period, therefore its security is well defined. In order to push cloud services at the edge, a future research can be conducted for designing security mechanism to protect MEC infrastructure from attacks, such as man-in-the middle, rogue servers etc. Technology experts foresee 5G to be introduced by 2019 and they often cite MEC as a central to 5G core network so there should be sufficient MEC testbeds prior to its industrial implementation.

This thesis based on mobile edge computing, has a lot of potential and hence it opens an opportunity for researchers to further study its features and functions.

7.5 Project Timeline

This project has gone through different phases during its research study that was timely managed to meet its submission deadline. On 30th November, a survey report on mobile edge computing was submitted to IEEE internet of things journal that was a part of this research project. In figure 7.1, the project timeline is summarized in the form of a gantt chart.

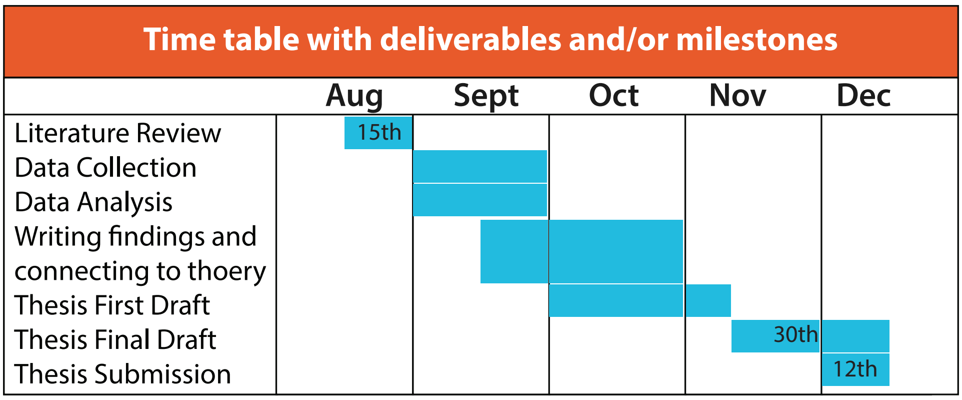

Figure 7.1: Gantt Chart

Chapter 8

Conclusion

Mobile edge computing has a great potential to be the future edge technology that offers bandwidth, battery life and storage to the resource-constraint mobile devices. MEC trends to provide elastic resources at the edge of the networks to the applications that are compute-intensive and demand high bandwidth and ultra low latency, especially in the scope of 5G networks. MEC deployment can build an ecosystem involving third-party partners, content providers, application developers, OTT players, network vendors and multiple network operators.

This research work was intended to address the problem statement, therefore, this thesis has presented a generic view of MEC. The conducted study has stated the importance and the use of MEC. Some challenges to deploy the MEC eco systen are also address in this thesis.

Beside MEC advantages, many challenges still remain though, with issues ranging from security to resource optimization still needs a depth of study for future work.

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