

**Planning of Mobile Edge Computing Resources in 5G Based on  
Uplink Energy Efficiency**

by

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## **Abstract**

Increasing number of devices demand for low latency and high-speed data transmission require that the computation resources to be closer to users. The emerging Mobile Edge Computing (MEC) technology aims to bring the advantages of cloud computing which are computation, storage and networking capabilities in close proximity of user. MEC servers are also integrated with cloud servers which give them flexibility of reaching vast computational power whenever needed. In this thesis, leveraging the idea of Mobile Edge Computing, we propose algorithms for cost-efficient and energy-efficient the placement of Mobile Edge nodes. We focus on uplink energy-efficiency which is essential for certain applications including augmented reality and connected vehicles, as well as extending battery life of user equipment that is favorable for all applications. The experimental results show that our proposed schemes significantly reduce the uplink energy of devices and minimizes the number of edge nodes required in the network.

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## List of Abbreviations

Symbol	Definition
AV	Autonomous Vehicle
AWS	Amazon Web Services
AR	Augmented Reality
BS	Base-station
CAPEX	Capital Expenditure
CW	Computational Workload
CWR	Computational Workload Requested
EPC	Evolved Packet Core
ILP	Integer Liner Programming
IP	Internet Protocol
IoT	Internet of Things
IoV	Internet of Vehicles
LTE	Long Term Evolution
MC	Macro-Cell
MCC	Mobile Cloud Computing
MEC	Mobile Edge Computing
MEN	Minimize Edge Node
MEP	Jointly Minimize Edge Node and Power
NFV	Network Function Virtualization
PC	Personal Computer
PPP	Public Private Partnership
PUSCH	Physical Uplink Shared Channel
QoS	Quality of Service
RAN	Radio Access Network
RTV	Radio Transmission Unit
SDN	Software Defined Network
SINR	Signal to Noise Ratio
UE	User Equipment
UL	Uplink
UP	Uplink Power
WAN	Wide Area Network
WAP	Wireless Access Point
WLAN	Wireless Local Area Network

# Chapter 1

## Introduction

Devices are becoming more and more reliant on internet services for applications such as social networks, application for smart wearables, and electric vehicles. There are also emerging technologies such as augmented reality and Internet of Things (IoT), which are primarily dependent on processing capacity. In other words, smart devices, applications and users demand considerable amount of computational resources which are generally fulfilled by the help of cloud technology. With these benefits some challenges arise in terms of latency, efficiency, mobility and scalability. An emerging technology that is known as Mobile Edge Computing (MEC) aims to overcome these issues by deploying edge nodes, which have computation, storage and network capabilities, physically closer to the users. MEC could be considered as an extension of the cloud to the network edge. Being a decentralized computing architecture, it distributes computing resources and application services to an optimal place for increasing efficiency and reducing latency. In that case, delay sensitive data can be processed at the nearest edge node whereas delay-insensitive data can be sent to centralized cloud servers for further processing and analysis. Edge node deployment is one of the major focuses for telecom companies wishing to take advantage of content-aware technologies, such as connected electric vehicles, which require high speed data connection and less response time. Therefore, placement of the edge nodes becomes a relevant research problem.

In this thesis, we propose two optimization models using Integer Linear Programming (ILP). First model aims to minimize the number of edge nodes so that deployment cost is

minimized. The second model aims to jointly minimize of uplink energy and the number of edge nodes. The second model aims to provide energy-efficient access to UEs by reducing their energy consumption upon accessing the nearest edge node.

## **1.1 Problem Statement**

The goal of this study is to optimally place MEC nodes under certain number of stationary users and their varying offloading demands (i.e. workloads). Dense deployment of MEC nodes increases the cost of deployment while providing energy-efficiency. Thus, there is a tradeoff between cost and energy efficiency. In this thesis, we propose two schemes. The first Integer Linear Programming (ILP)-based model aims to minimize the number of MEC nodes, while second ILP model jointly minimizes the number of MEC nodes and the uplink energy spent by the UEs.

## **1.2 Motivation**

The increasing number of devices connected to the internet and their need for computation is the primary motivation of this work. Ericsson mobile report of 2018, states that mobile users will grow to 8.9 billion from 7.8 billion in 2017 whereas, mobile data traffic will surpass 100 Exabytes from 15 Exabytes in 2017 [1]. With such an increase in generation and consumption of data, and with the evolution of devices which are becoming more dependent on high-speed data traffic and requiring less latency, distributed computing becomes a strong alternative to the centralized cloud. In addition to IoT, advancement in technology is expected to automate the manufacturing process in the upcoming years which also require low latency. This can only be provided by the introduction of MEC. MEC will be a necessary asset for various upcoming technologies and will

account for an increasing number of sensors deployed on roads, vehicles, buildings, etc. In summary, to connect these technologies to the internet, process data with reduced latency, MEC emerges as a promising solution. Thus, this thesis is motivated by these recent advances and proposes optimization schemes for the placement of MEC nodes in the wireless mobile network.

### **1.3 Contributions**

This thesis addresses the placement of Mobile Edge Computing (MEC) nodes and uplink energy efficiency for User Equipment (UE). Following are the major contributions of our research work:

- We proposed an ILP model, namely Minimize Edge Node (MEN) scheme, which minimizes the number of mobile edge nodes in the wireless networks and reduces deployment cost for edge devices.
- We proposed another ILP model, namely Joint Minimization of Edge Node and Power (MEP) scheme, which minimizes the placement of mobile edge nodes and significantly reduces the uplink energy consumption upon accessing the nearest edge node.
- We compare both schemes to a baseline scenario. Our results show that for 100 UEs and 40 units of workload, MEN scheme needs 74.7% of less MEC nodes than MEP. In the meanwhile, MEP scheme reduces the energy consumption by 82% under same conditions.

## 1.4 Organization

We have organized our thesis in the following manner:

- Chapter 2 discusses about the background and related work in Mobile Edge Computing, fog computing, deployment of cloudlets and energy efficiency techniques proposed for minimizing the uplink energy of user equipment.
- Chapter 3 presents the system model for the placement of edge nodes. Furthermore, we provide the optimization models which address the deployment of edge nodes and joint minimization of the uplink power and edge nodes for the wireless network.
- Chapter 4 presents a detailed analysis and results for the models proposed under varying number of resources and users for three different schemes.
- Chapter 5 concludes the thesis with a summary of the contributions and future work.

## Chapter 2 – Background and Related Work

### 2.1 Cloud Computing

Cloud computing has been an emerging technology in the last decade. The centralized paradigm of cloud computing comprises network, storage, and processing capabilities that are accessible to anyone with an internet connection. One way this particular technology has encouraged growth in both small and large enterprises is its pay-as-you-use feature, wherein clients can have instant access to resources and can access that data from anywhere in the world. Cloud computing has taken advantage of advancements in networking and computing technologies to such a degree that it is now possible to store the data in a different part of the world from where the data is accessed [2]. Additionally, there is evidence that data is increasing exponentially in data centers worldwide. The emergence of technologies such as the Internet of Things (IoT), Augmented Reality (AR), and Autonomous Vehicles (AV), all of which demand real-time responses and data-processing from various sensors with mobility factors, necessitates bringing cloud features closer to the user [2]. This emergence has led to the introduction of Mobile Edge Computing (MEC), in which nodes are placed close to the user in order to provide functionalities like storage, and processing power for data collected by a variety of sensors, including those deployed in autonomous vehicles, traffic lights, charging stations, etc.

Furthermore, IoT has introduced a variety of devices which can connect to the cloud. These devices, however, are equipped with low processing power and limited storage capacity, likely due to the introduction of other technologies, such as computational offloading. With computational offloading, devices with a finite capacity of resources can offload part of their

computational loads to the cloud, thus saving energy, memory, and processing power [3]. It is important to note that offloading computation to the cloud also has some drawbacks, such as long latency for the exchange of data between the cloud and devices. To solve this problem, offloading based on cloudlet was introduced. Therefore, cloudlets will be discussed in the next section.



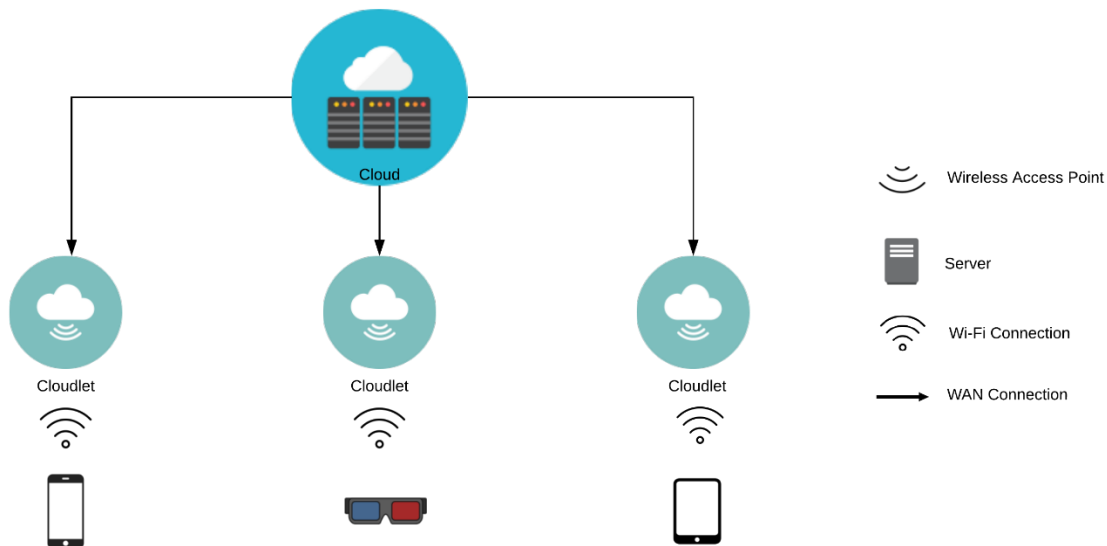
**Figure 2.1 : Cloud Computing Paradigm [10].**

## 2.2 Cloudlet

Cloudlet is a cluster of computers which provides cloud computing services to devices such as smartphones, tablets and wearable technology. It can be used by any device located near the cloudlet [4].

Cloudlet is the solution for mobile devices which can offload computational loads using a Wi-Fi access point [5]. Real-time interactive response issues can also be solved by using the cloudlet, given that it is nearly analogous to the cloud and therefore there is low latency when accessing the cloudlet. With regard to mobile devices whose users are clients, there are a few possible concerns which may be raised: the issue of determining each client's storage needs and predicting the computation power the cloudlet ought to have. Furthermore, if no cloudlet is discovered nearby, the client may experience interruptions. One source [5] proposes that the device should return to the normal mode; that is, it should connect to the distant cloud or allow the device

to depend on its own built-in resources. Cloudlet features will then return once a cloudlet is discovered in the range of the device.



**Figure 2.2: Architecture of Cloudlet Based Cloud Computing [4].**

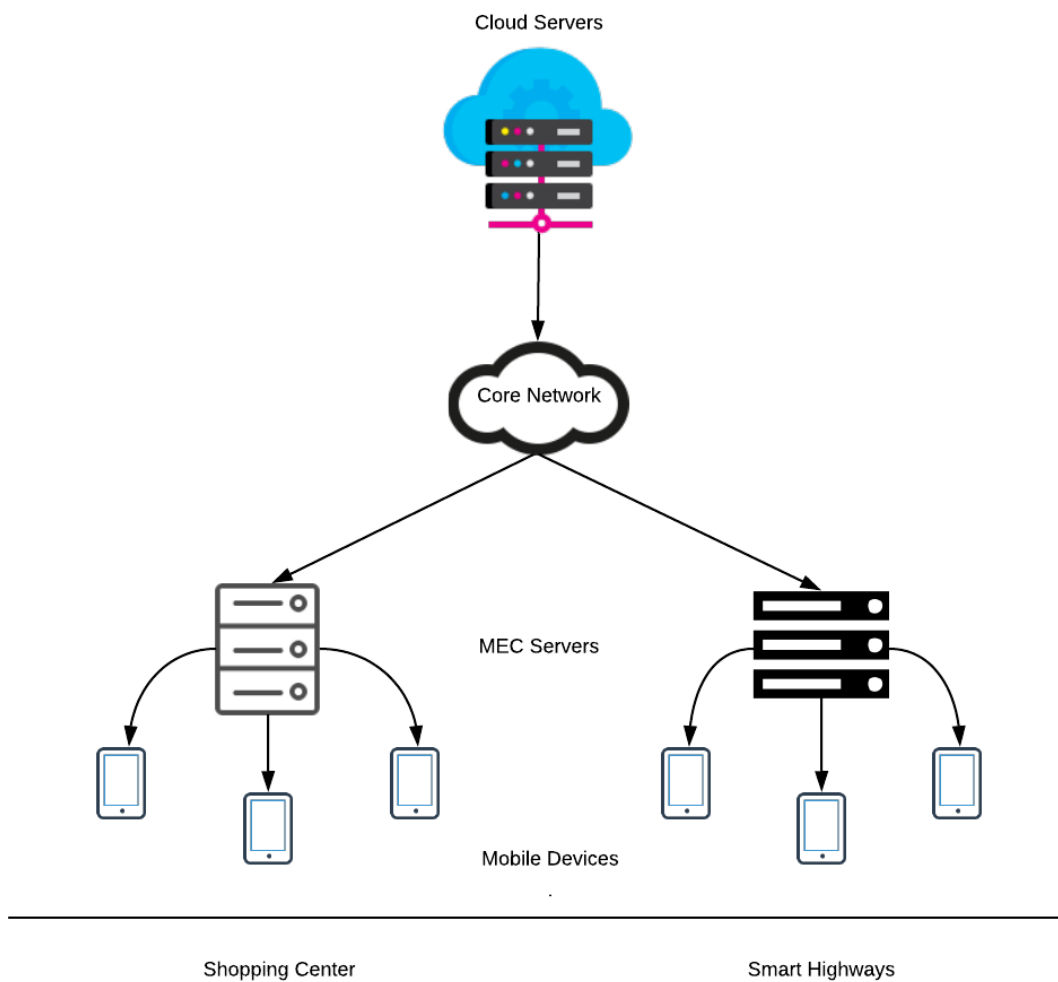
Figure 2.2 (above) represents how cloudlets can be widely scattered and are decentralized in nature, thus providing computational and storage capabilities useful to any nearby devices. Cloudlets also called data-centers-in-the-box connected to the internet, require minimal power to operate. These can be deployed in consumer-heavy areas such coffee shops or shopping centers where the customers can take full advantage of these small data centers. The same source [5] also discusses the concern over which organizations or clients which must pay for these cloudlets installation. The fundamental question is: will the cost will be borne by the coffee shops and shopping centers, or will the network operator bear the cost [6]?

Overall, the cloudlet system was determined to be ineffective. Primarily, this is due to distance constraints as it can only be accessed through a Wi-Fi access point. Secondly, cloudlet was less resourceful in comparison to the cloud due to issues with scalability and resource allocation [3] [6]. Yet, the cloudlet concept is similar to mobile edge computing and fog computing with slight modifications on certain aspects. In the following sections, we introduce these technologies.

### **2.3 Mobile Edge Computing**

With the growing demands of the industry, contemporary customers want more reliability and faster processing of data. Users are also increasing exponentially, and a result of this is the proposal of a new trend in computing termed Mobile Edge Computing (MEC) [7]. MEC makes available cloud computing services close to the users using Radio Access Network (RAN). This is one of the main features where MEC is different than cloudlets and fog computing. Bringing computational and storage in close proximity of the user helps to reduce latency and bandwidth consumption, and also minimizes uplink power (UP) consumed by a user equipment (UE) upon reaching the nearest edge-node or base-station (BS). This process ultimately saves the battery power of the device [3] besides reducing latency. The MEC model helps to accommodate the applications which are sensitive to delay as well as content-aware applications. An example of one such application is online gaming where the gamers can use processing power to reduce the workload, battery drain and can benefit from reduced strain on devices instead of accessing the cloud computation. MEC can further enhance the gaming experience without experiencing the lag due to having low latency [11] [60].

Fig 2.3 below describes the architecture of Mobile Edge Computing which comprises of three components: first, devices at the edge such as mobile phones, electric vehicles, wearable technology, and IoT devices; second, the Edge Cloud which is integrated with its base station, which is essentially a less resourceful cloud; and thirdly, the public cloud.



**Figure 2.3: Architecture of Mobile Edge Computing [3].**

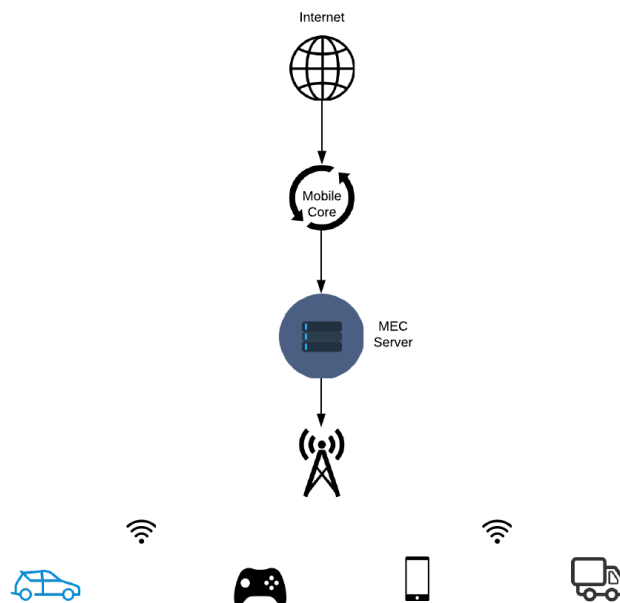
In MEC, the network operator can provide content-aware services by utilizing the real-time network which uploads its user's location to the developers. These services can be used to improve the experiences of their users. By using MEC platform, a number of applications can be made available to the user, such as a network of Electric and Autonomous vehicles, Smart Highways, Big Data Analytics, as well as Computational offloading for IoT devices. All of these will be described in detail in the next section.

### *1. Network of Electric and Autonomous Vehicles*

MEC can be useful for network of electric and autonomous vehicles (AV) which mostly require delay-sensitive service. For instance, edge computing can be used by vehicles for sharing real-time images and video with the nearby vehicles and can be stored on nearest edge nodes to improve situational awareness. An example is when vehicles in a snow storm with already captured images and routes can help the other AVs obtain valuable information [8]. As illustrated in Figure 2.4, an AV can generate one gigabyte of data every second which requires real-time processing of data in order for the vehicle to make accurate decisions according to its surroundings [9]. Sending huge amounts of data to the cloud for processing will not be feasible, as the delay would be too long. Moreover, current network bandwidth would not be able to handle a very large number of AVs in a particular area. Therefore, AV data needs to be computed at the edge for timely responses and smaller network pressure [10].

## 2. Smart Highways and Transportation

In the near future, it will be common for every vehicle to exchange data with the components of highways such as roads, traffic lights, roadside charging facilities, parking lots, and many more. Data will be exchanged in order to ease transportation facilities, to prevent any overloading of parking lots, to improve the efficiency of public transportation, and to improve road safety [11]. These transportation challenges can be controlled from the edge network using real-time data from sensors and cameras installed along the roadside. Moreover, edge devices can inform the drivers about parking situations, charging stations using the data from the edge devices installed around the destination and then guide them to the available location [3], [12].



**Figure 2.4: Various Devices Connected to the Edge [13].**

### *3. Computational Offloading for IoT Devices*

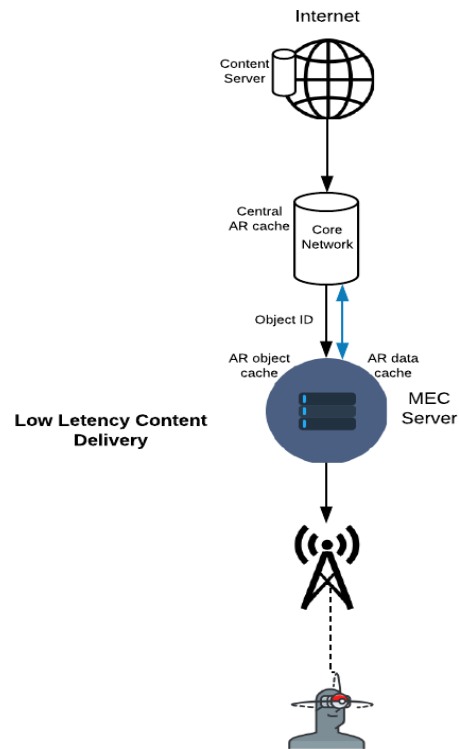
Recently, IoT devices have become very popular due to their convenient features, which have been made possible by connecting them to the cloud. However, sometimes connecting IoT devices to the cloud can be difficult. Because they are dependent on having a Wi-Fi network and they must be within a specific range. Furthermore, these devices have low processing capabilities and therefore cannot support computation-intensive applications on the device itself, such as augmented reality and community surveillance systems [13]. Rather than offloading these heavy-computation processes to the public cloud and burdening the network, these computation problems can be solved by offloading the tasks to the nearest edge server, thus further reducing latency [3].

### *4. Big Data Analytics*

Large volume of data is collected by various sensors installed in automated vehicles, devices, buildings, IoT, and many other connected technologies. This data is analyzed by organizations in order to understand consumer behaviors and patterns to provide solutions to various problems. Big data analytics could involve anything from improving energy efficiency for devices to determining optimal locations of charging stations for electric vehicles [12], [14]. Usually, data collected by these devices is sent to the core network for further data analysis [14], [15]. As in the other example applications, this method consumes high bandwidth and increases latency. Instead, the analysis could occur within the edge devices, evenly distributing the computational loads among devices on the edge network, and after analysis is complete, final results may then be sent to the core service for long-term storage [3] [16].

### *5. Augmented Reality (AR)*

One of the technologies that will be supported by MEC infrastructure is augmented reality and its associated devices. For many of these devices, users will be able to use them on-the-go, which requires high data rates and low latency. Augmented reality gives the users an immersive and realistic experience by combining graphics or video with sound. This technology can be of great use in museums, classrooms, art galleries, and numerous tourist attractions. Figure 2.5 below shows how the MEC can be used to build an augmented reality service. This example application requires user location either from the camera of the device or via positioning techniques in order to enhance the user experience. When the user approaches a point of interest, AR engine can provide additional information or simulations to the user, and should the position of the user change, the simulation or additional information can also be refreshed according to the new point of interest. MEC environment emerges as a suitable platform for providing the accurate position of the device due to its localized environment when compared to the cloud [13].



**Figure 2.5 Scenario Making Augmented Reality Possible on the Go [13].**

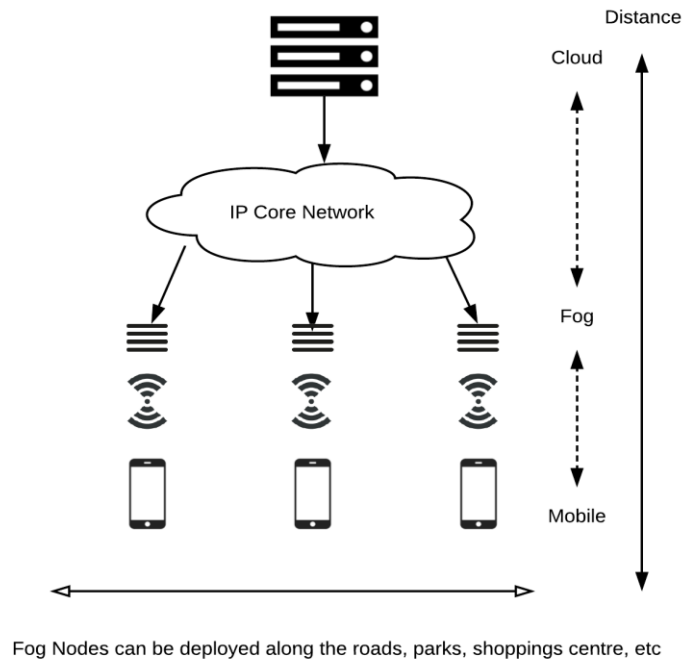
In conclusion, MEC will be an essential component of upcoming 5G networks and many of the related verticals as it provides computing services with reduced latency.

## 2.4 Fog Computing

With cloud computing being popular there is an increasing demand of cloud computing features closer to the UE's which tends to adopt decentralized architecture instead of centralized environment in which computation capacity can be moved closer to the users, but the cloud continues to be an essential part of the picture [17].

Edge computing aims to bring computational processing power closer to the users which does not require sending the data to cloud for processing, reduces latency and shortens the distance that takes for sending the data to the centralized cloud. Whereas, Fog Computing, is known as the paradigm which explains the working of edge computing and simplifies the operations such as storage, computation and networking services between the edge nodes and centralized data centers [18].

Fog computing differs from Mobile Edge Computing in terms of scope, with Fog computing being broader, through both involve bringing the features of cloud computing nearer to the user and necessitated by the evolution of IoT, 5G, Internet of Vehicles (IoV) and augmented reality [17]. Basically, the edge is the known as the concept; fog computing is the principle used for implementing the edge computing [18].

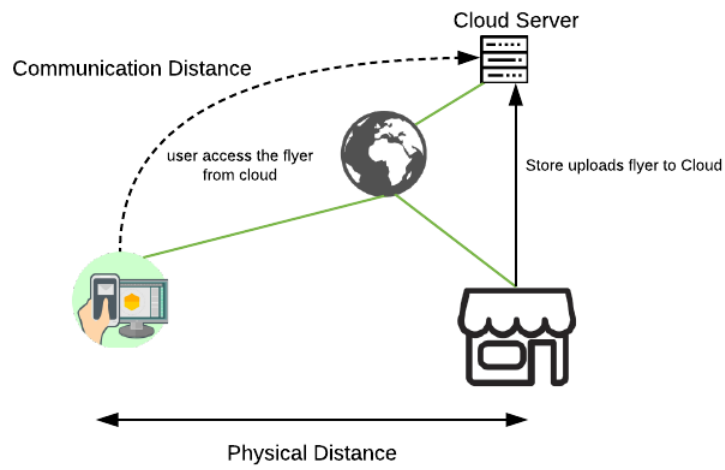


**Figure 2.6: Architecture of Fog Computing [19].**

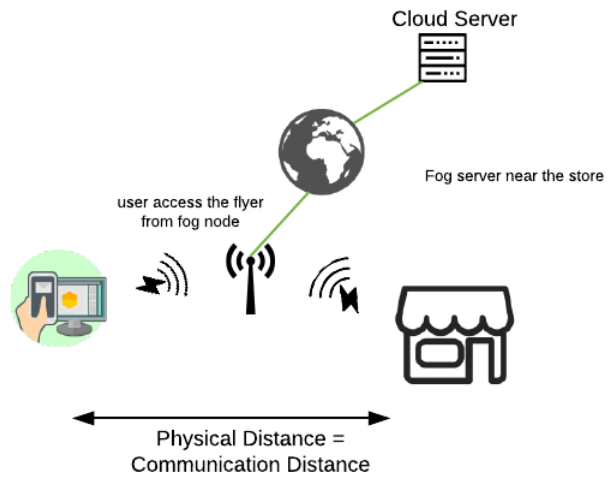
As depicted in Figure 2.6, fog computing is an extension of cloud computing which has an additional “fog layer” between the users and the cloud. This additional layer is composed of various fog nodes deployed in places like restaurants, bus stations, shopping malls, parks, traffic lights, etc. A fog node is a virtualized device which has networking, computing and storage capabilities. These features of the fog servers are used by the devices which are in close proximity of the placed node using high-speed wireless connection [19]. These fog nodes can easily be integrated with current infrastructure of cellular networks, Wi-Fi access points, or small cells deployed indoors or outdoors. A fog server is a small, self-contained data center which can be easily installed even on the streets or on a moving bus. Fog computing can, therefore, be called a “cloud close to ground” [21] and it is similar to cloudlets.

The demand of mobile phone users can be predicted by the location of the user, which differs from the demand of the traditional PC user [20]. Fog computing makes the content available as close as possible to the user, and therefore makes it location-aware. For instance, a user in a shopping mall is likely to require hours of operation, parking availability, restaurants nearby, events in and around the area. A person new to the city may search for notable locations, accommodation or hotel availability, weather forecasts, and any information relevant to their visit [13]. While cloud computing lacks location awareness, which tends to be suitable for fixed PCs with high speed wired connections, mobile users must be able to find relevant information from the large volumes of data present in the cloud for specific local content [19].

Figure 2.7, depicts a scenario where a user tries to access the flyer of the local supermarket by using the conventional cloud, in which the store uploads the flyer to the remote cloud. In this example, the link is long-distance when instead the content could be accessed locally by deploying the fog node inside the supermarket and pre-cache the local contents [45]. As shown in Figure 2.8 accessing a fog node will save bandwidth, have low latency and, moreover, one can benefit from high-speed connections without going to cloud. A large number of applications are possible through fog computing, which means it is possible to save resources [19].



**Figure 2.7: Accessing the Content from Cloud [13].**



**Figure 2.8: Accessing the Content from Nearest Fog Node [13].**

The above illustration show that fog computing has the following advantages:

- Increases efficiency of the network: –

Fog computing diverts alternating traffic in between cloud and the mobile user which not only saves bandwidth but also makes network energy efficient. This, in turn, reduces the carbon footprint of the network. It also significantly reduces uplink power consumed by these mobile devices due to the deployment of various edge devices in a particular area [19].

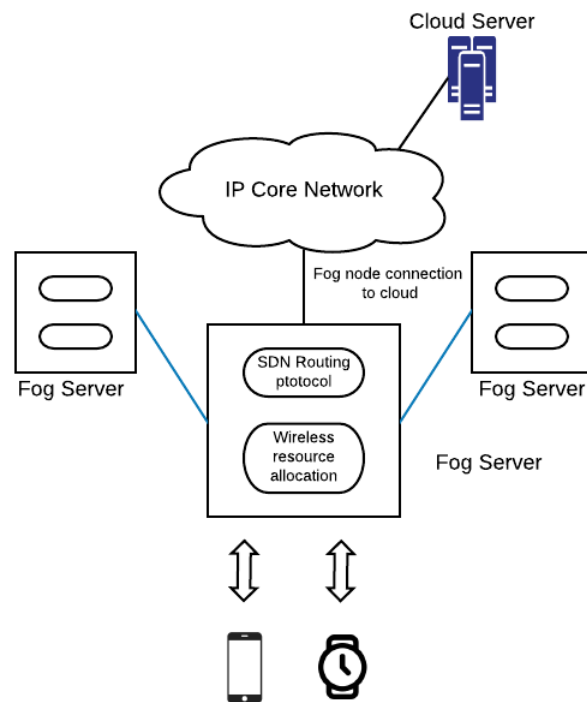
- Improves Quality of Service (QoS): –

By accessing the data from the local connection, fog computing automatically reduces latency and response time along with data rates. Furthermore, it also benefits the users from the decreased bandwidth cost [22] [19]. According to the architecture shown in Figure 2.6, every fog node will have three type of connections any given time: a wireless connection from the fog node to the device; a wired or wireless connection between the fog nodes; and wired or wireless connections to the cloud as depicted below in Figure 2.9.

### 2.4.1 Fog Computing Networking Connections

- Communication between user and fog node: –

Fog nodes will have the capacity to connect with users using cellular and Wi-Fi networks and reduce response time for users significantly. Along with fast networks, devices with low processing power can offload their computation load and use resources of these nodes, made possible due to low latency and high-speed wireless connections [24]. To provide optimal efficiency, fog nodes can make use of cross-layer design by managing all the communication layers. Being closer to the users and their decentralized architecture makes them easily accessible and can remarkably reduce uplink power to save battery consumption of the devices [19].



**Figure 2.9: Fog Computing Networking Connections [19].**

- Communication between fog node and cloud: –

The cloud can be called the backbone of all the fog nodes deployed at various locations, as there is constant synchronization of data in between the fog node and cloud [25]. Moreover, the cloud is also responsible for controlling the fog nodes and ensuring the effectiveness of all nodes. Therefore, failure in any node can be traced by the cloud [19].

- Communication among fog nodes :-

Fog nodes can be interconnected by wireless or wired links to establish communication between the nodes. Fog computing is also known as the interconnection of various nodes. For example, a vehicle connected to a particular node can access the charging station location and condition which is connected to a different node [19] [26]. The interconnection between the nodes will not only promote sharing of resources required by the different nodes but also expand the overall storage and computation capacity of the network.

Fog computing can be considered as a generalized form of MEC where any entity, cars, traffic lights, etc. can be computing nodes. In MEC, this is simplified to base stations and the operation of resources are left to mobile network operators such as Rogers, Telus and others. In MEC, bringing the resources closer to the users not only provides low latency, high speed data transmission but also proves to be energy efficient for the UE's. Presence of multiple edge nodes in the network reduces the uplink energy consumed by the devices for accessing the nearest edge nodes which can considerably reduce battery consumption.

## 2.5 Energy Efficiency Management for Devices

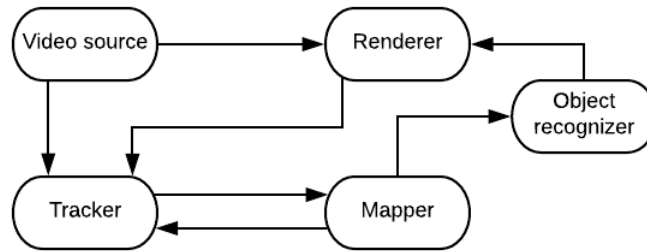
Energy efficiency is a fundamental requirement for mobile devices. Day by day, the importance to decrease the energy consumption of the mobile devices is escalating, as modern devices and applications consume more and more power. This increasing consumption is due to larger screens, an increase in online connectivity, high definition multimedia, high-speed wireless communication, and content-rich applications. Notably, the development of battery technology is not progressing as quickly as it needs to in order to match increasing consumption. There is a limited amount of energy that can be stored in the battery and it is growing at only 5% annually. Additionally, simply putting larger batteries into the devices is not an appealing option as it increases the size of devices [29].

Cloud servers and infrastructures are usually located centrally in the core network which is often far away from the users. This usually results in long transmissions which can cause delays, excessive traffic and energy consumption in the network [32]. Mobile Edge Computing (MEC) can be a solution to this problem by placing the MEC servers nearer to user, as this will not only decrease latency but increased density of radio access points will also decrease the uplink energy consumed by the devices in comparison to reaching a macro cell base station. MEC architecture has a capability to integrate with radio access network (RAN) which provides cloud computing capabilities and services closer to the mobile users through operators resources [33] [27]. MEC not only saves uplink energy but can also save processing energy by offloading their computation to the nearest MEC servers [27].

Devices can offload their computation loads to these resource-rich, local servers which will optimize their performance and will improve computation time [28]. The research in [29] points out the need to ensure that the extra energy consumed for additional communication should not exceed savings from offloading the computation. Meanwhile, the study in [30] [31] proves that the MEC approach will necessarily reduce energy consumption in content-aware and delay-sensitive applications such as Augmented Reality (AR) by optimizing computational and communication resources.

The research in [28] presents a joint optimization approach, wherein the AR applications some tasks can be executed locally by the mobile device and some can be offloaded to the nearest edge server. The study in [27] proposes a similar procedure by dividing the energy aspect of these applications into two parts: Firstly, by optimizing energy consumed for transmission of packets for computation to the MEC servers [35-37]; and secondly, the mobile device decides which task should be offloaded to the MEC servers, and which will be different for all devices and will depend on the processing power of the device. Accordingly, this decision can be made by comparing energy consumption between offloading of tasks to nearest MEC server or computing the tasks locally on the device [27].

AR, drones and connected vehicles involve various content-intensive applications listed below in Figure 2.10 which require their tasks to be offloaded to the nearest MEC server. These applications include: i) video source, which gets the frames from the device camera; ii) renderer, which prepares the processed frames for displaying; iii) tracker, which is used to monitor the user position; iv) object recognizer, which is used capture the objects; and v) mapper, which is used to build model of the overall environment.



**Figure 2.10: Content Intensive Applications of AR [28].**

Among these, tracker, mapper and object recogniser are the most content intensive applications and thus should be offloaded according to the research in [28]. If these applications also collect input from the users connected in the same area, they can avoid repeating information which will ultimately save uplink energy for all the devices. Meanwhile, less intensive applications such as video source and renderer can be processed locally based on [28].

## 2.6 MEC and 5G

The fourth generation (4G) wireless networks (also known as LTE) will be gradually replaced by fifth generation (5G) networks. 5G will be operational in some parts of the world as early as 2019. 5G aims to support the connectivity of over 100 billion devices at 1Gbps throughput with 1ms over-the-air latency [21]. Peak data rate, user experienced data rate, spectrum efficiency, mobility management, density of connections, energy-efficiency and traffic capacity per area are all expected to be significantly improved in 5G. MEC is an essential component for 5G networks. Particularly with the development underway toward green 5G networks, energy efficiency has become one of the important criteria for the future generations of wireless networks [34].

In 5G, MEC will provide IT services and cloud-computing features at the edge of the network with the help of radio access network (RAN) in close proximity to the UEs. MEC is also considered as the evolution of the future base-stations (BS). European 5G PPP (Public Private Partnership) considers MEC as the integrated part of the upcoming 5G networks along with Network Function Virtualization (NFV) and Software Defined Networks (SDN). Therefore, MEC is perceived as primary technology and architectural concept for the future of 5G, which can contribute for the transformation of mobile networks. Benefits of adopting the MEC environment such as, reduced latency, response time, real-time insight in to radio network information, high bandwidth, and location awareness have been summarized in previous sections. These advantages can be profitable and create opportunities for the network operators, content providers and applications.

## **2.7 Deployment of Cloudlets**

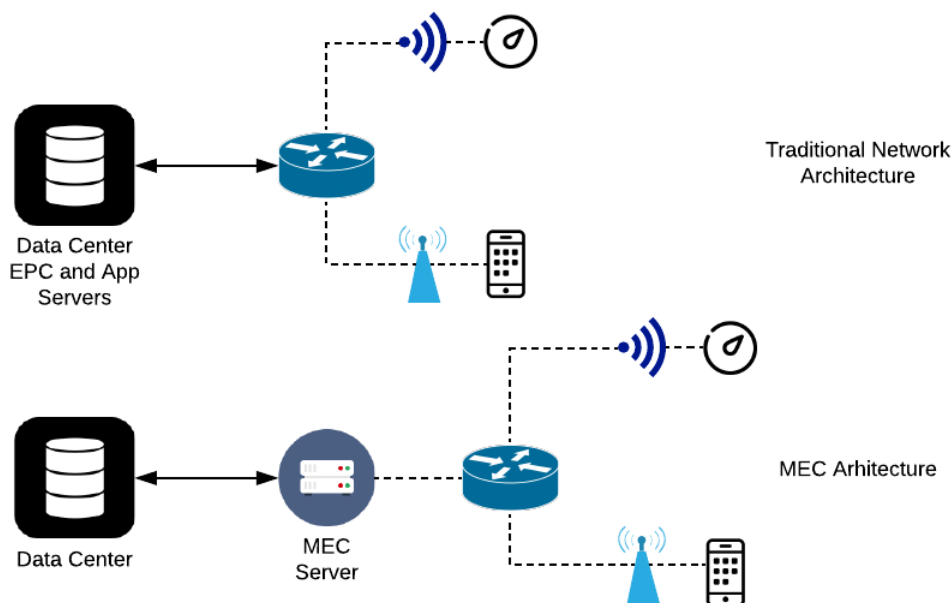
Popular topic for an earlier decade also known as Mobile Cloud Computing (MCC) used similar topology as MEC but was dependent on WLAN. Study in [39] discusses mobile devices send resource-intensive tasks to cloudlets and after processing of these are sent back to the user which saves energy consumption and reduces transmission delays [31].

These cloudlets can be installed by the enterprises for instance coffee shops, food courts, airports to provide effective communication services to the user. It can also be an alternative for an organization using specific cloud services and can use cloudlet which will ease the load on its cloud resources and will be connected to the public cloud for synchronization. It can also enhance the networks of sensors and wearable devices by deploying cloudlet in their surroundings providing one hop connection to the cloud computing services [31] [38].

## 2.8 Deployment of Mobile Edge Computing

In order for a MEC environment to be successful, the deployment of MEC plays an important role. Organizations have started to launch products with inbuilt capability to support Multiple Edge Computing environments. Earlier in June 2017, Amazon Web Services (AWS) launched Green-grass with local decentralized enhancement of its AWS IoT platform. As stated previously, MEC has gained a lot of importance due to rise in the number of IoT devices [40]. This AWS platform can run in multiple edge computing environments which includes MEC. Many cloud organizations are also developing their MEC supported products. Nokia, for example, recently partnered with a local telecom company in Taiwan for the Taiwan Museum of Natural Science, where they developed augmented reality for a dinosaurs show using edge-delivered video [40]. Moreover, recently in Olympic winter games held in Pyeongchang represented the world's first broad- scale deployment of 5G using MEC nodes with collaboration of Korean Telecom, Intel and Samsung. Where tiny 5G linked cameras streamed live videos to the users worldwide. Further, self-driving shuttles were equipped with video screens instead of windows to stream live coverage of events using MEC technology.

There will be an exponential increase in the number of devices, which is difficult for the LTE to handle. Researchers are planning to integrate MEC with 5G architecture, for which there will be a change in the traditional network system, as there will be an extra layer, MEC as illustrated in the figure below [41] [40].

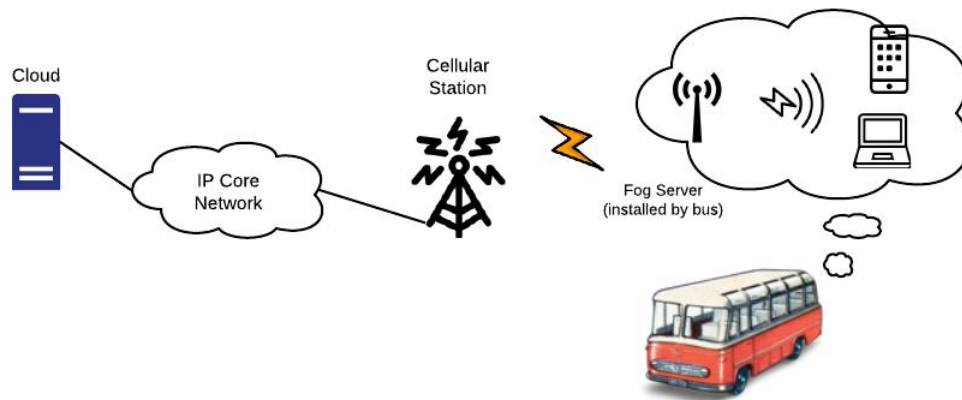


**Figure 2.11: Difference between Traditional and MEC Architecture [40].**

Adding the extra layer also supports network level security for MEC traffic as shown in the figure above [40]. In this case, if an enterprise wants their own private instance of the evolved packet core (EPC) which can be deployed within the local MEC architecture, they can acquire that. They would simply need to ask for a virtual EPC rather than having shared EPC resources in the operator's network [42] [40].

Mobile Edge Servers have to be deployed at specific locations in order to make the Edge environment possible. These locations can be LTE or 5G macro base-station (BS) sites, or Multi-Radio Access Network (RAN) cells, and small cells [40]. A Multi-RAT site can be located indoors or outdoors, so MEC can be deployed in restaurants, hospitals, corporate headquarters, stadiums, shopping malls, etc. The deployment flexibility enables the direct delivery of locally-relevant and faster services from nearest base stations [13].

MEC servers can address two types of user environments, both static and mobile. An example of a static model is the deployment of edge servers on buses and trains as depicted in figure 2.12. In this model, users will have less mobility and will be confined to a specific area. Blue was launched by Greyhound bus services which features mobile edge computing services for their fleet of buses. The fog server can be deployed in a bus which will connect to the cloud using a cellular connection and will provide entertainment facilities such as movies, games, maps, and general internet access [20].



**Figure 2.12: Deployment of Edge Server in Bus [19].**

Lufthansa also uses similar kind of unit which has computing, storage and networking facilities in which passengers can connect to the device through Wi-Fi on board and have access to various services such as video, audio, games, and moving map. Content is automatically updated when the aircraft is on the ground. Moreover, it provides the data for the crew such as food preferences of passengers and seat arrangements. Furthermore, data collected from the flight can be sent to the cloud for further analysis for improving customer service [61].

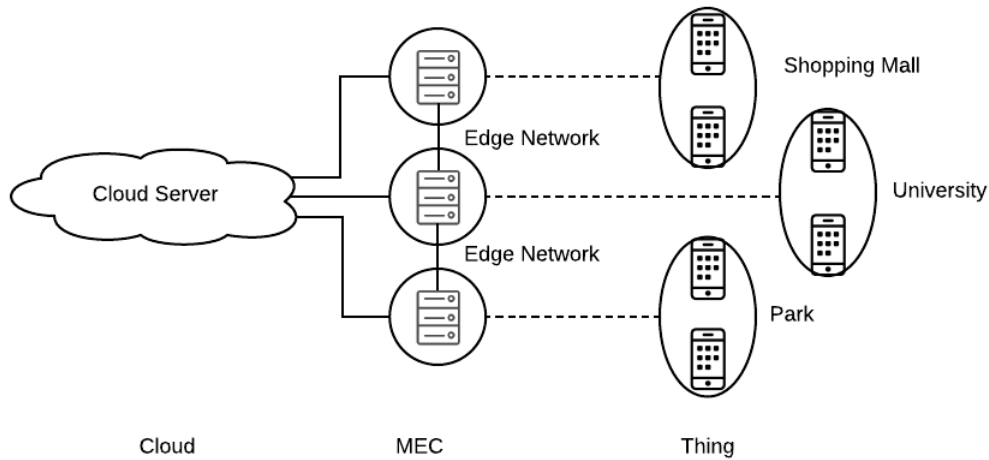
An example of a mobile model is the deployment of MEC servers on the roadside. MEC servers can be deployed along the roadside in order to connect vehicles using a cellular connection which addresses diverse mobility of the users and provides support for features like trip data, nearest charging stations, traffic conditions etc [19].

Deployment is dependent on a number of factors including scalability, analysis of performance criteria for specific areas such as QoS, latency, etc.

## **2.9 Optimization of Edge Nodes Deployment**

Mobile Edge computing has already been discussed in detail from a theoretical perspective, but in order to develop edge networking in the real environment, there are several issues and techniques which need to be addressed in order to make the edge networking feasible [43].

The research in [43] presents an issue in determining the minimum number of nodes which should be upgraded to fog nodes for maximizing average data rate and minimize transmission delay for fog network. Different simulation scenarios have been taken into consideration to find the optimal number of MEC nodes required in the particular area. Optimization necessitates having no less or more MEC nodes than required, or else it will result in degradation of the data rate whereas, this thesis is also taking uplink energy efficiency into consideration along with minimization of MEC nodes.



**Figure 2.13: Cloud-MEC-IoT hierarchical network model [43].**

The above architecture in figure 2.13 shows the inter-relation between centralized cloud computing and decentralized MEC computing. To support 5G networks, the Cloud-Edge-IoT network will not only maximize the average data rate, it will also minimize transmission delay [43] [44].

To determine which node should be upgraded to MEC node, the authors in [43] propose a similar approach used for clusters to find their cluster-heads in ad-hoc wireless networks. To determine the optimal number of MEC nodes, each node assumes itself to be edge node with some probability ( $p$ ). The total number of nodes become  $np$ , where every  $n$  nodes can be an edge node in a particular area with probability  $p$  [46 – 50]. The study in [51] states the optimum number of MEC nodes by using a PPP model which also optimizes the energy efficiency for the wireless networks. Parameters are little different here in MEC computing as compared to wireless ad hoc networks. In addition, all nodes are assumed to have MEC capability and some are activated

depending on the needs of users. However, the cost of making each base station MEC-enabled needs to be considered.

## Chapter 3 - Placement of MEC nodes with Uplink Energy Efficiency

### 3.1 Scenario Description

Due to increasing demand for low-latency and high-processing capability from applications, deploying MEC-enabled nodes or base stations have become inevitable in 5G networks. In order to serve better, MEC-enabled nodes will be deployed at the edge, i.e. closer to the users such as along with base stations, roadsides transmission units (RTU), on traffic lights or hot spots such as in shopping complexes, coffee shops, buildings, campuses, buses, airplanes, etc. Essentially, MEC nodes will act as small data centers which can be easily installed as depicted in the figure 3.1. Cellular networks will act as the medium between the cloud, MEC nodes and the users.

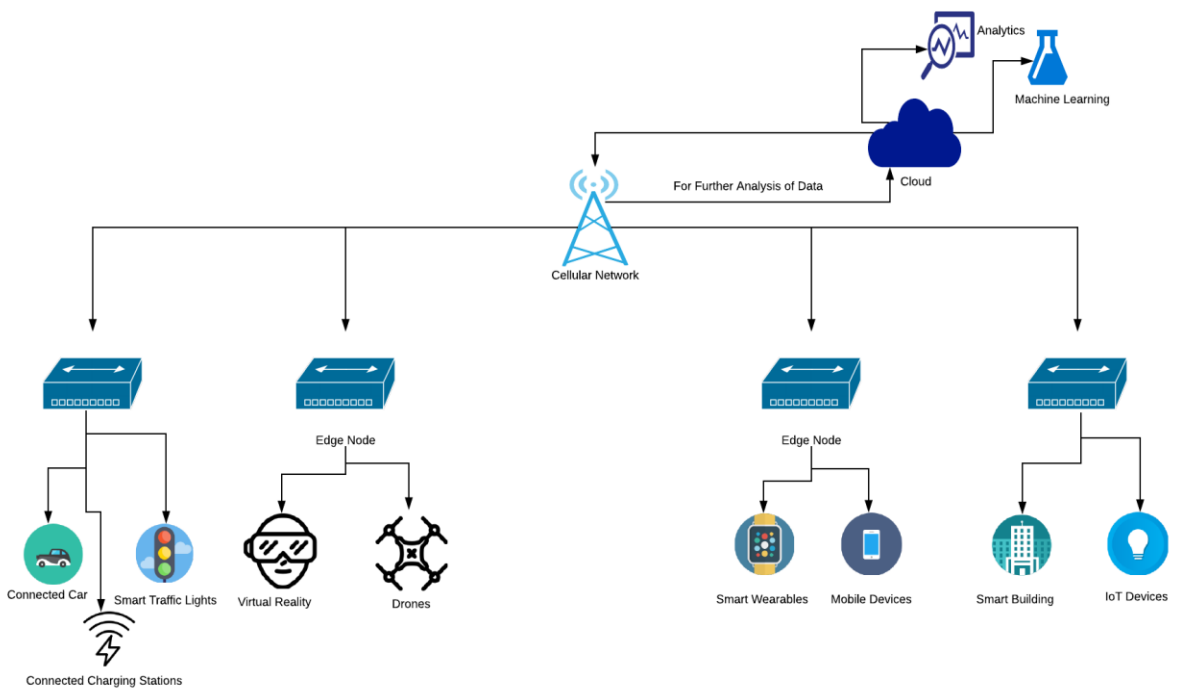


Figure 3.1: System Model.

According to Figure 3.1, MEC nodes can help various applications, from connected cars to virtual reality and further, making small IoT devices capable of handling large computational problems by using the computing resources provided by the resource-rich edge nodes. Being closer to the UEs and having decentralized architecture makes MEC nodes easily accessible and can remarkably reduce uplink power to save battery consumption of the devices.

But here the question arises: how many MEC nodes should be required in a particular area? What would be their optimal location? How much energy savings they would provide? In this thesis, we focus on the placement problem and consider the energy-efficiency aspect along with serving capability of MEC nodes. We propose two algorithms for placement of MEC nodes. The first scheme, minimize edge node (MEN), optimizes the number of MEC nodes required in the particular area for making that area MEC – enabled, by which we mean devices can use computation workload of nearest MEC nodes deployed in the network. The second scheme, jointly minimize edge nodes and power (MEP), has been proposed which jointly minimizes uplink energy and the placement of MEC nodes. Here uplink energy is referred to energy consumed by UEs for accessing nearest RAN node. These schemes are explained in detail below.

### 3.2 Problem Formulation

The goal of our work is to find the minimum number of MEC nodes required for making a particular area mobile edge computing-enabled and minimizing the uplink energy consumed by UEs when reaching the nearest MEC node. We propose two schemes: optimized placement of MEC nodes (MEN) and placement of MEC nodes with uplink energy efficiency (MEP). We are using an uplink energy minimization term which accounts for the energy consumption by the UE when accessing the BS. Our proposed methods are two ILP models, each of which addresses a case which is interrelated to both.

We also compare our results with a baseline scenario where a single macro-cell BS serves all the UEs. This is called as Single Edge Node (SEN), where SEN is traditional network architecture having single node and used to compare with purposed schemes. Further, SEN is not an optimization solution. It is also important to note that our scheme does not take the workload processing capacity constraints at the MEC nodes. In other words, we assume the MEC resources are available at all conditions.

The list of notations is given below in Table 3.1. To further understand the difference between variables, we can think of the rectangular domain having grid points, variable  $M_{xy}^k$  is the points with computing workload (k), variable  $E_{xy}$  is the points with MEC nodes. Therefore, variable  $\Omega_{xy}^k$  takes requirement of MEC nodes and computing workload into account and effectively places the nodes. Here, the workload is considered to be discretized into a certain combination of resources available at the MEC node. For instance, for a task arriving to a MEC node, 5% CPU usage and 1MB memory usage corresponds to resources that can serve 1 unit of workload.

$E_{xy}$	Binary variable that is 1 if there is MEC node at (x,y).
$M_{xy}^k$	Binary variable is 1 if MEC node at (x,y) that can serve workload k.
$U_i^k$	Binary value indicating whether UE i demands computing capacity k or not.
$\beta_{xy,i}^k$	Binary variable that is 1 if the UE i is computing its content k from the MEC node at (x,y).
$\omega_{xy}^{ik}$	Binary variable is 1 if there is a edge node at (x,y) and UE i is receiving the k <sup>th</sup> content from the MEC node (x,y).
$T_{xy}^{ik}$	Uplink power of UE i to compute the content k <sup>th</sup> from the MEC node at (x,y).
$\Omega_{xy}^k$	Binary variable is 1 if there is a MEC node at (x,y) and that MEC node can serve workload.
$d_{xy,i}$	Distance between UE i and MEC node at (x,y).
$D_R$	Distance between UE and the relay.
$\rho$	Weight factor.
k	Index for workload.
$S^{coff}$	Scaling factor.

**Table 3.1: List of Notations**

### 3.3 Energy Model

In the LTE standard, the transmission power emitted to the physical uplink shared channel (PUSCH) is defined as [52] [53]:

$$P_u(\text{dbm}) = \min\{P_{\max}, P_O + 10\log_{10} M_u + \gamma PL + \Delta_{mcs} + f(j)\} \quad (1)$$

Here  $P_{\max}$  is the maximum power allowed by higher layer framework. It has, an upper limit of 23dBm.  $P_O$  is a cell specific parameter having 1-dBm resolution. Its value is shared with the UEs using the shared downlink control channels.  $M_u$  indicates the number of assigned resource blocks according to the uplink (UL) scheduling grant. This parameter is transferred to the UEs using the dedicated downlink channel.  $PL$  is the downlink path-loss estimate in dB which is calculated by UE, where  $\gamma$  is cell specific path loss compensation factor which takes value from 0.4 to 1 in intervals of 0.1 [57]. Lastly,  $\Delta_{mcs}$  is signaled to radio resource control unit, and  $f(j)$  is power correction function for closed loop power for sub-frame  $j$ . Equation (1) represents the uplink power calculation for closed-loop PUSCH. In the open-loop version feedback from the base station is not used. In this case,  $\Delta_{mcs}$  and  $f(j)$  are omitted and  $\gamma$  is taken as 1 to compensate for full path loss. Thus, the uplink transmit power calculation changes for the open-loop PUSCH as [54] [58]:

$$P_u(\text{dbm}) = \min\{P_{\max}, P_O + 10\log_{10} M_u + PL\} \quad (2)$$

Free space PL, is the only distance-related term and is specified in the equation below:

$$P_u(\text{dbm}) = 20\log_{10}(d) + 20\log_{10}(f) = 147.55(m) \quad (3)$$

Where  $d$  denotes the distance between UE and the MEC node or the BS. For simplicity

$f = 2.6$  GHz is taken for LTE network [55].

Computing the energy consumed by a device is not straightforward as explained in [56].

Hoque et al. [56] discusses the detailed issues in energy consumption of real devices. According to their measurements from several commercially available smart phones, power consumption of an UE increases as a piece wise liner function of the uplink transmission power. The below equations show the analytical formulation of measurements taken from various smart phones:

$$P_{UE}(mW) = \begin{cases} \sigma_L P_u + \omega_L, & \text{if } P_u \leq \theta \\ \sigma_H P_u + \omega_H, & \text{if } P_u > \theta \end{cases} \quad (4)$$

Where,  $\sigma_H$  and  $\omega_H$  used for the high power consumption regime with steep slope, whereas  $\sigma_L$  and  $\omega_L$  are used for low power consumption regime. In this thesis we substitute equation (2) into equation (4), then we use the resulting  $P_{UE}$  to determine the energy consumed per each workload:

$$E_{UE} (mJ) = \frac{P_{UE} * N_d * S_k}{T} \quad (5)$$

Where,  $N_d$  is the number of contents demanded by the MEC node,  $S_k$  is the size of the computational workload, and  $T$  is throughput.

Note that we assume computational loads are quantizable into uniform loads, which means we can denote, for example, an image detection request from an AR application with 10 workloads while the request for computing the location of the best charging station in an EV application needs 4 workloads. Thus, each UE will have a workload of certain units that it will aim to offload to a nearby MEC node. Similarly, all MEC nodes are assumed to have uniform workload handling capacity. In real-world, matching MEC resources with UE requests will be more complex since the types of resources and the types of needs will vary. In addition, some requests might not allow being distributed over different MEC nodes. For simplicity, we assume all workloads and the resources that can satisfy those workloads are uniform, can be quantized and any UE can be served by any MEC node as long as the MEC node has the available capacity to match the workload.

### 3.4 Minimize Edge Node (MEN)

Our first model, MEN, aims to minimize the number of MEC nodes deployed in a region. Ultimately, placing more MEC nodes will increase Quality of Service (QoS) but a necessary consequence is an increase of the deployment cost. This can make the technology nonviable for the network operators. MEN addresses this concern by placing only the required number of MEC nodes given a geographic region, serving customers with certain load levels.

**The objective function of MEN is given below:**

$$\text{Min} \left( \sum_x \sum_y \Omega_{xy}^k \right) \quad (6)$$

Here,  $\Omega_{xy}^k$  is binary variable is 1 if there is a MEC node at (x,y) and that MEC node can serve workload k.

$$\Omega_{xy}^k = E_{xy} M_{xy}^k \quad (7)$$

Where,  $E_{xy}$  denotes the binary variable that is 1 if there is MEC node at (x, y) and  $M_{xy}^k$  is a binary variable that is 1 if MEC node at (x, y) can serve workload k. Hence, equation (6) aims to minimize the number of nodes.

The objective function of MEN is solved to the following constraints set:

$$\beta_{xy,i}^k \leq E_{xy} U_i^k M_{xy}^k \quad \forall x, y, i, k \quad (8)$$

According to equation (8), a UE can use the computing services from MEC node (x,y) if there is a node at (x, y), where  $\beta_{xy,i}^k$  is a binary variable that is 1 if the UE i is computing its content k from the MEC node at (x,y) and  $U_i^k$  defines the binary value indicating whether UE i demands computing capacity k or not.

$$\beta_{xy,i}^k d_{xy,i} \leq D_R \quad \forall x, y, i, k \quad (9)$$

$$\beta_{xy,i}^k = 0 \quad \forall d_{xy,i} > D_R \quad (10)$$

Equations (9) and (10) ensure that UE can download contents from the MEC node if they are within the cell coverage of those nodes. Where  $d_{xy,i}$  denotes distance between UE i and MEC node at (x, y)

$$\sum_x \sum_y \beta_{xy,i}^k = U_i^k \quad \forall i, k \quad (11)$$

$$\sum_i \sum_k \beta_{xy,i}^k \geq E_{xy} \quad \forall x, y \quad (12)$$

Equations (11) and (12) respectively guarantee that each UE can access the computing resources from one and only one MEC node, and if there is a node at  $(x, y)$ , then at least one UE could use the service.

$$M_{xy}^k \leq E_{xy} \quad \forall x, y, k \quad (13)$$

Equation (13) ensures that if there is a resource at  $(x, y)$ , there should be MEC node as well.

$$M_{xy}^k \leq \sum_i U_i^k E_{xy} \quad \forall x, y, k \quad (14)$$

At least one UE could use the computing service, if there is a resource at  $(x, y)$  as stated in equation (14). This ensures the optimization does not tend to place MEC nodes when there are no users in need of computation. Finally,  $\Omega_{xy}^k$  should be linearized such that an ILP formulation is satisfied.

$$\Omega_{xy}^k \leq E_{xy} \quad \forall x, y, k \quad (15)$$

$$\Omega_{xy}^k \leq M_{xy}^k \quad \forall x, y, k \quad (16)$$

$$\Omega_{xy}^k - E_{xy} - M_{xy}^k \geq -1 \quad \forall x, y, k \quad (17)$$

Linearization constraints for binary variable  $\Omega_{xy}^k$  are specified in equations (15) to (17).

Note that the optimization solution considers a certain number of nodes with certain level of workload, and does not take mobility into account. This means throughout the day the number of users and their demands will change. However, it will not be possible for operators to deploy new MEC nodes based on varying demands throughout a day. Hence, planning needs to be done considering the peak user level and the peak workload or by using historical averages. In that case, operators will be able to use optimization models and decide the number of MEC nodes as well as their locations.

### 3.5 Joint Minimization of Edge Node and Power (MEP)

The second model, MEP, proposes to enhance energy efficiency of UEs along with minimizing the number of MEC nodes. This model determines where to place the MEC nodes by jointly optimizing the MEC node deployment cost, and the uplink power. As expected, uplink power will be less when the MEC nodes are located closer to the UE. Therefore, placing more MEC nodes will innately lead to a reduction of uplink power. Still, deploying the MEC nodes is costly. Hence, there is a tradeoff between cost and energy-efficiency. MEP aims to address this trade-off by considering a normalized weight factor ( $\rho$ ).

**The objective function of MEP is given below:**

$$\text{Min } \rho \left( \sum_x \sum_y \Omega_{xy}^k \right) S^{coeff} + (1-\rho) \sum_i \sum_k \sum_x \sum_y T_{xy}^{ik} \omega_{xy}^{ik} \quad (18)$$

Where  $T_{xy}^{ik}$  defines uplink power of UE  $i$  to compute the content  $k^{\text{th}}$  from the MEC node at  $(x,y)$ , and  $\omega_{xy}^{ik}$  is a binary variable which is 1 if there is a MEC node at  $(x,y)$  and UE  $i$  is offloading the  $k^{\text{th}}$  workload to the MEC node at  $(x, y)$ .  $S^{coeff}$  is a constant for scaling the second part of expression.  $\Omega_{xy}^k$  is defined in Section 3.4.

$$\omega_{xy}^{ik} = \Omega_{xy}^k \beta_{xy,i}^k \quad (19)$$

Here,  $\beta_{xy,i}^k$  is binary variable that is 1 if the UE  $i$  is computing its content  $k$  from the MEC node at  $(x,y)$ .

$$\Omega_{xy}^k = E_{xy} M_{xy}^k \quad (20)$$

Where,  $E_{xy}$  denotes the binary variable that is 1 if there is MEC node at  $(x, y)$  and  $M_{xy}^k$  is a binary variable that is 1 if MEC node at  $(x, y)$  can serve workload  $k$ .

The objective function of MEP is solved to the following constraints set:

$$\beta_{xy,i}^k \leq E_{xy} U_i^k M_{xy}^k \quad \forall x, y, i, k \quad (21)$$

Equation (21) ensures that UE can use the computing resources from  $(x, y)$  if there is a MEC node at  $(x, y)$ . Where  $U_i^k$  defines Binary value indicating whether UE  $i$  demands computing capacity  $k$  or not.

$$\beta_{xy,i}^k d_{xy,i} \leq D_R \quad \forall x, y, i, k \quad (22)$$

$$\beta_{xy,i}^k = 0 \quad \forall d_{xy,i} > D_R \quad (23)$$

Equations (22) and (23) guarantee that UE can only access the services of the particular node at if they are within the cell coverage of those MEC nodes. Where,  $d_{xy,i}$  denotes the distance between UE  $i$  and MEC node at  $(x, y)$ , and  $D_R$  is distance between UE and the relay.

$$\sum_x \sum_y \beta_{xy,i}^k = U_i^k \quad \forall i, k \quad (24)$$

$$\sum_i \sum_k \beta_{xy,i}^k \geq E_{xy} \quad \forall x, y \quad (25)$$

The equations in (24) and (25) state that every UE accesses the computing resources from only one MEC node; and if there is a MEC node at  $(x,y)$ , at least one UE can access computing resources, minimum one content from that MEC node. The latter ensures there are no redundant MEC nodes.

$$M_{xy}^k \leq E_{xy} \quad \forall x, y, k \quad (26)$$

If there is a resource at  $(x,y)$ , there should be an MEC node  $(x,y)$  as denoted in (26).

$$\omega_{xy}^{ik} \leq \Omega_{xy}^k \quad \forall x, y, i, k \quad (27)$$

$$\omega_{xy}^{ik} \leq \beta_{xy,i}^k \quad \forall x, y, i, k \quad (28)$$

$$\omega_{xy}^{ik} - \Omega_{xy}^k - \beta_{xy,i}^k \geq -1 \quad \forall x, y, i, k \quad (29)$$

Linearization of the binary variable  $\omega_{xy}^{ik}$  is handled by equations (27) to (29).

$$\Omega_{xy}^k \leq E_{xy} \quad \forall x, y, k \quad (30)$$

$$\Omega_{xy}^k \leq M_{xy}^k \quad \forall x, y, k \quad (31)$$

$$\Omega_{xy}^k - E_{xy} - M_{xy}^k \geq -1 \quad \forall x, y, k \quad (32)$$

Equations (30) to (32) are the linearization constraints for the binary variable  $\Omega_{xy}^k$ .

$$M_{xy}^k \leq \sum_i U_i^k E_{xy} \quad \forall x, y, k \quad (33)$$

If there are computing resources available at the MEC node (x,y) then at least one UE should be using that service according to equation (33).

In summary, in this thesis we propose two schemes: optimized placement of MEC nodes (MEN) and placement of MEC nodes with optimal uplink energy efficiency (MEP). We are using integer linear programming (ILP) for both of the models. The first ILP model, MEN, aims to minimize the number of edge nodes when deployed in the local locations. The second ILP model, MEP, jointly minimizes the number of MEC nodes and the uplink power of the UE. In the next section, we provide their performance evaluation and compare them to a baseline scenario.

## Chapter 4 – Results and Analysis

### 4.1 Performance Evaluation

We evaluate the performance of our schemes using CPLEX. CPLEX is an optimizer which is developed by IBM Corporation for solving linear optimization problems which are also called Linear Programming (LP) problems. To maximize and minimize any problem the first requirement is that we need the objective function and constraints and it computes the optimal solution in the form of variables which are obtained in .lp file format. We are using 12.8<sup>th</sup> version of CPLEX 12.8 for solving our problem which is specified as ILP for both MAN, and MEP schemes.

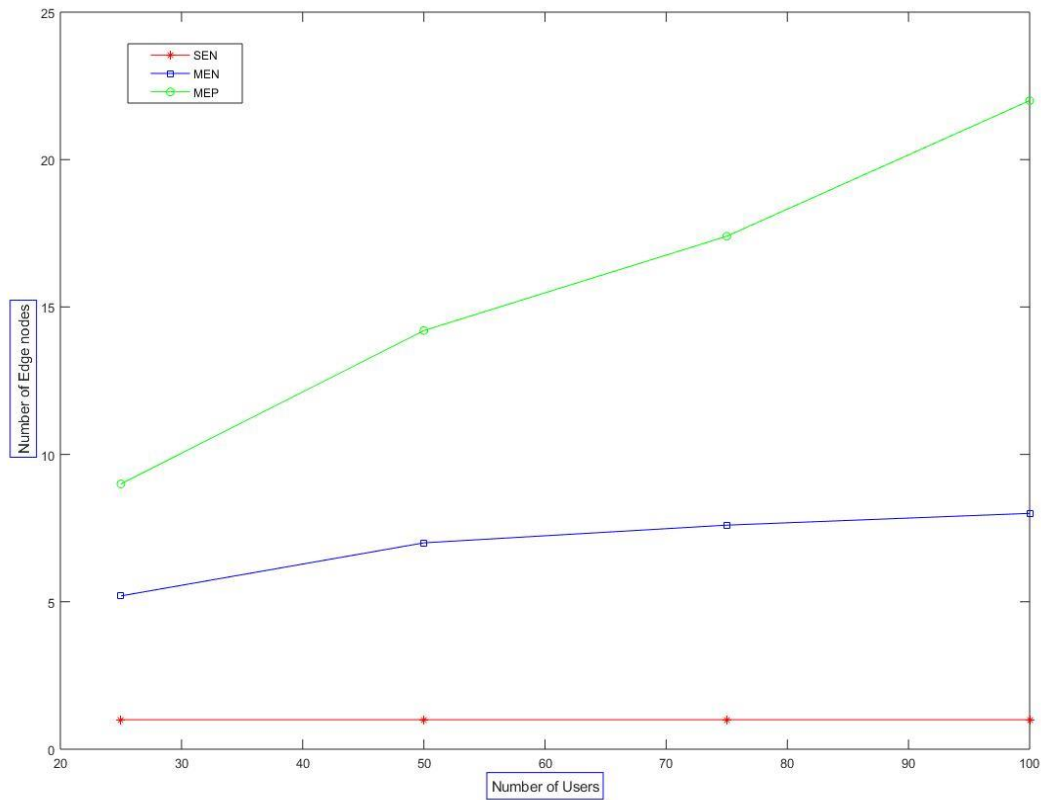
We consider the cell area with 1-kilometer radius, where MEC nodes will be deployed at certain points in the terrain. The range of the MEC nodes is set to 300 m, which is based on [39]. Although in urban environments the number of users can range upwards of 300, for now we assume that the number of active users range from 20 to 100 based on the data from [62] and [63]. Therefore, we are only assuming the active users to be in the range of 20 to 100 [59]. UEs are randomly distributed over the area and they are stationary. For both ILP models, the number of MEC nodes is calculated by performing the optimization. We also assume all User Equipment (UE) to be stationary during the optimization. The maximum number of the Computational Workload Requirement (CWR) by each user are assumed to be in between 10 to 40. For results we are taking the average of 5 runs. For scheme, MEP weight factor ( $\rho$ ) is set to 0.8.

## 4.2 Simulation Environment

This section presents the results for different scenarios for SEN, MEN, and MEP in terms of MEC nodes required and total uplink power consumed by UEs in accordance to particular scheme.

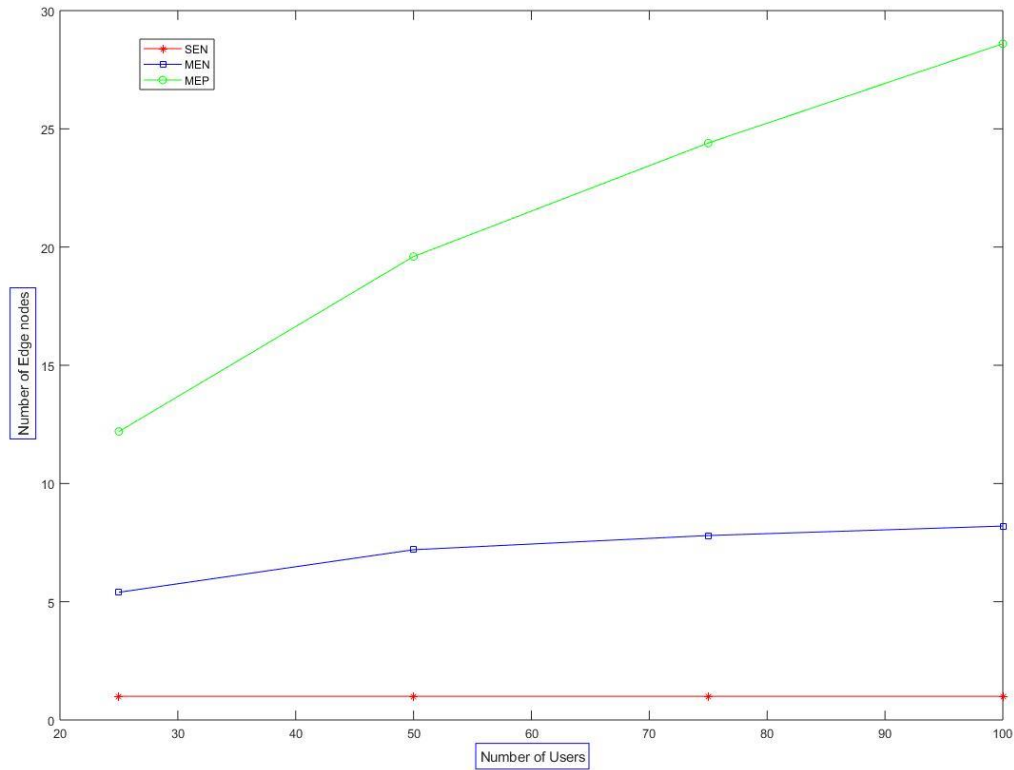
### 4.2.1 Analyzing the minimum number of MEC nodes for varying number of UEs.

Following figures represent, the number of MEC nodes required when the number of users is increased from 25 to 100 and CWR for each UE is constant at 10, 20, 30, and 40 units. The results are shown in Figure 4.1, 4.2, 4.3, and 4.4.



**Figure 4.1: Total number of MEC nodes for computing resources under varying number of UEs (assuming each UE has 10 units of computational workload)**

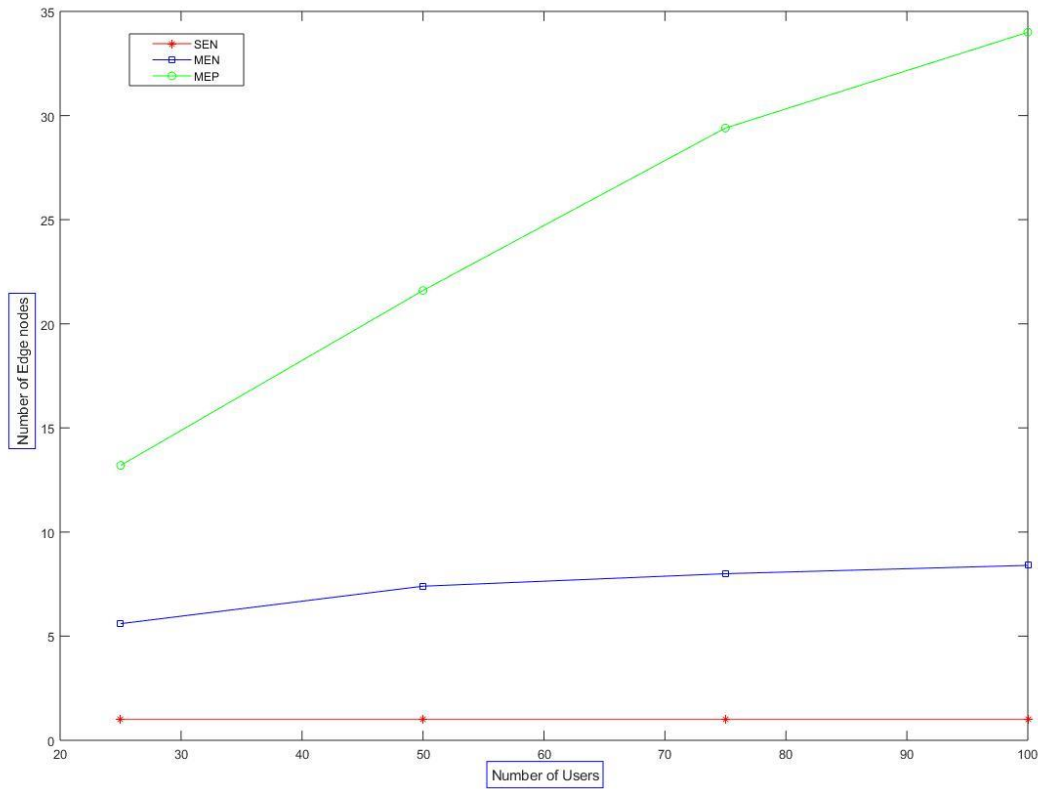
Figure 4.1 represents the number of MEC nodes for three different schemes, when users are increasing from 25 to 100 and the request for computational workload per UE remain constant at 10 units. In the SEN (Single Edge Node) scheme, the node remains constant at 1, when users are increasing from 25 to 100. In the MEN scheme, the number of MEC nodes increase from 5.2 to 8, when users are increased from 25 to 100. Moreover, in the MEP scheme, where the uplink power of devices is minimized along with MEC nodes increase from 9 to 22 when users increases from 25 to 100. Lastly, MEC nodes in MEP is increasing linearly, while MEN show smooth trend when UE's are increasing from 25 to 100, similar trend is seen in the following graphs. As the results show, MEN scheme is able to reduce the number of MEC nodes when compared to the energy-efficient technique. The number of MEC nodes will be always higher than SEN scheme since it only allows the macro cell base-station (1 node) to have MEC capabilities. Moreover, one of the drawbacks of using SEN scheme would be that it might also not be able to cover all the UE's in the assigned area. Which can be achieved by MEN and MEP schemes. The impact of these numbers will be jointly discussed after presenting the power consumption results.



**Figure 4.2: Total number of MEC nodes for computing resources under varying number of UEs (assuming each UE has 20 units of computational workload)**

Figure 4.2 presents the number of MEC nodes when computational workload for each UE is equal to 20 units. Here, the computational workload have been increased per user which in turn increases the number of MEC nodes, which now ranges between 5.4 to 8.2 and 12.2 to 28.6 for MEN and MEP respectively. Further, there is a gradual increase in the number of MEC nodes in the case of MEN scheme as compared to MEP scheme there is steep change when users increase from 25 to 50. This result from the increased computational load per UE. While the optimization of MEN keep the number of MEC nodes stable, the MEP scheme needs to consider uplink power and it becomes more pronounced as the workload and the users increase at the same time. This

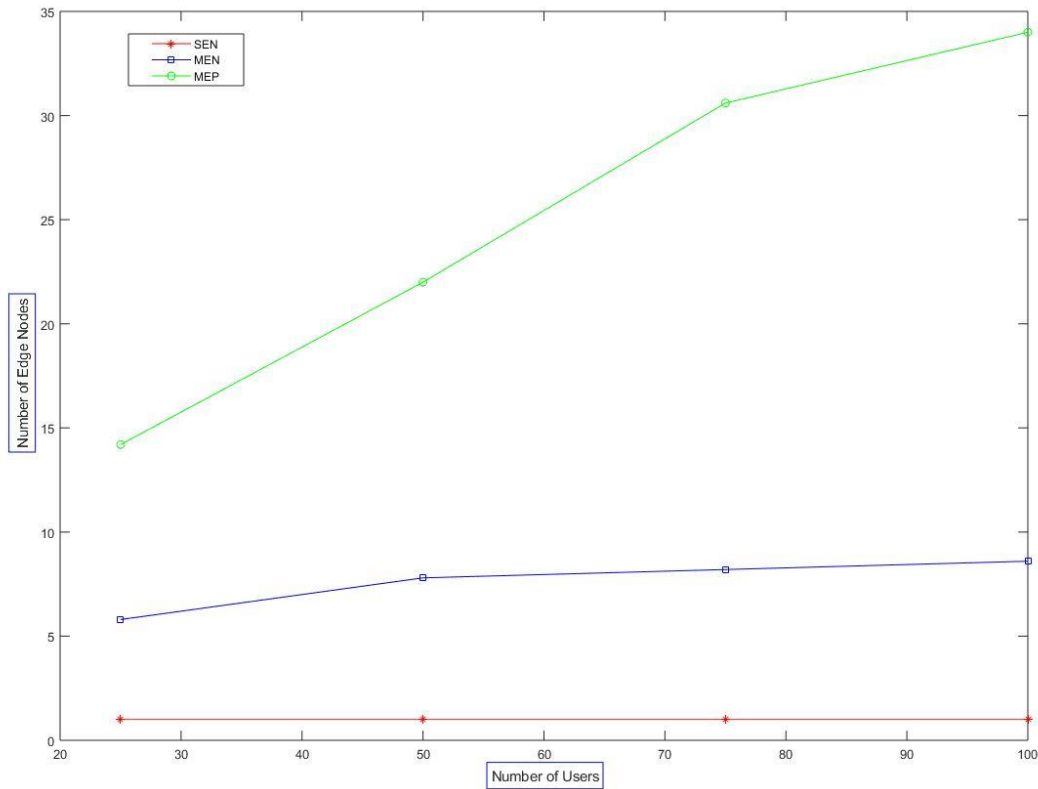
trend is observed in the following plots and the increase in MEC nodes become more obvious as the workload is increased.



**Figure 4.3: Total number of MEC nodes for computing resources under varying number of UEs (assuming each UE has 30 units of computational workload)**

Similarly, in Figure 4.3, when assuming each UE has 30 units of computational workload and users are increased from 25 to 100, there is increase in number of MEC nodes from 5.6 to 8.4 for the MEN scheme. Meanwhile, nodes increase from 13.2 for users = 25 to 34.0 when users = 100 for the MEP scheme. This further follows the trend as there is a steep rise when UE change from 25 to 75 because of the change in the computational requirement of each UE and the change

in number of UEs. This tends to increase in the number of required MEC nodes, as explained before.



**Figure 4.4: Total number of MEC nodes for computing resources under varying number of UEs (assuming each UE has 40 units of computational workload)**

In Figure 4.4, we compare the number of MEC nodes of SEN, MEN, and MEP schemes under different numbers of users where computational workload for each user is set to 40 units. As observed in the figure, there is a successive increase in the number of nodes which goes up to 8.6 and 34 for MEN and MEP respectively when  $UE = 100$ . There is significant increase in number of MEC nodes in MEP when UEs are increased from 50 to 100 as compared to MEN scheme, which signifies that taking uplink energy into account will considerably change the requirement

of MEC nodes, the result of which is a reduction of energy consumption for various number of UEs, as analyzed in the following graphs in the next section.

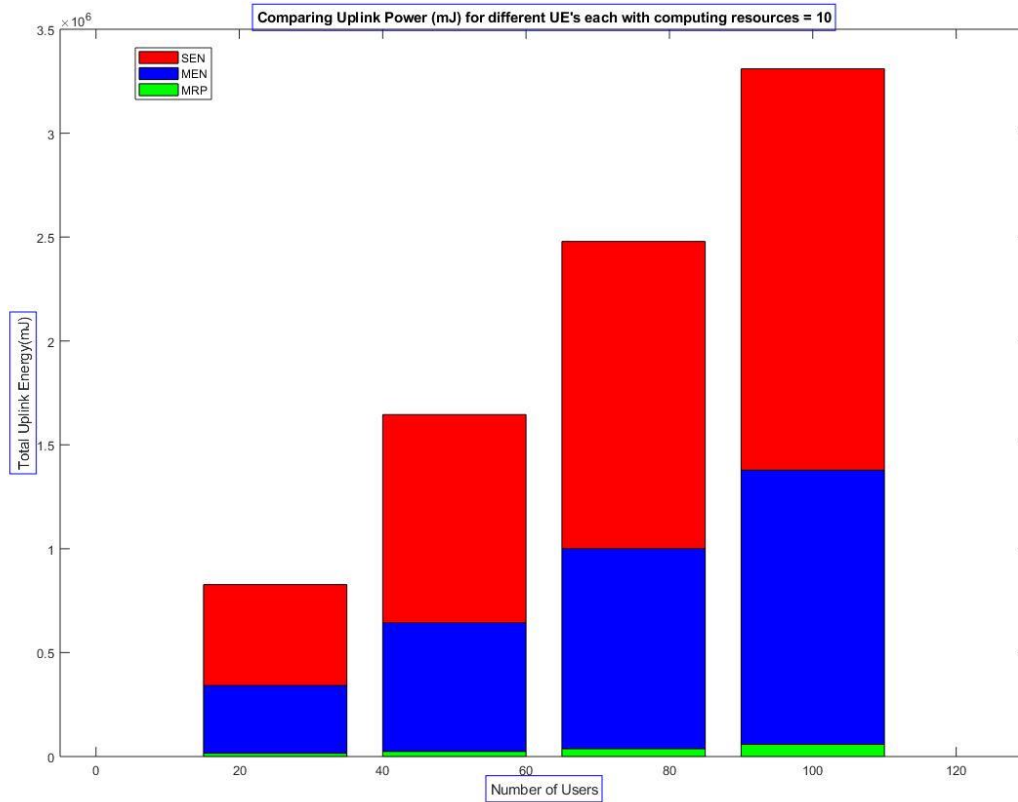
Following table 2 summarizes the results in a tabular format. The following table also shows that after computation workload by each UE reaches to 30 units, number of MEC nodes gets stable, whereas compared to the increase in MEC nodes when workload requirement by each UE gets increased from 10 to 20 units for MEP scheme.

CWR	10	10	20	20	30	30	40	40
	MEN	MEP	MEN	MEP	MEN	MEP	MEN	MEP
UEs = 25	5.2	9	5.4	12.2	5.6	13.2	5.8	14.2
UEs = 50	7	14.2	7.2	19.6	7.4	21.6	7.8	22
UEs = 75	7.6	17.4	7.8	24.4	8	29.4	8.2	30.6
UEs = 100	8	22	8.2	28.6	8.4	34	8.6	34

**Table 4.1: Comparison between Different Computational Loads.**

#### 4.2.2 Analyzing the Total Uplink Power for varying Number of UEs.

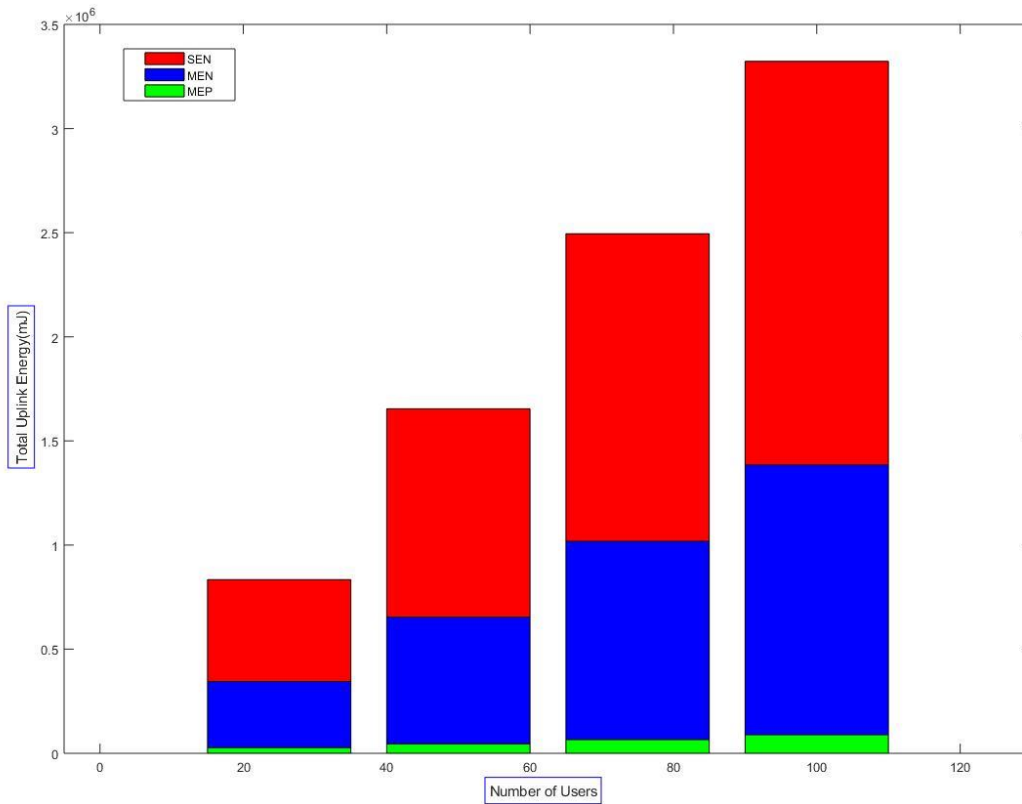
Following figures present total uplink power (mJ) when users are increased from 25 to 100 and computational workload is constant for each UE at 10, 20, 30, and 40 units at each figure, which is illustrated in the figure 4.5, 4.6, 4.7, and 4.8 respectively for three different schemes proposed.



**Figure 4.5: Total Uplink Energy for Computing Resources under varying Number of UEs (assuming each UE has 10 units of computational workload).**

Figure 4.5 represents the total uplink energy for the 3 different schemes, when users are increased from 25 to 100 and the computational workload remain constant per UE at 10 units. In the SEN (Single Edge Node) scheme, total uplink energy increases from  $0.82 \times 10^6 \text{mJ}$  to  $3.30 \times 10^6 \text{mJ}$  when users are increased from 25 to 100. In the MEN scheme, total uplink energy increases from  $0.34 \times 10^6 \text{mJ}$  to  $1.37 \times 10^6 \text{mJ}$ , where UE's are successively increased from 25 to 100. Lastly, in the MEP scheme, the uplink power of devices is minimized along with MEC nodes, resulting in a decrease of the uplink power consumed by the devices. Here, the total uplink power increases from  $0.015 \times 10^6 \text{mJ}$  to  $0.058 \times 10^6 \text{mJ}$  when the number of users increases from 25 to 100.

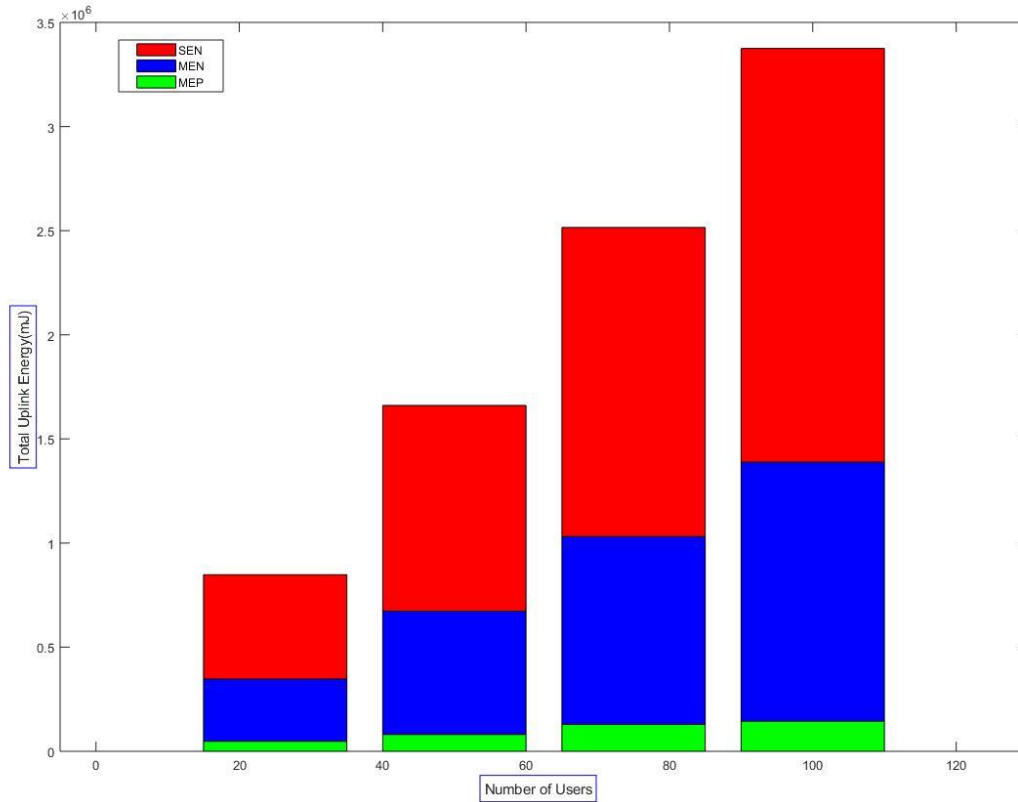
For 100 UE's and 10 unit of workload per each UE, there has been a decrease of  $1.32 \times 10^6$  mJ from MEN, by taking the minimization of uplink energy into account which will considerably save the battery consumption of devices.



**Figure 4.6: Total Uplink Energy for Computing Resources under varying Number of UEs (assuming each UE has 20 units of computational workload).**

Figure 4.6 illustrates a comparison of total uplink energy of SEN, MEN, and MEP under varying number of UE. We assume the number of computational workload for each UE is set to 20 units for SEN, MEN, and MEP schemes. We can see that as the number of UE increases, the uplink energy increases as expected due to the demand of workload per UE is increasing simultaneously. If we compared the increase in different schemes, we can analyze that there is

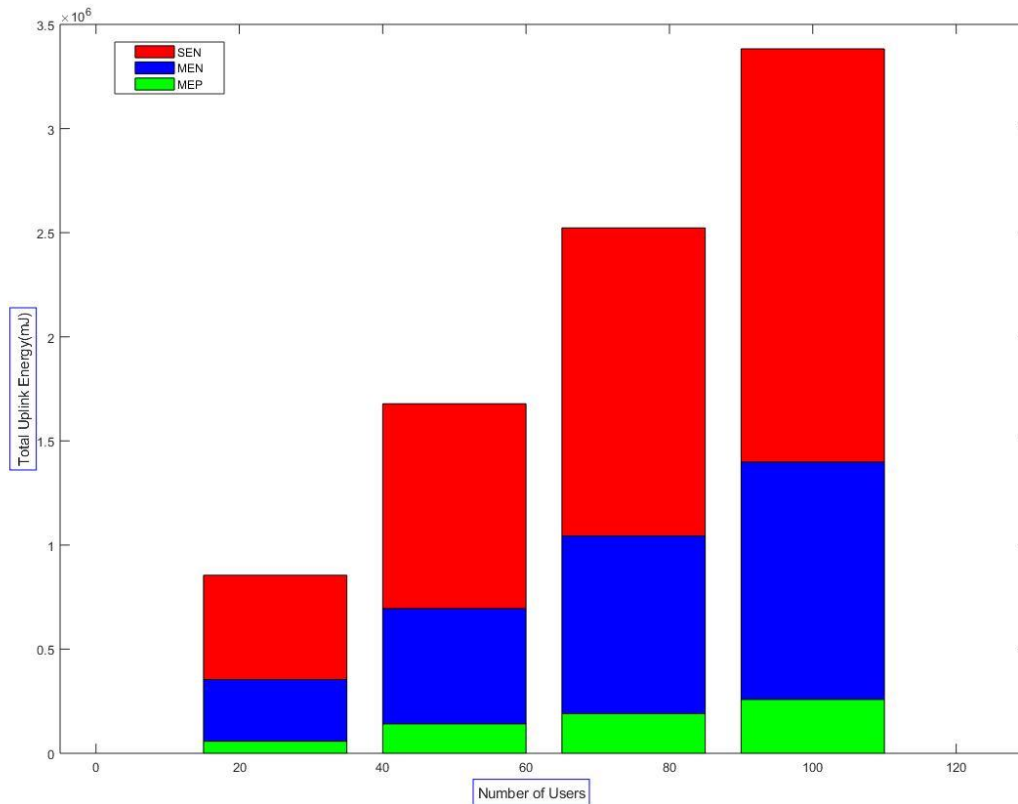
significant change for SEN and MEN schemes. However, in the optimized uplink power scheme, MEP effectively manages and reduces the uplink energy for each UE.



**Figure 4.7: Total Uplink Energy for Computing Resources under varying Number of UEs (assuming each UE has 30 units of computational workload).**

Figure 4.7 depicts the total uplink energy for changing number of UE's, where computational workload for each UE is constant at 30 units. Analyzing the values, the uplink energy for the SEN ranges in between  $0.84 \times 10^6$  mJ for UEs = 25 goes up till  $3.37 \times 10^6$  mJ for UEs = 100. We compare this to the MEN scheme where the MEC nodes increases in the network from a single node in SEN to multiple nodes. This in turn leads to reduction of uplink energy to some extent, which ranges from  $0.34 \times 10^6$  mJ for UEs = 25 to  $1.38 \times 10^6$  mJ when UEs are 100. The MEP

scheme saves the uplink energy overhead significantly, which minimizes the uplink power that lies in between  $0.04 \times 10^6 \text{mJ}$  when  $UE=25$  to  $0.14 \times 10^6 \text{mJ}$  for  $UE=100$  which proves that MEP scheme not only optimizes the MEC nodes, it is also energy efficient for UE.



**Figure 4.8: Total Uplink Energy for Computing Resources under varying Number of UEs (assuming each UE has 40 units of computational workload).**

By analyzing Figure 4.8, in which computational workloads per UE is set constant to 40 units, we see that uplink energy increases along with the increase in a number of devices. The MEP scheme effectively optimizes the uplink energy which is at  $0.25 \times 10^6 \text{mJ}$  for  $UE's=100$  in comparison to MEN scheme having the uplink power of  $1.04 \times 10^6 \text{mJ}$  for the same number of UE's.

Uplink power of MEN scheme is also less if compared to SEN scheme which has one node/BS in which total uplink power increases to  $3.37 \times 10^6 \text{mJ}$  when users = 100.

The following Table 3.1 and Table 3.2 shows the comparison of uplink power when the number of UE's are set to 25 and 100 for three different schemes, SEN, MEN, and MEP. It is clear that difference is increasing from the scheme, SEN from  $2.48 \times 10^6 \text{mJ}$  to  $2.53 \times 10^6 \text{mJ}$ . For MEN, the total uplink power consumed by each device is less than SEN due to the presence of multiple MEC nodes, while MEP scheme, considerably minimizes the uplink energy of devices as compared to SEN and MEN. This proves that the MEP scheme effectively reduces the uplink energy for UE's to access the nearest MEC node which will make these devices energy efficient along with receiving the contents at faster speeds.

CWR	10	10	10	20	20	20
	SEN	MEN	MEP	SEN	MEN	MEP
UEs = 25	$0.82 \times 10^6 \text{mJ}$	$0.34 \times 10^6 \text{mJ}$	$0.01 \times 10^6 \text{mJ}$	$0.83 \times 10^6 \text{mJ}$	$0.34 \times 10^6 \text{mJ}$	$0.02 \times 10^6 \text{mJ}$
UEs = 50	$1.64 \times 10^6 \text{mJ}$	$0.64 \times 10^6 \text{mJ}$	$0.02 \times 10^6 \text{mJ}$	$1.65 \times 10^6 \text{mJ}$	$0.65 \times 10^6 \text{mJ}$	$0.04 \times 10^6 \text{mJ}$
UEs = 75	$2.47 \times 10^6 \text{mJ}$	$1.00 \times 10^6 \text{mJ}$	$0.03 \times 10^6 \text{mJ}$	$2.49 \times 10^6 \text{mJ}$	$1.01 \times 10^6 \text{mJ}$	$0.06 \times 10^6 \text{mJ}$
UEs = 100	$3.30 \times 10^6 \text{mJ}$	$1.37 \times 10^6 \text{mJ}$	$0.05 \times 10^6 \text{mJ}$	$3.32 \times 10^6 \text{mJ}$	$1.38 \times 10^6 \text{mJ}$	$0.08 \times 10^6 \text{mJ}$

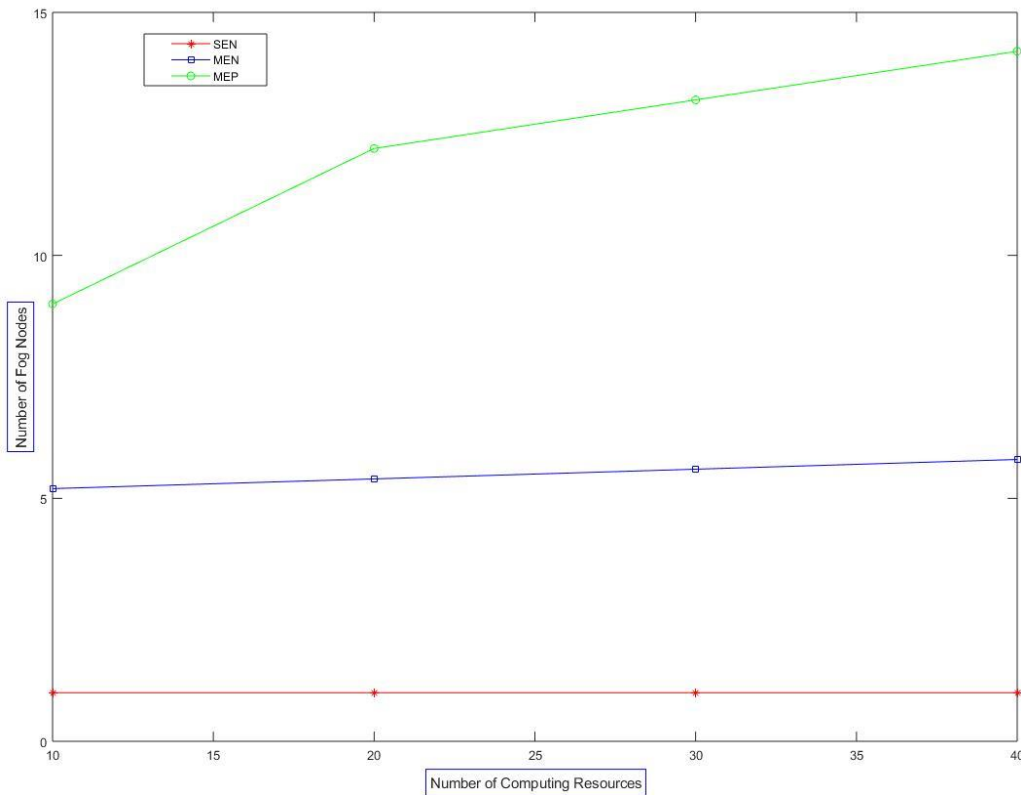
**Table 4.2: Comparison of Uplink Power for Computational Workloads of 10 and 20 units.**

CWR	30 SEN	30 MEN	30 MEP	40 SEN	40 MEN	40 MEP
UEs = 25	$0.84 \times 10^6 \text{mJ}$	$0.34 \times 10^6 \text{mJ}$	$0.04 \times 10^6 \text{mJ}$	$0.85 \times 10^6 \text{mJ}$	$0.35 \times 10^6 \text{mJ}$	$0.05 \times 10^6 \text{mJ}$
UEs = 50	$1.66 \times 10^6 \text{mJ}$	$0.67 \times 10^6 \text{mJ}$	$0.82 \times 10^6 \text{mJ}$	$1.67 \times 10^6 \text{mJ}$	$0.69 \times 10^6 \text{mJ}$	$0.14 \times 10^6 \text{mJ}$
UEs = 75	$2.51 \times 10^6 \text{mJ}$	$1.03 \times 10^6 \text{mJ}$	$0.12 \times 10^6 \text{mJ}$	$2.52 \times 10^6 \text{mJ}$	$1.04 \times 10^6 \text{mJ}$	$0.19 \times 10^6 \text{mJ}$
UEs = 100	$3.37 \times 10^6 \text{mJ}$	$1.38 \times 10^6 \text{mJ}$	$0.14 \times 10^6 \text{mJ}$	$3.38 \times 10^6 \text{mJ}$	$1.39 \times 10^6 \text{mJ}$	$0.25 \times 10^6 \text{mJ}$

**Table 4.3: Comparison of Uplink Power for Computational Workloads of 30 and 40 units.**

#### **4.2.3 Analyzing the Minimum Number of MEC nodes for a varying Number of Computational Workload Requirement of UE.**

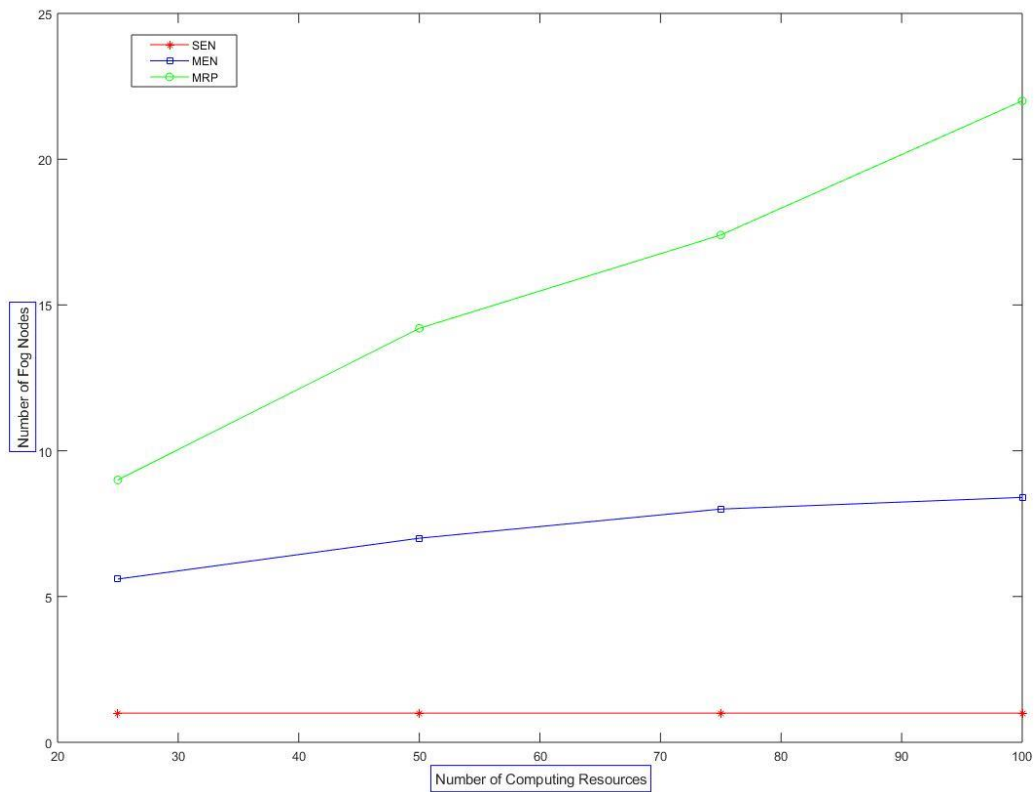
Following figures represent, the number of MEC nodes required when computational workload per UE are increases from 10 to 40 units and UE's are constant at 25, 50, 75, and 100 which is illustrated in figure 4.9, 4.10, 4.11, and 4.12 respectively for three different schemes proposed in chapter 3. The results are redrawn from the values presented in the previous sections. They are included to provide a visual comparison in terms of workload.



**Figure 4.9: Total Number of MEC nodes under a varying Number of Computing Resources Requested per UE (The number of UEs is 25).**

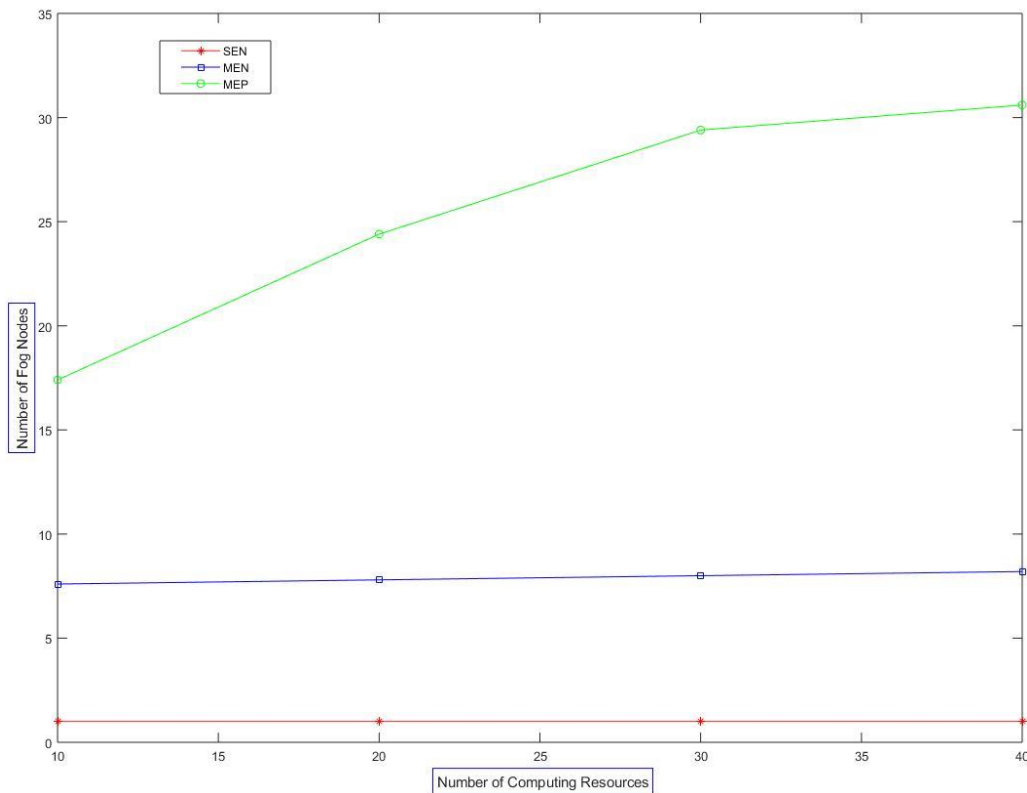
Figure 4.9 represents the minimum number of MEC nodes required for three different schemes SEN, MEN, and MEP. In this representation, UE remains constant at 25 while computational workload required by each UE changes. In SEN, the number of MEC nodes remain at 1. With MEN, there is a gradual increase in the number of MEC nodes from 5.2 to 5.8 when CWR by each UE increases from 10 to 40 units respectively. Meanwhile, the number of MEC nodes changes significantly for MEP scheme which minimizes uplink power for UEs while minimizing the number of MEC nodes. In MEP, there is a steep rise in the number of nodes when CWR requested by each UE increase from 10 to 20 units, that is from 9 nodes to 12.2 nodes.

Taking energy efficiency for UEs into account in MEP increases the number of MEC nodes required, however, this scheme provides a variety of benefits such as making devices energy efficient and increasing the data transfer speed, both of which will ultimately improve QoS factor. This scheme also possesses long-term benefits. For instance, it can also reduce the energy cost for MEC nodes which can cover deployment cost over a couple of years. Moreover, further research can be done to develop an algorithm for turning off and on MEC nodes when the users drop from the certain threshold.



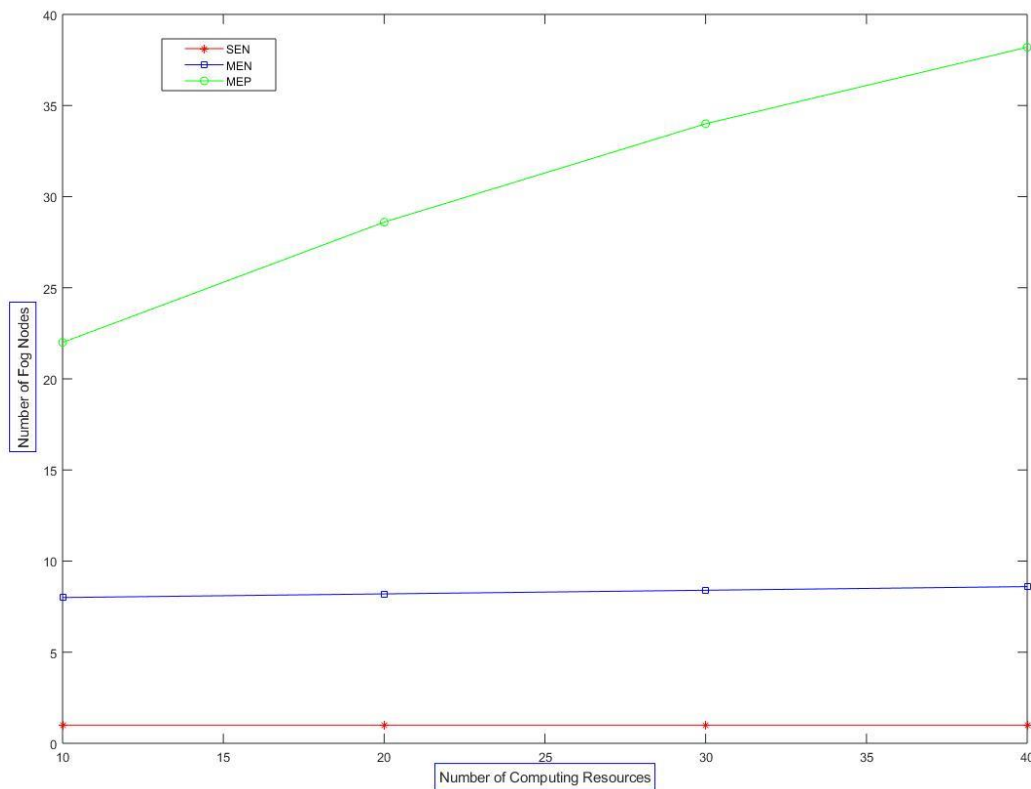
**Figure 4.10: Total Number of MEC nodes under a varying Number of Computing Resources Requested per UE (The number of UEs is 50).**

Figure 4.10 illustrates, the number of MEC nodes for a different number of CWR by each UE, where UEs = 50. The first Scheme, SEN, has 1 node throughout the graph. To compare, the second Scheme, MEN, which minimizes the placement of MEC nodes, it shows a surge when requirement of workload for each UE increase from 10 to 20 units, and afterward nodes increase at a constant rate. The third Scheme, MEP minimizes the uplink power of UEs along with placement of nodes, which observes the difference of 11 MEC nodes when computational workload per UE changes from 10 to 40 units. This shows that an increase in demand of resources leads to an increase in the number of required MEC nodes which are closer to users.



**Figure 4.11: Total Number of MEC nodes under a varying Number of Computing Resources Requested per UE (The number of UEs is 75).**

Similarly, in Figure 4.11, when the number of devices are equal to 75 and computational workload demanded by each UE increases from 10 to 40 units, there is an increase in the number of MEC nodes from 7.6 to 8.2 for MEN scheme. Meanwhile, nodes increase from 17.4 for Computational Workload (CWR) = 10 to 30.6 when CWR = 20 for MEP scheme. Further observing the plot, there is additional rise when the demand of resources from each UE changes from 20 to 40 in MEP scheme, which tends to increase in the requirement of MEC nodes from 24.4 to 30.6 nodes.

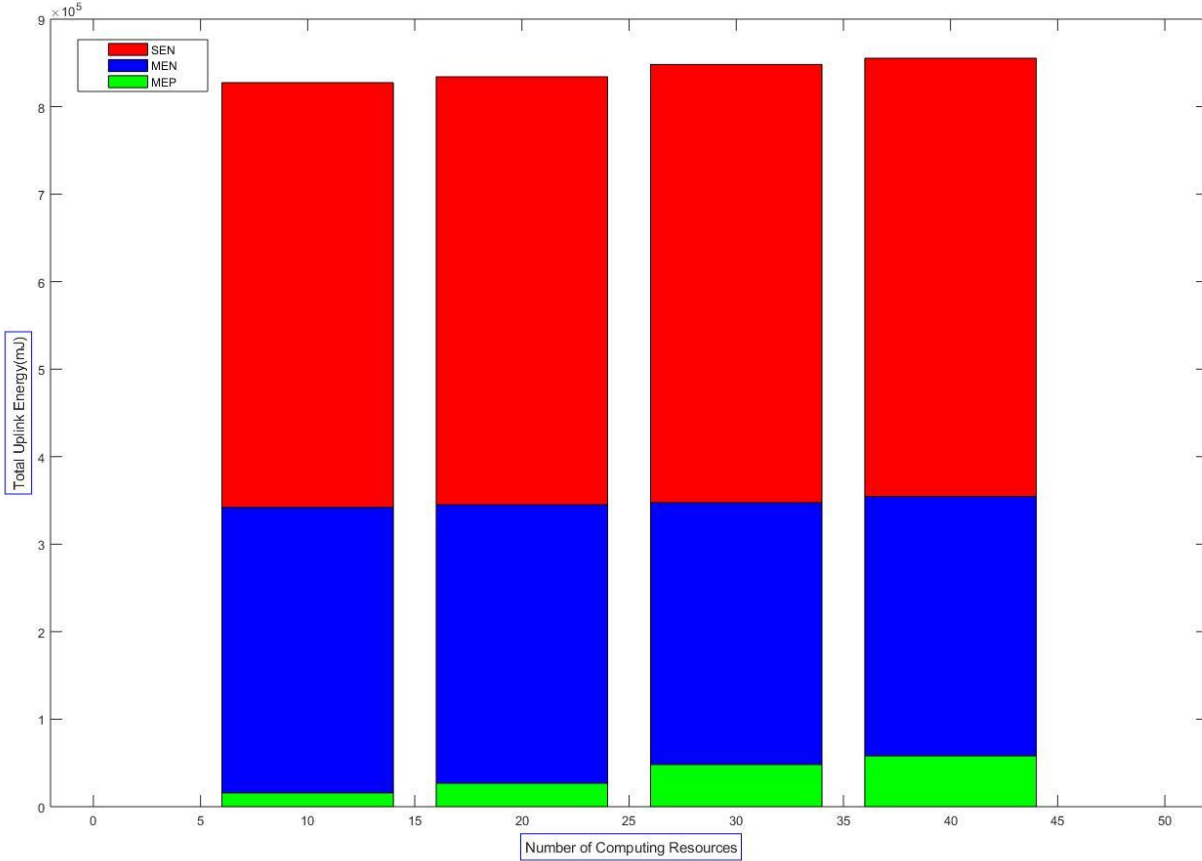


**Figure 4.12: Total Number of MEC nodes under a varying Number of Computing Resources Requested per UE (The number of UEs is 100).**

In Figure 4.12, we compare a number of MEC nodes of SEN, MEN, and MEP schemes under a different number of computational workload demanded per UE and where the number of UEs is set to 100. Correspondingly, there is a successive increase in the number of nodes which increase to 8.6 and 38.2 for MEN and MEP, respectively, when computational workload is at 40 units. There is a significant increase in a number of MEC nodes in MEP when the demand of workload increases from each UE from 10 to 40 units as compared to MEN scheme. This is because the MEP scheme takes uplink energy into account, which substantially changes the requirement of MEC nodes in order to save energy for various UE.

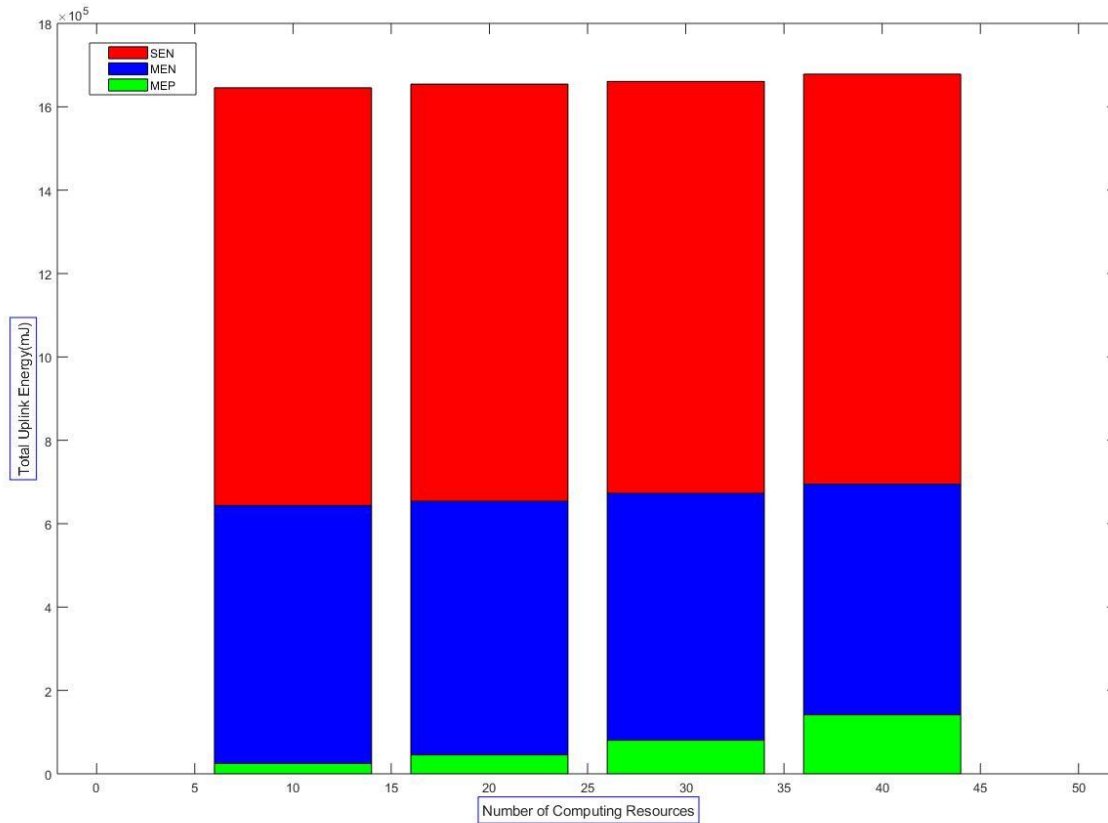
#### **4.2.4 Analyzing the Total Uplink Power for varying units of Computational Workload.**

Following figures represent, total uplink power when computational workload required by each UE increases from 10 to 40 units and UE's are constant at 25, 50, 75, and 100 which is illustrated in the figure 4.13, 4.14, 4.15, and 4.16 respectively for three different schemes.



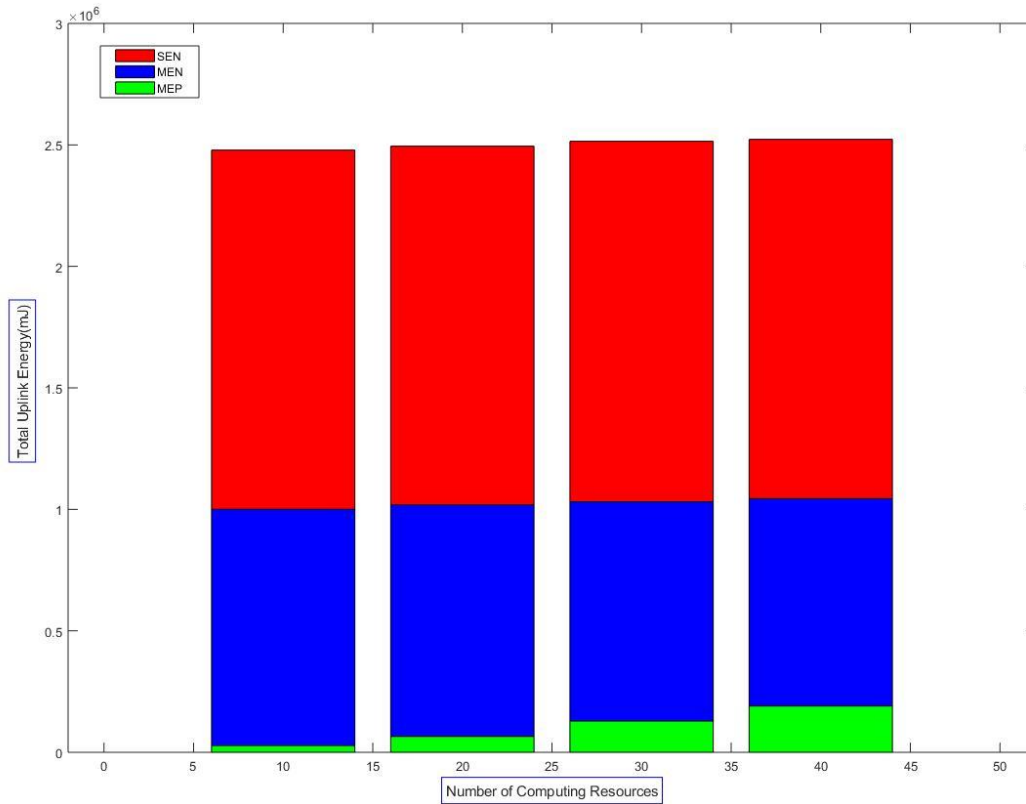
**Figure 4.13: Total Uplink Energy under varying Number of Computing Resources (The number of UEs is 25).**

Figure 4.13 represents total uplink energy for 3 different schemes, when computational workload for each UE increases from 10 to 40 units where the UEs are constant at 25. In SEN scheme total uplink energy increases from  $0.82 \times 10^6 \text{mJ}$  to  $0.85 \times 10^6 \text{mJ}$  when CWR increases from 10 to 40 units. In MEN scheme total uplink energy increases from  $0.34 \times 10^6 \text{mJ}$  to  $0.35 \times 10^6 \text{mJ}$ , when workload successively increases from 10 to 40 units. Meanwhile, in MEP scheme, the uplink power of devices are also being minimized along with MEC nodes, and thus we see decrease in the uplink power consumed by the devices. Here, the total uplink power increases from  $0.015 \times 10^6 \text{mJ}$  to  $0.058 \times 10^6 \text{mJ}$  when computational workload per UE increases from 10 to 40 units.



**Figure 4.14 Total Uplink Energy under varying Number of Computing Resources (The number of UEs is 50).**

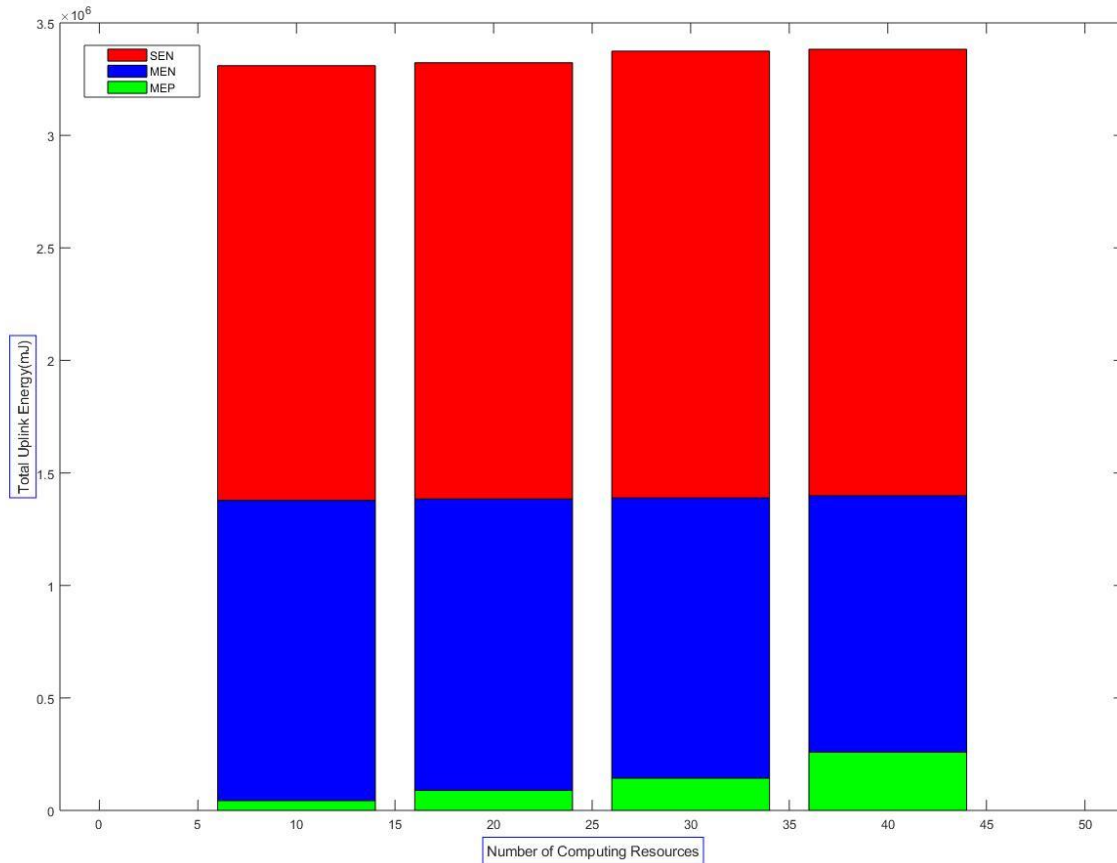
Figure 4.14 illustrates a comparison of total uplink energy of SEN, MEN, and MEP under varying number of computation workload per UE. The number of UEs is set to 50 for SEN, MEN, and for MEP. We can see that as computational workload for each UE increases, the uplink energy increases as expected due to the demand of resources increases simultaneously. However, in the optimized uplink power scheme, MEP effectively manages and reduces the uplink energy for the UEs as compared to SEN and MEN.



**Figure 4.15: Total Uplink Energy under varying Number of Computing Resources (The number of UEs is 75).**

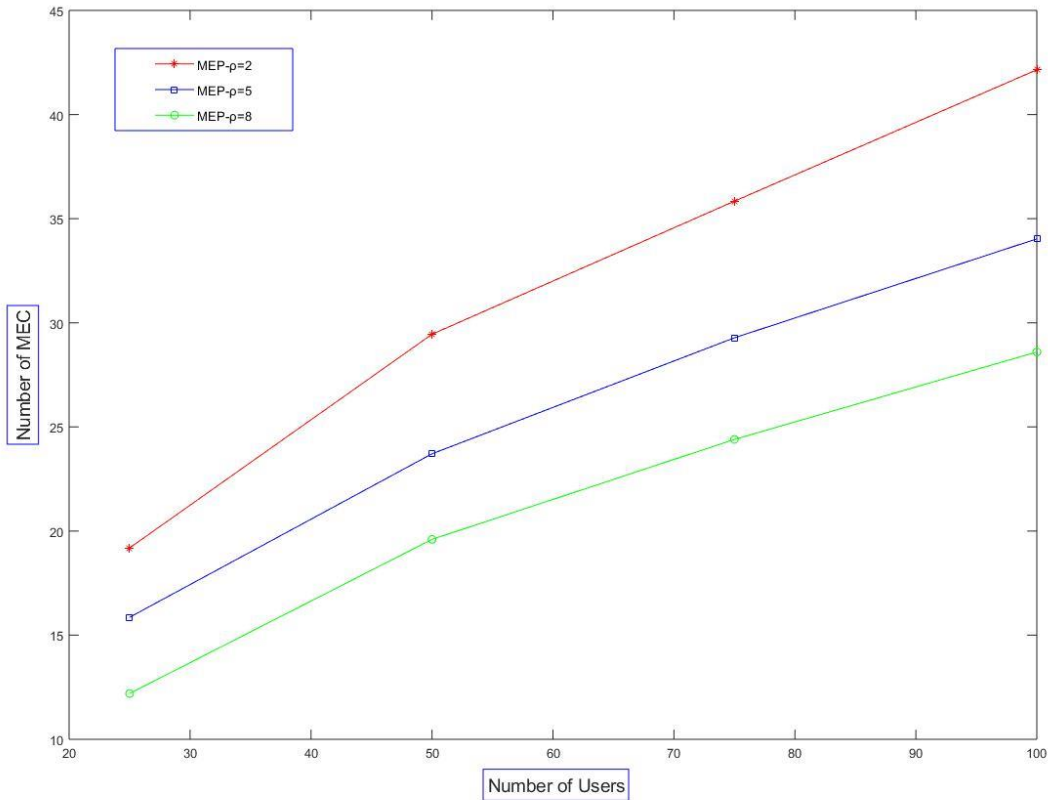
Figure 4.15 depicts, the total uplink energy for the changing computational workload requested by each UE, where users are constant at 75. Analyzing the values, the uplink energy for SEN ranges in between  $2.47 \times 10^6$  mJ for CWR = 10 to  $2.52 \times 10^6$  mJ for CWR = 40. Now compare this to MEN scheme, where the requirement of resources increases in the network, and topology also changes from single node in SEN to multiple nodes, in MEN. This change leads in minimization of uplink energy of UE to some extent which ranges from  $1.00 \times 10^6$  mJ for CWR = 10 units to  $1.04 \times 10^6$  mJ for UEs = 40. The MEP scheme optimizes uplink energy uplink energy overhead more effectively, which remains between  $0.02 \times 10^6$  mJ when CWR = 10 units to

$0.19 \times 10^6 \text{mJ}$  for  $\text{CWR} = 40$  units, proving that the MEP scheme not only optimizes the MEC nodes, as well as it is energy efficient scheme for devices.



**Figure 4.16 Total Uplink Energy under varying Number of Computing Resources (The number of UEs is 100).**

In 4.16, in which number of devices are set constant to 100, uplink energy increase along with the increase in computational workload requirement for each UE. The MEP Scheme significantly optimizes the uplink energy which is at  $0.04 \times 10^6 \text{mJ}$  for  $\text{CWR} = 40$  units in comparison to the MEN scheme, which has uplink power of  $1.39 \times 10^6 \text{mJ}$ . Uplink power of MEN scheme is considered less when compared to SEN scheme, where computational workload requested per UE is at 40 units in which total uplink power increases to  $3.38 \times 10^6 \text{mJ}$ .



**Figure 4.17 Number of MEC nodes for weight factor 0.2, 0.5, and 0.8 for MEP.**

Figure 4.17 represents total number of MEC nodes for different UEs assuming each UE has 10 units of computational workload with weight factor ( $\rho$ ) of 0.2, 0.5, and 0.8 respectively for the MEP scheme. It is evident from the graph as weight increases, MEP scheme tries to reduce the number of MEC nodes. To emphasize more towards deployment cost of network, weight ( $\rho$ ) = 0.8 can be considered better tradeoff for MEC nodes and uplink energy efficiency.

### 4.3 Conclusion

In this thesis, we addressed the placement of mobile edge nodes problem in wireless networks using two ILP models with the objective of minimizing cost and maximizing energy efficiency. We have proposed the MEN scheme, which reduces the edge node deployment cost by optimizing the number of edge nodes using ILP. Furthermore, we proposed the MEP scheme which aims joint minimization of uplink energy and edge node deployment cost using ILP. We have shown and compared the results of these schemes with respect to a baseline scheme which has one centrally located computation resource to cater all user equipment.

MEN scheme minimizes the number of edge nodes and MEP scheme has higher nodes as compared to MEN by taking energy efficiency for UEs into account. However, this scheme provides a variety of benefits such as making devices energy efficient and increasing the data transfer speed, both of which will ultimately improve QoS factor. This scheme also possesses long-term benefits. For instance, it can also reduce the energy cost for MEC nodes which can cover deployment cost over a couple of years.

Our results shows that for 100 UEs and 40 units of workloads, MEN scheme needs 74.7% of less MEC nodes than MEP. In the meanwhile, MEP scheme reduces the energy consumption by 82% under same conditions.

## Chapter 5 - Contribution and Future Work

### 5.1 Contribution

The work of this thesis has been motivated by the following publications on Electric Vehicles and Data analytics. The need for MEC and optimization techniques are emphasized in these works:

- B. Li, M. C. Kisacikoglu, C. Liu, N. Singh and M. Erol-Kantarci, "Big Data Analytics for Electric Vehicle Integration in Green Smart Cities," in *IEEE Communications Magazine*, vol. 55, no. 11, pp. 19-25, November 2017.
- N. Singh, M. Kisacikoglu, Melike Erol-Kantarci, "Big Data for Electric Vehicle Integration (EVGI) Decision Making," *IEEE MMTTC Communications Frontiers Journal*, November 2017.

This thesis has been focused on the development of Mobile Edge Computing technology and addresses the primary concerns for the deployment of edge nodes. MEC can be a platform for various upcoming technologies, such as connected electric vehicles, augmented reality, IoT devices, and so many more.

As a summary of our contributions, our proposed approach effectively optimizes the placement of edge nodes. Apart from this, we have also proposed a scheme which minimizes uplink power of user equipment and the placement of edge nodes, which in return reduces the deployment cost and the energy consumption of UEs.

## 5.2 Future Work

With devices increasing exponentially, and their need for computing growing at a tremendous speed day by day, strategies and methods for catering to the growing demand of UEs must be proposed. This thesis discussed the placement of edge nodes in 5G with objectives of minimizing cost and uplink energy-efficiency. We further plan to extend our work by solving this problem using other optimization techniques such as evolutionary algorithm, and researching energy-efficiency techniques for the network side, such as automatically powering down edge devices when demand falls under specific threshold, thus saving the energy consumption of these nodes. This research, when developed, will not only save energy cost but can also be used to compensate the cost of deploying more nodes and therefore achieving reduction of capital expenditure (CAPEX) for operators.

In the future, we plan to work with real data where historical averages of user density and their computational needs can be incorporated. In addition, this study does not consider mobility. Additional algorithmic approaches are needed to ensure MEC nodes are able to serve all users. Another future work, is related to using more realistic workload – resource matching mechanisms. This thesis assumes workloads are uniform, so are the resources. Yet, in real-world UEs will raise variable computational requests such as one task needing response with low-latency while another needing processing power. Similarly, MEC nodes will have varying capabilities. These need to be considered in future works.

Additionally, algorithms can be proposed for implementing machine and deep learning on the edge devices instead of sending data to cloud for processing that can have benefits such as real time demand analysis, which will further improve functioning and efficiency of MEC nodes.

Security and privacy is also a major concern. This thesis assumes all workloads can be processed by all MEC nodes, however in real-world sensitive information should be shared only with trusted nodes, as well as the information that comes available as an artifact of MEC-enabled architecture should be privacy-preserving.

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