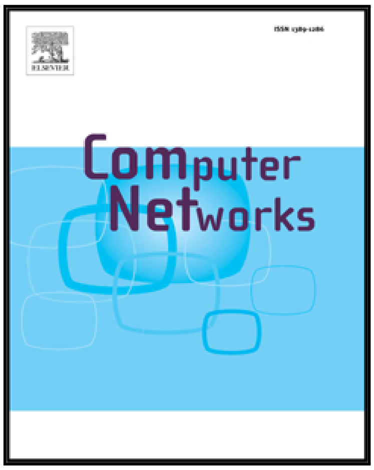
Accepted Manuscript



Potentials, Trends, and Prospects in Edge Technologies: Fog, Cloudlet, Mobile Edge, and Micro Data Centers

Kashif Bilal , Osman Khalid , Aiman Erbad , Samee U. Khan

PII: S1389-1286(17)30377-8
DOI: 10.1016/j.comnet.2017.10.002
Reference: COMPNW 6317

To appear in: *Computer Networks*

Received date: 21 April 2017
Revised date: 26 September 2017
Accepted date: 9 October 2017

Please cite this article as: Kashif Bilal , Osman Khalid , Aiman Erbad , Samee U. Khan , Potentials, Trends, and Prospects in Edge Technologies: Fog, Cloudlet, Mobile Edge, and Micro Data Centers, *Computer Networks* (2017), doi: 10.1016/j.comnet.2017.10.002

Potentials, Trends, and Prospects in Edge Technologies: Fog, Cloudlet, Mobile Edge, and Micro Data Centers

Kashif Bilal[1,2], Osman Khalid[2], Aiman Erbad[1], and Samee U. Khan[3]

[1]Qatar University, Doha, Qatar

[2]COMSATS Institute of Information Technology, Pakistan

[3]North Dakota State University, USA

[1,2] kashif@qu.edu.qa, [2]osman@ciit.net.pk, [2]aerbad@qu.edu.qa, and [3]samee.khan@ndsu.edu

ABSTRACT

Advancements in smart devices, wearable gadgets, sensors, and communication paradigm have enabled the vision of smart cities, pervasive healthcare, augmented reality and interactive multimedia, Internet of Every Thing (IoE), and cognitive assistance, to name a few. All of these visions have one thing in common, i.e., delay sensitivity and instant response. Various new technologies designed to work at the edge of the network, such as fog computing, cloudlets, mobile edge computing, and micro data centers have emerged in the near past. *We use the name ñedge computingò for this set of emerging technologies*. Edge computing is a promising paradigm to offer the required computation and storage resources with minimal delays because of ñbeing nearò to the users or terminal devices. Edge computing aims to bring cloud resources and services at the edge of the network, as a middle layer between end user and cloud data centers, to offer prompt service response with minimal delay. Two major aims of edge computing can be denoted as: (a) minimize response delay by servicing the usersô request at the network edge instead of servicing it at far located cloud data centers, and (b) minimize downward and upward traffic volumes in the network core. Minimization of network core traffic inherently brings energy efficiency and data cost reductions. Downward network traffic can be minimized by servicing set of users at network edge instead of service providerôs data centers (e.g., multimedia and shared data) Content Delivery Networks (CDNs), and upward traffic can be minimized by processing and filtering raw data (e.g., sensors monitored data) and uploading the processed information to cloud. This survey presents a detailed overview of potentials, trends, and challenges of edge computing. The survey illustrates a list of most significant applications and potentials in the area of edge computing. State of the art literature on edge computing domain is included in the survey to guide readers towards the current trends and future opportunities in the area of edge computing.

1. INTRODUCTION

Cloud computing brought a technological revolution and paradigm shift in the Information and Communication Technology (ICT) sector in the last decade. Cloud computing experienced a massive adoption in almost every domain of human life [1][2][3][4]. Data centers, the backbone and underlying resource architecture of cloud computing are constantly growing in size and number to meet the increasing resource demands [2]. Technological advances in personal gadgets and wearable computing are enabling a new stream of real-time and pervasive applications, such as cognitive assistance, augmented reality, traffic monitoring, vehicular tracking, and interactive video streaming [5]. Such applications demand real-time response, which is one of the major constraints in the cloud paradigm because of the delays from distant cloud data centers. As indicated in Fig. 1, a userôs request to the cloud has to traverse multiple hops before reaching the cloud servers, thus increasing the response time.

The proliferation of mobile devices, which are predicted to be more than 50 Billion devices by the year 2020, will produce massive amounts of data [6]. Moreover, the ever increasing data rates from the Internet of Things (IoT) devices will impose further challenges on the cloud computing infrastructure. IoT is an emerging technology that extends Internet connection to devices embedded with sensors, actuators, and RFID tags [7]. IoT devices collect sensory data from the surrounding environment with a requirement to provide scalable infrastructure to communicate, process, and store the data [8][9]. The number of such devices will reach billions in the coming years, with a large number of sensors monitoring and flooding the network with dynamic real-time data. According to Cisco Global Cloud Index [10], by the year 2019, 500 zettabytes of data will be produced by people, machines, and things, and 2.3 trillion GBs of data will be produced every day in the year 2020 [11]. IoT platforms demand low latency communication, need support for high degree of mobility, and real-time data analytics. Although cloud computing provides many benefits, the latency sensitive and data intensive IoT applications appear to be a challenge

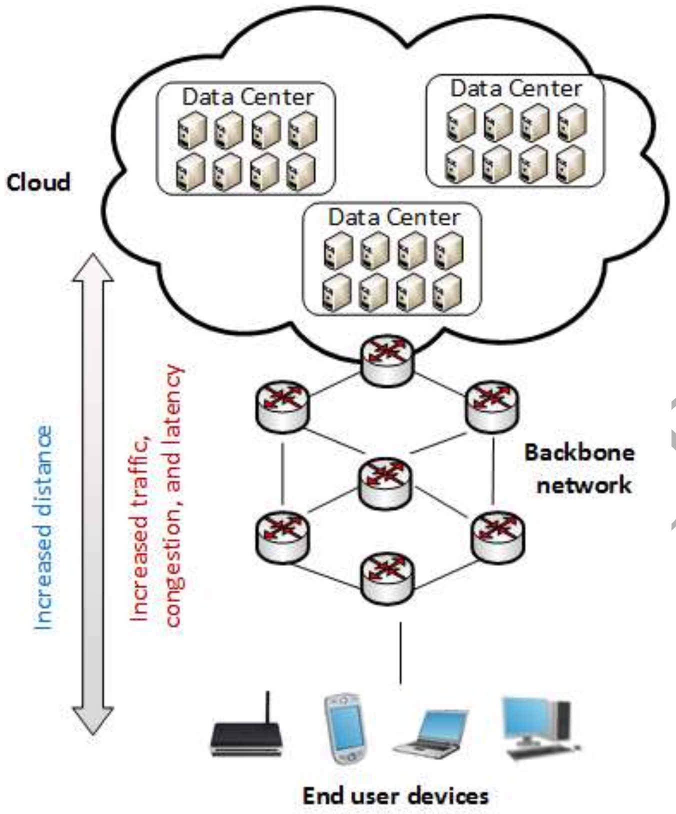


Fig. 1: Multiple hops between end user/devices and cloud data centers result in delayed response.

for current cloud computing system. The needs for real-time response and ever increasing data demands novel solutions. Edge computing (fogs, cloudlets, micro datacenters, and mobile edge computing) is emerging as a viable solution to these challenges, offering real-time response and near to end cloud services. Edge computing augments cloud computing by bringing networking and computational resources on edge devices near to the end user. An edge device can be a router, gateway, switch, or a base station, that provides an entry point into the service providerôs core network. Edge devices are proposed to have sufficient computational and storage resources to meet real-time and resource intensive demands of end user. Generally, the edge computing platform comprises of a heterogeneous infrastructure of access points, switches, edge routers, servers, and end user devices. Compared to cloud computing, the edge provides low latency and reduced data traffic, as the applications are localized to the region where the edge is deployed.

We use the term *ñEdge Computing Technologiesò to encompass different emerging technologies situated at the edge of the network to provide computational and storage resources to deliver real-time communication with minimum latency*. Examples of such technologies include Fog computing, Mobile Edge Computing (MEC), Micro Data Centers (MDC), Cloudlet, and related technologies. The term edge computing or edge technologies used in this article refers to the set of these emerging technologies. Fog computing represents a platform that brings cloud computing to the proximity of end users [12][13]. The term Fog computing was coined initially by Cisco [13][14]. The main focus of fog computing is to equip the network edge and network devices with virtualized services, in terms of processing and storage along with offering network services. MEC is the edge technology initiated by European Telecommunications Standards Institute (ETSI) [15][16]. The major focus of MEC is Radio Access Networks (RANs) in 4G and 5G cellular networks. MEC offers edge computing by proposing a collocation of computation and processing resources at base stations. MDCs, initiated by Microsoft are small scaled version of data centers to extend the hyperspace cloud data centers [17][18]. MDCs aim to provide small size data centers extending the offered services of the cloud near to the end users. Concept of cloudlet, initiated by Carnegie Mellon University

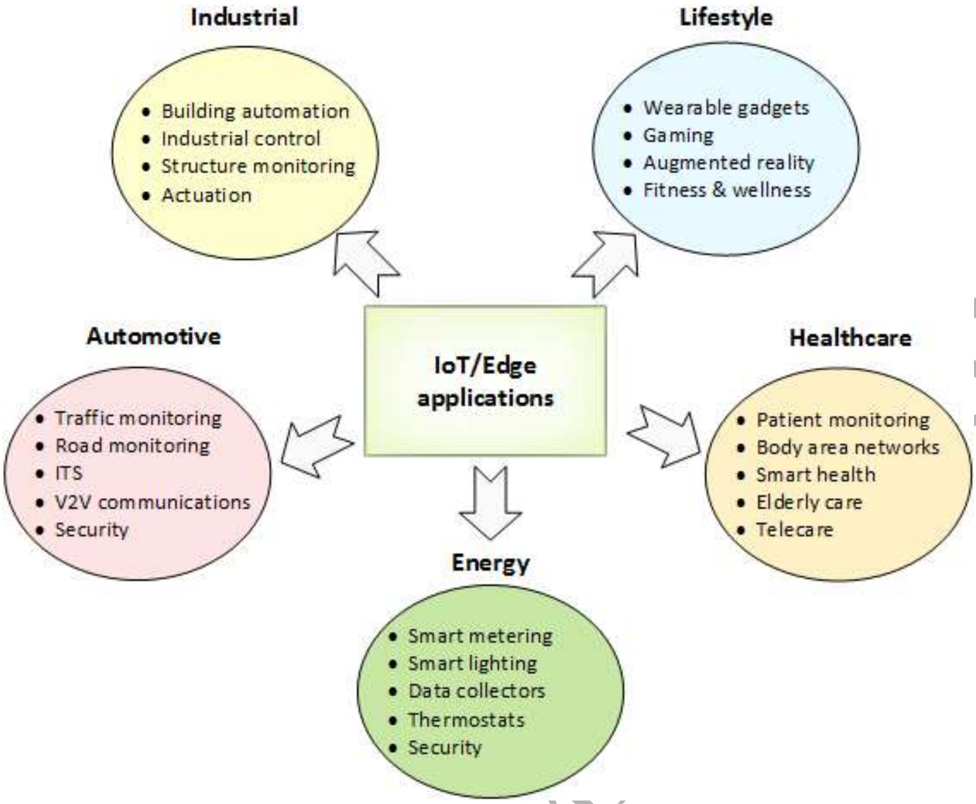


Fig. 2: Potential application areas of edge computing.

(CMU) is similar to MDC, as small scaled virtualized data center to serve users near the edge in a distributed fashion [19][20]. Some similar terms, such as Nano-data centers are also used in literature for similar concepts and objects [21][51].

Different edge technologies are defined independently; however, these technologies can cooperate and work together [12]. Considering the futuristic aspects of the Internet of Everything (IoE) [143] and recent trends in technology cooperation, such as Content Distribution Network Interconnection [22] and Heterogeneous Networks (HetNets) [144], it can be foreseen that various edge technologies will work in cooperation to support the overall vision of the IoE. Edge computing enables a large number of applications including vehicular communications, smart cities, smart grid, wireless sensor networks embedded with actuators, road traffic monitoring, pipe line monitoring, wind farms, smart traffic light system, railway monitoring, industrial control systems, and the applications in oil and gas explorations. IDC reported that by the year 2019, 45% of the data generated by IoT will be processed, stored, and analyzed on the edge [8]. Fig. 2 shows the some of the potential application areas of IoT and edge computing.

Edge computing technologies are in their infancy, with no standardized definitions, architectures, and protocols. Various researchers define edge technologies from their own perspective and models, which is expected for non-standardized technologies. A similar trend was observed in cloud computing as well before standardization of an official definition of cloud computing by National Institute of Science and Technology (NIST) in 2011 [23]. The lack of a standard definition leads to misconceptions in the relation among edge technologies, IoT, and cloud. Examples of such misconception mentioned in the literature, where authors claim that edge computing technologies will ñmoveò or ñreplaceò cloud with fog or decentralize the cloud paradigm to edges. For instance, [24] mentions that ñCloud is migrating to the edge of the network and the traditional Cloud Computing paradigm is not enough for the storage of Big Data produced by IoTò. It needs to be clearly understood that edge computing technologies should not be considered as a substitute of cloud paradigm, rather, as shown in Fig. 3, these technologies will complement cloud and extend cloud services to the edges, so that the needs of applications with real-time requirements are satisfied [25]. For the big data analytics, and lengthy, resource intensive batch jobs, the cloud is a must. Similarly, there is also a confusion in understanding and perceiving the architecture of edge technologies, for instance, some authors treat fog computing as micro datacenters [26][27], while others focus mainly on the idea of strengthening and equipping networking components with extra processing and storage capabilities [25].

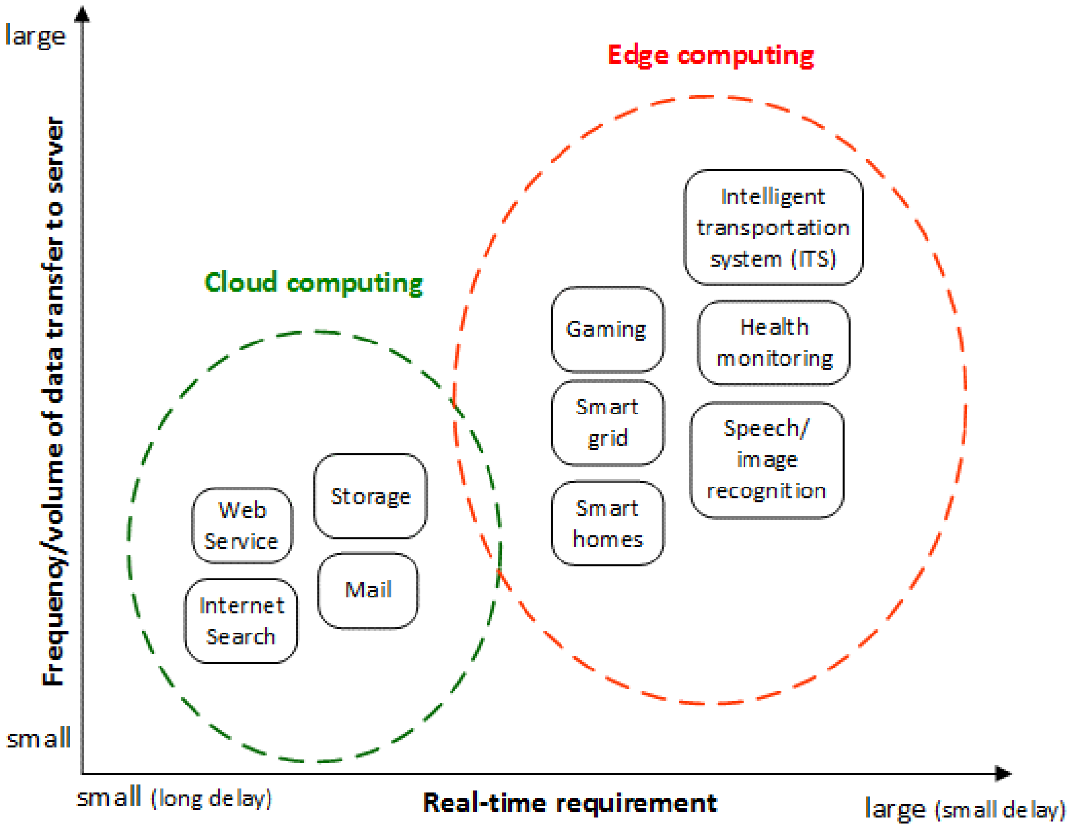


Fig. 3: The applications designed for traditional cloud computing have usually less frequent data transfer to cloud and can afford some slow response. However, the edge specific applications have more frequent interactions with edge servers and require a quicker response.

In this survey, we discuss various edge computing technologies, their potentials, applications, and challenges. Specifically, we provide a list of some potential areas in the field of edge computing (please see Fig. 4 for the taxonomy and topics discussed in this survey). The state of the art in various edge computing technologies are also discussed in the article. Some of the authors have presented various aspects of edge computing in the literature. Luan *et al.* [28] highlighted main features of fog computing including its concept, architecture, and design goals. However, the other edge technologies are not covered. In a similar study, Bonomi *et al.* [13] outlined key characteristics of fog computing and discussed the role of fog computing in the IoT. Some basic applications are also discussed in the survey. A report on edge technologies [16] discussed and briefly compared the three technologies of edge computing: mobile edge, cloudlets, and fog computing, with no discussion on potential areas and applications. Stojmenovic *et al.* [29] discussed motivation and advantages of fog computing, and considered only these application areas: smart grid, smart traffic lights, and software defined networks. The authors in [30] discussed basic definition of fog computing and similar concepts and discussed various application scenarios. However, in [30] the discussion on existing techniques on edge computing is missing. Bonomi *et al*. [13] presented a discussion on fog computing in the context of IoT. Ahmed *et al.* [31] and Beck *et al.* [15] discussed the taxonomy and key attributes of mobile edge computing. Azam *et al*. presented an article focusing on IoT and Cloud of Things (CoTs) [32]. The authors presented some of the potentials of the fog computing specifically considering the CoTs, i.e., amalgamation of IoTs and cloud computing. The authors presented various aspects of fog in consideration of edge computing as middleware to cloud, without presenting in-depth details. Dastderji and Buyya highlighted the

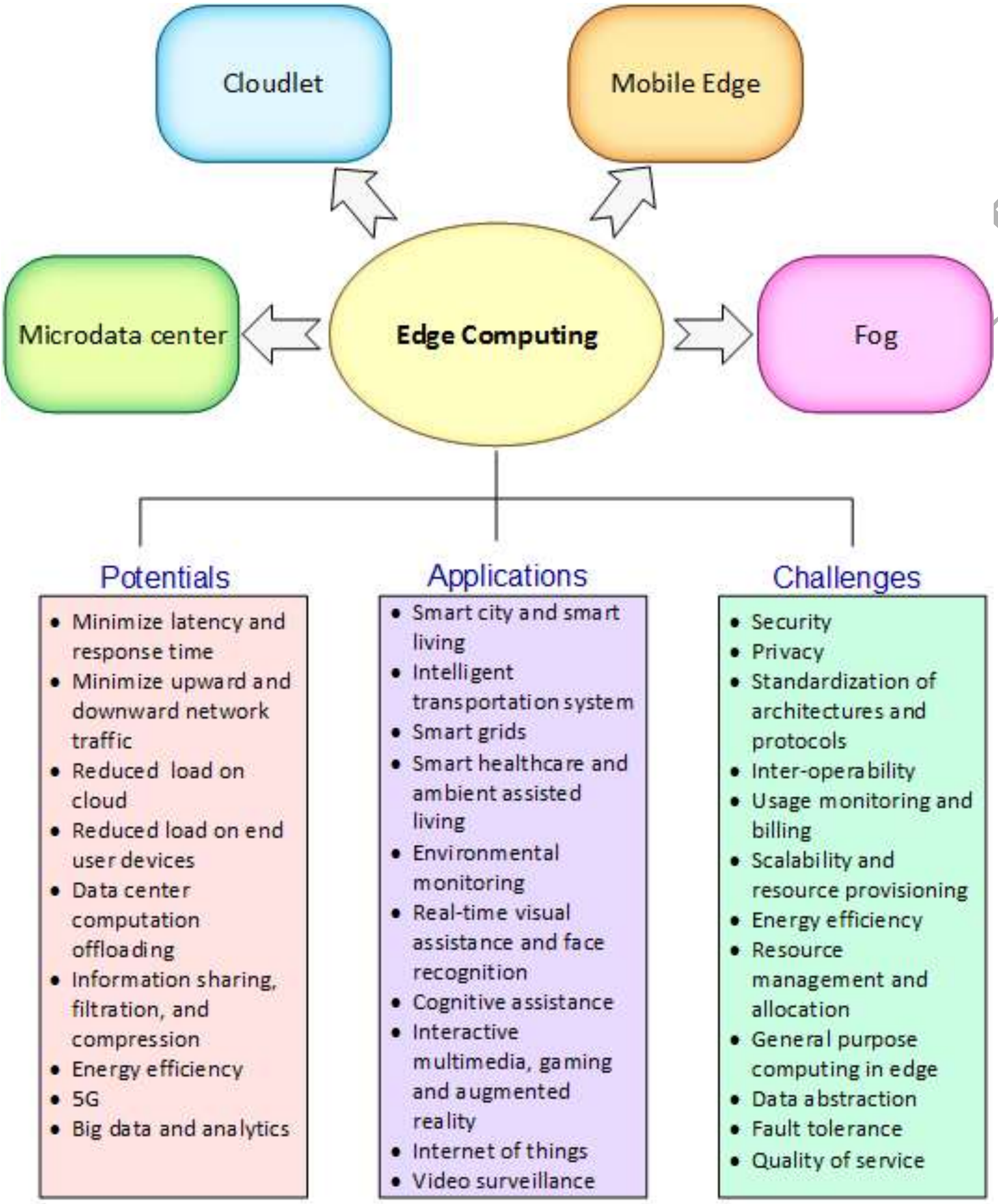


Fig. 4: Edge computing potentials, applications, and challenges

potentials of fog computing for IoTs [33]. The authors briefly presented how fog computing may impact IoT systems to work better in a real-time environment and how it can save unnecessary transit traffic. The authors presented generic fog computing architecture and fog based distributed data processing models, and discussed various components involved in the model. Yi *et al*. presented an overview of various concepts, applications, and issues in fog computing [30]. The authors in [34] discussed motivational scenarios of fog computing and provided some simulation results. Shi *et al.* [7] have discussed a few case studies of edge computing along with challenges and opportunities. The authors in [35] presented a limited discussion on motivation, challenges, and opportunities of edge computing, without discussing the other edge technologies.

Most of the above mentioned surveys discussed various characteristics and applications of edge computing technologies in limited and isolated way. However, detailed study on various edge computing technologies, their potentials, applications, challenges, and the state of art, still needs to be addressed. Our survey attempts to address deficiencies in the existing surveys and provides a focused study on various edge computing technologies, their challenges, potentials and applications. To the best of our knowledge this is the first survey that provides in-depth details pertaining to edge computing and its various trends and potential areas. Moreover, this survey also presents state of the art in edge computing, which is missing in most of the existing surveys. Specifically, our contributions in this survey are as follows. In Section 2, we present an introduction of edge computing technologies and some motivational scenarios, followed by details of various edge computing technologies, i.e., Fog, Cloudlets, MDCs, and MECs. Section 3 presents a detailed study on the edge computing potential and most recent works in those areas and applications. Moreover, a detailed explanation on edge computing architectures, implementations, and evaluation mechanisms is provided. Section 4 highlights the open research challenges in the edge computing technologies, followed by conclusions in Section 5.

2. EDGE COMPUTING TECHNOLOGIES

The edge computing is based on the idea of placing small servers called edge servers or resource rich networking devices in the vicinity of end users/devices (see Fig. 5). In this way, some of the computational and data storage load is transferred from cloud platform to the edge servers. The end usersô devices usually consist of wireless sensor networks, smart phones, wearable gadgets, and various IoT devices that require real-time response. Deploying computation and storage resources at the edge of the network can enable a large number of applications that require real-time response. A few examples of such applications include, but not limited to: (a) traffic monitoring and navigation, that involves traffic reporting and computation of routes for a specific region near to the edge, (b) data filtering and aggregation, that performs pre-filtering of content and data at edge before sending it to cloud to reduce the data volume, and (c) augmented reality, real-time interactive video streaming, and health monitoring systems that can produce fast responses using edge nodes, thereby improving user experience for time-sensitive applications. In this section, first we discuss some motivational use cases and scenarios indicating why we should use edge computing in addition to cloud. Later, we explain various technologies within the domain of the edge computing.

2.1. Edge computing motivation

2.1.1. Reduced traffic load

The traditional User-Internet interaction model involves short requests from user to Internet services and receiving response. Some of the requested services, e.g., file downloading and specifically, Video on Demand (VoD) or live video streaming are comprised of very small data requests from user to the Service Provider (SP), and large volume of data flowing from SP to users. Considering the gigantic amount of data flowing from Internet to users, various solutions have been employed, such as CDN and caching to minimize the data and delay from SP to user [145]. For instance, cacheable contents are cached at ISP caches or CDN networks to minimize transit network data flow and delay [146][147][148]. However, the advent of new technologies, gadget proliferations, smart environments, and IoE are changing the data flow paradigm and patterns. Futuristic vision of smart and pervasive environments is foreseen to transmit massive volumes of data to the Internet. Consider live streaming, specifically crowd-sourced live streaming as an example, significant amount of data per second now flows from the users to SP and then disseminated globally from various SPs, such as Twitch (a crowd-sourced live gaming system) [149], YouTube Live [150], Periscope [151], and YouNow [152]. Netflix hosts a huge collection of entertainment video content. If 10% of 8 million people in New York want to stream movies from Netflix at the same time, it would require an infrastructure capacity of 1.6 Tera bits per second (Tbps) to handle all requests in parallel [36]. Despite remarkable improvements in bandwidth and server- side processing, the networks may still suffer in performance with huge viewership spikes. For instance, in a recent boxing match held in Las Vegas, USA, the live video streaming pay-per-view servers crashed and network got congested due to sudden rise in viewership [156]. If CDNs are not deployed within the networks, then the centrally hosted content must travel through many networks to reach the end users. In the futuristic scenario, current CDN based content delivery model is expensive, because, data still has to travel many hops between CDN and Internet Service Provider (ISP), before reaching to viewersô. For instance, consider the scenario of European football tournament final match, where the Akamai network served 3.3 million video streams concurrently to viewers, experiencing a peak load of 7.3 Tbps [142]. If multicast is not enabled, which is the general case because of configuration and security issues, then 5.7 Tbps data passing through multiple hops between CDN and ISP results in significant energy consumptions and network cost and management. Moreover, CDNs are passive

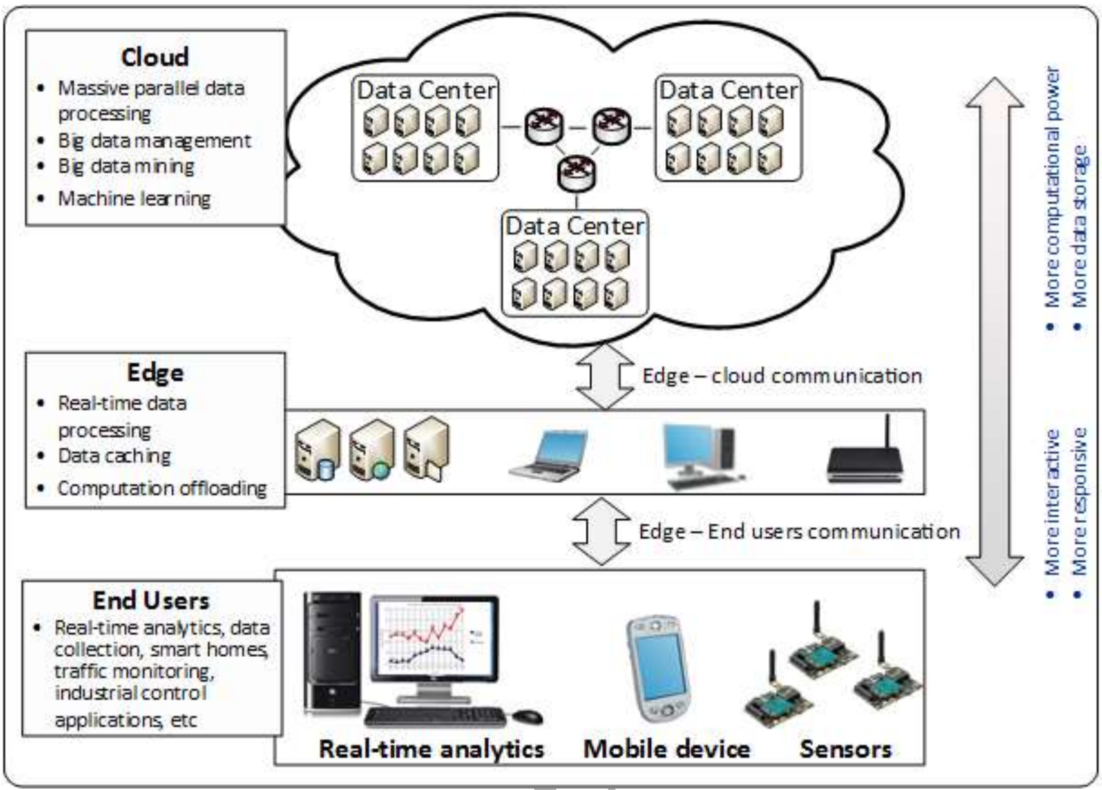


Fig. 5: Edge computing architecture.

storage designs, hosting large volumes of data, with generally no or very limited processing capabilities. On the fly transcoding of the videos are not available in the current CDN designs. Edge computing technologies offer a feasible solution in terms of very small delay and data filtration to fulfill the futuristic IoT, IoE, and smart world visions. If edge locations are used as data delivery and sharing points, huge volumes of transit data between CDNs and network edge can be saved [169]. Caching at the mobile edge (base stations/eNodeBs) may save considerable amount of backhaul network traffic. It has been shown that caching at the edge of the network considerably reduce access latency and network traffic [170]. Edge locations can perform on the fly video transcoding to create required video representation versions, minimizing the storage requirements, minimizing access delays, and maximizing viewersô QoE. Moreover, edge technologies may host dedicated services at edge to provide real-time response and data filtration. For instance, Akamai network have deployed edge computing networks to provide distributed execution of Java applications [37].

2.1.2. *Minimizing the latency*

The inherent cloud computing delays are challenging for applications that require real-time response, e.g., intelligent transportation systems, games, live streaming applications, and other safety critical applications, where such delays are intolerable. It is studied in [41] that for real-time visual guiding services, the preferred response time is between 25ms to 50ms. Moreover, high processing load imposed on cloudôs central servers may cause scalability problems for the compute intensive applications and increase network overhead, resulting in slow response time and excessive utilization of the Internet bandwidth [42]. Inter-network data transfer leads to increased latency and congestion. Generally, Internet comprises of thousands of interlinked networks, with each network providing access to a small percentage of end users. Even largest networks are usually accessed by only about 5% users [37]. As per statistics collected by Akamai, over 650 networks participate in reaching 90% of all access traffic [37]. A request to/from cloud may take several milliseconds to seconds to travel from client to cloud service provider [38]. Even a slight delay in a userôs request may lead to the loss of subscribers and revenue. For instance, it was reported by Bing that a reduction of -1.8% in queries per user and -4.3% in revenue per user was observed due to queries slowing down by an interval of just 2 seconds [39]. A survey conducted by Forester concluded that majority of the online shoppers

Table 1: Effect of distance on round trip time (RTT), packet loss, throughput, and down time [37]

Distance (Server to User)	Network Round Trip Time	Packet Loss	Throughput	4GB download time
Local: <100 miles	1.6 ms	0.6%	44 Mbps	12 min
Regional: 500 ï 100 miles	16 ms	0.7%	4 Mbps	2.2 hrs
Cross-continent ~ 3000 miles	48 ms	1.0%	1 Mbps	8.2 hrs
Multi-continent ~ 6000 miles	96 ms	1.4%	0.4 Mbps	20 hrs

have suggested the website response time as a primary factor in giving their customer satisfaction feedback [37]. The survey also found out that more than 40% of the customers can only wait for 3 seconds for a page to load before leaving the website [37]. In another survey conducted by IDC, it was reported that improvement in performance and reliability of Akamaiôs enterprise application acceleration services yielded an annual increase from 0.2 million to 3 million dollars [40]. Therefore, content deployment at local ISPs (network edge) is critical for areas with low connectivity and high response time [37]. Recently, increasing number of ISPs have opened their edge services to other providers and subscribers, and offer various edge-based solutions, such as cloudlets, network functions virtualizations, and mobile edge computing. Table 1 shows that edge provides low latency and reduced data traffic, as the applications are localized to the region where the edge is deployed.

2.1.3. Reduced load on cloud

With the increase in location aware services, huge volumes of data is generated by end user devices on daily basis. For instance, the location-based service Foursquare has 60 million registered users [43] and it receives on the average, >5 million check-ins per day [44]. Similarly, several sports activity logging applications, such as Nike+ [45], Runtastic [46], Runkeeper [47], and Endomondo [48] are becoming popular. These applications run on smartphones and log daily activities of users with the help of various sensors, e.g., accelerometers, GPS, gyroscope, and temperature sensors, typically installed on smartphones. Mostly, the data recorded by the applications is sent to the cloud in the form of tuples, where each tuple contain several pieces of information, such as user id, longitude, latitude, time, distance, speed, duration, calories, weather, and other related items. For instance, a recent study on Endomondo revealed that a single workout on the average generates 170 GPS tuples, and average number of tuples generated per month is between 2.8 and 6.3 billion [49]. With 30 million users, the number of tuples generated per second could reach 25,000 tuples/sec [49]. Considering the IoT enabled smart cities, with thousands of sensors deployed, the numbers of tuples generated per second would be many times higher. When such high velocity real-time data streams will be sent to the centralized cloud servers, the backbone network will get congested and the cloud servers may get overburdened. Moreover, not all of the sensed data is useful. For instance, sensors deployed in Large Hadron Collider (LHC) project generate around 500 Exabyte data per day. However, 99.999% data is filtered out [49]. Edge computing can be leveraged by the application providers to locally process the data to filter unnecessary data, and generate real-time response for the users in the vicinity of the deployed edge. Moreover, data can be trimmed/filtered before sending to the cloud, thereby reducing the network traffic and processing burden from cloud servers.

2.1.4. Reduced load on end user devices

As discussed earlier, the end user devices and IoT generate huge volumes of data on which some form of analytics needs to be performed to generate useful information. However, if end devices, such as smartphone are subjected to such complex tasks, they may sooner run out of resources, e.g., battery drainage. Moreover, the devices may not be compatible due to heterogeneity of technologies. Therefore, the end devices can offload some of their high processing tasks to the nearby edge to reduce their load. Moreover, not all the data generated from the end device may contribute in the computation of useful information. For example, the study conducted on Endomondo sports activity tracking application revealed that even if a jogger stops to take rest, his sensorsô stores the same values at regular intervals [49]. Therefore, some form of data filtering can be employed on the edge to discard the redundant data and only filtered data is sent to the cloud. Similarly, in interactive multimedia applications, such as free-view video, clientôs device is generally used to perform complex tasks like virtual view generation, which are resource intensive and results in battery depletion [87]. Performing such resource intensive jobs at the edge of the network, and delivering synthesized virtual view may result in significant bandwidth and energy savings at clientôs device.

2.1.5. Reducing energy consumption

Generally, the end user mobile devices and IoT are constrained by computing capabilities, battery life, and heat dissipation. Edge computing enables the offloading of energy consuming application from resource constrained end user devices to the edge servers. The majority of algorithms aim to minimize the energy consumption at the mobile device while subject to the execution delay acceptable by the offloaded application, or to find an optimal tradeoff between these two metrics. The energy consumption in using a cloud service usually depends on the following factors [51]: (a) energy consumption of end user device accessing the service, (b) energy consumption of data center, including energy consumed by internal network, storage, and servers, (c) the volume of traffic exchanged between the user and cloud, (d) the computational complexity of the task to be performed, (e) factors such as the number of users sharing a compute resource, and (f) the energy consumption of the transport network (aggregation, edge, and core networks). Costenaro *et al.* studied energy consumption due to data transportation on the internet. The authors found out that 14% of the energy consumption in the Internet is due to the data transportation [50]. Jalali *et al.* performed a detailed analysis of energy consumption by certain cloud-based applications, when those applications are run directly on cloud and on locally deployed fog based nano data centers [51]. The authors showed that online interactive applications generate a substantial amount of traffic and consume more energy due to overheads arise from real-time interaction with the Cloud. The authors used various network analyzing tools to acquire traffic logs that showed the large traffic overhead is associated with establishing/tearing down TCP sessions very frequently and the volume of data transported to and from the user per session (measured in tens to hundreds of Kilobytes). The authors recommended that the fog based nano servers can complement the cloud for certain applications that can lead to energy savings, if the application or its components can be offloaded from centralized data centers and run on nano servers. Moreover, energy can be saved by employing intelligent client-side caching techniques, and optimizing the synchronization frequency of contents between edge and cloud [51]. Furthermore, data caching at edge locations reduce burden on the core network, which enable to reduce link rates using green technologies like Adaptive Link Rate (ALR) to make links energy proportional [4].

2.1.6. Data center computation offloading

Edge computing can also be exploited to offload computation from data centers that require limited resources to the edge nodes. For example, the live streaming applications, like Facebook Live, YouTube Live, and Livestream [153] allow users to perform live broadcast. It is reported that during a period of one minute, YouTube users upload 72 hours of new video, Facebook users share 2,460,000 pieces of content, WhatsApp users share 347,222 photos, Instagram users post 216,000 new photos, and Vine users share 8,333 videos [52][7]. Usually, when a video or photo is uploaded, e.g., to Facebook or YouTube, it is subjected to lossy compressions to reduce the media size. Uploading the high resolution photos and videos from user devices to the cloud occupy lots of bandwidth and may take lot of time in areas where internet connectivity is poor. Similar issues arise in live health monitoring applications, or smart city applications where live streams of data from surveillance cameras and other sensors needs to be uploaded to cloud. Edge computing can be utilized to transfer some of the compression related tasks to the edge devices near to the end users, before uploading to the cloud. Moreover, edge can also be used to encrypt the user data instead of uploading the raw data to the cloud, thereby ensuring security and privacy of user data in the intermediate hops.

In the next subsection, we discuss various technologies that we covered under the domain of edge computing. We discuss characteristics, similarities, and dissimilarities of these technologies, along with some practical examples.

2.2. Edge computing technologies

2.2.1. Fog

boxes to improve the website experience. The users connect with the internet via edge servers (fog boxes) using HTTP. The fog boxes perform various optimizations to reduce latency.

Table 3: Summary of edge computing architectures, resource management, evaluations, and simulations

Area/Application	Reference	Idea presented
Edge Computing Architectures	[120]	Zhang et al. presented a multi-tiered architecture for delay sensitive cloud Data Service Subscribers (DSS). Three considered tiers are DSS, Massive Data Centers (MDCs), and Fog instances.
	[121]	Eui-Nam et al. presented an architecture of a smart gateway with fog computing. The proposed architecture had several layers, such as physical and virtualization layer, monitoring layer, preprocessing layer, transport layer
	[126]	Zeng et al. proposed a fog computing supported software-defined embedded system (FC-SDES). Task scheduling problem is investigated in FC-SDES. The system consists of edge devices equipped with computation and storage resources and embedded client systems are general purpose hardware.
	[129]	Proposed an architecture of Fog nodes as an IoT hub using CoAP protocol. Fog node can be placed at the edge of the network to interact with multiple physical IoT networks.
	[25]	Sarkar and Misra presented theoretical modeling and mathematical formulation of fog computing architecture considering its various components. The authors carried out a comparative analysis of fog model with cloud computing considering service latency and energy consumption.
Edge Computing Resource Management	[120]	Resource management is achieved using Game programming. Multi-leader, multi-follower Stakelberg games are used for interaction between fog and MDCs, and single-leader single-follower Stakelberg game between DSS and MDCs are implemented.
	[122]	Yin et al. proposed Tentacle, a dynamic and on the fly resource provisioning algorithm to procure edge servers for online service providers. The framework identifies the best location based on the usersô proximity and service requirements considering the Network Coordinate (NC) system based ranking.
	[26]	Azam and Hu presented a service oriented strategy to effectively and efficiently manage resources in fog computing. The authors considered a customer based resource estimation model considering various traits of customers. In their model, Cloud Service Customer (CSC) and fog negotiate for resource requirements to provide specific services and SLA.
	[27]	The authors categorized IoT devices based on devicesô mobility and nature to efficiently perform resource allocation. A detailed pricing model was also discussed
	[123]	Do et al. proposed a resource allocation algorithm to optimize the traffic distribution between fog and data center for video streaming applications
	[26]	A service oriented model for resource management within IoT devices is proposed that utilized fog computing for fair management of resources and addresses issues related to resource management, such as resource prediction, resource estimation, advance reservation, and pricing.

	[122]	Dynamic edge service provisioning and its prospects are discussed in this proposal.
Edge Computing Evaluation	[121]	Eui-Nam et al. used a testbed to evaluate the performance of their architecture by analyzing the communication between gateway and the cloud. The performance parameters were upload delay, bulk-data upload delay, synchronization delay, and bulk-data synchronization delay.
	[128]	Butterfield evaluated Googleôs Go language for IoT and fog scenario. The results depicted that Go language can be used to implement fog architecture for IoT solutions. The authors used RPi for prototype implementation and detailed simulation.
Edge Computing Implementation	[124]	Nippon Telegraph and Telephone Corporation (NTTC) developed an edge accelerated web platform (EAWP). The EAWP enables edge support for web applications. The userôs device is relieved of processing the whole application, as the loads are distributed close to the user on the edge servers.
	[26]	A service oriented model for resource management within IoT devices is proposed by Aazam et al. The implementation of the proposed work is performed in java, whereas the model was evaluated with CloudSim simulator.
	[129]	The authors implemented the Fog node using Californium, which is a java based CoAP implementation. Fog node implements various protocols and act as CoAP server to perform various functions, CoAP and HTTP gateway for inter-communication, and caching.
	[132]	The authors proposed a MEC based programming framework CloudAware that allowed the users to offload their compute-intensive tasks from smartphones to the edge servers. This facilitates the users to speed-up the execution and develop scalable and elastic mobile applications for mobile edge.
	[133]	Ciscoôs ParStream is a platform that allows handling of massive volumes of high-velocity data to provide real-time analytics at the edge.
	[134]	Vortex fog computing provides platform independent interoperable solutions for embedded, mobile, and enterprise environments, thereby targeting areas such as healthcare, energy, transportation, and industrial automation.
	[53]	Cisco Data in Motion (DMo) technology allows data management and analysis of large volumes of data coming through IoT at the edge. The DMo is based on extensible, scalable, and modular architecture and is designed to capture real-time data and control flows, translating data into information for use by higher order applications within the system.
	[135]	Cisco IOx is an application environment that is a combination of Cisco IOS, a network operating system, and Linux. The IOx allows hosting capabilities for fog applications, and allows management of network components, such as routers, switches, and compute modules.
	[124]	Nippon Telegraph and Telephone Corporation (NTTC) developed an edge accelerated web platform (EAWP). The EAWP enables edge support for web applications. The userôs device is relieved of

		processing the whole application, as the loads are distributed close to the user on the edge servers.
	[125]	Zhu et al. [125] proposed the concept of fog boxes to improve the website experience. The users connect with the internet via edge servers (fog boxes) using HTTP. The fog boxes perform various optimizations to reduce latency.
Edge Computing Simulation	[130]	Gupta et al. presented iFogSim, a simulation environment focusing on evaluation of resource management strategies for fog computing. The simulator evaluates the impact of resource allocation on energy consumption, latency, operational cost, and network congestions.

For instance, the fog boxes perform caching of the content and reduce the size of HTML objects in case the network is slow. In case of network congestion, the fog boxes reduce the graphicsô resolutions, thereby maintaining the acceptable response times for end users.

To summarize, we presented numerous state of the art architectures, implementations, and simulation models/platforms for edge computing. It can be observed from the above discussion that because of a relatively new technology and in its evolutionary phase, the edge computing lacks any standard architecture and simulation platform. Most of the above discussed architectures and implementations are specialized, i.e., they target specific application scenarios and with aims to optimize various parameters, such as latency, response time, and energy consumption, etc. Moreover, there is yet to exist a complete simulation platform for edge computing that can be configured with numerous architectures and edge based pricing models. In Table 3, we present a summary of various state of the art edge-based architectures, implementations, and simulations. Next section presents the various challenges faced in adoption of edge computing technologies.

4. EDGE COMPUTING CHALLENGES

Being a new technology, edge computing faces numerous challenges, in addition to the challenges it inherits from cloud computing. Most of the challenges faced by edge computing is due to the non-standardization of edge technologies. In this section, we highlight some of the important challenges of edge computing that pave the path for future research in the edge technologies. Table 4 presents a summary of research works in the areas selected.

4.1. Resource Management and Allocation

Some generic edge architectures and resource allocation and management mechanisms have been proposed in the literature. However, in-depth and detailed analysis and testing is still missing. In [117], a comparison of computation and communication latency is presented. It has been observed that computational latency may increase based on the current load of the fog server. Therefore, appropriate resource management and allocation is a key. For time critical and real-time system, priority-aware computation is required in Fog instances. Delay sensitive tasks may be marked as high priority, and fog node needs to handle such requests immediately. Appropriate cost model also needs to be formulated and designed, where extra charges may be received from priority jobs in case of high load. Cloud providers already depict such cost model, where the cost incurred during peak hours is different from off-peak hours. For instance, Amazon costs different for scheduled Reserved Instances in peak and off-peak hours [136]. No standard, detailed, and realistic design is available to standardize edge computing architecture, resource management, cost models, and interaction with cloud [65]. Some of the initial and simple architectures have been proposed, however, they lack practical implementation and resource management aspects [65]. One of the challenges is to identify the edge provisioning site based on the dynamic number of users and application demands. Edge site provisioning mandate two basic requirements: (a) good proximity between users and edge servers and (b) sufficient capacity to serve user demands [122]. Workload allocation is another challenge because of the complex real-time decision making involved about putting how much workload on each edge layer. If too many edge layers are involved, the latency may reach cloudôs latency, or even greater. The workload allocation strategy needs to balance various conflicting objectives, such as latency, bandwidth, energy, and cost. Some metrics need to be prioritized over others, and optimization must be performed dynamically making the task challenging.

4.2. General Purpose Computing in Edge

An important consideration is to enable General Purpose Computing (GPC) in edge technologies. For instance, base stations are equipped with customized Digital Signal Processors (DSPs) for specific tasks and workloads, which are unsuitable for GPC [35]. Moreover, base stations are not considered suitable because of cost and architectural concerns to be used for GPC [64]. Furthermore, existing edge computing software solutions, such as Cisco IOx [135] and Nokia software solution [137] are specialized solutions designed from specific hardware and are unsuitable in heterogeneous edge environments. Considering general purpose processors to be used in base stations or routers or other edge devices require heavy investments and may pose performance concerns [35]. Being in its infancy, there are very limited insights in edge to cloud interaction models. Edge resources or services may act as a proxy on behalf of user, or act as a forwarding agent in case edge is unable to service the usersô request. As edge instances also cache data, therefore, appropriate models for synchronization and updates is also required. The programming models for edge will require task and data level parallelism to support real-time applications. The programming languages involved in programming models will need to take into account the diversity and heterogeneity of devices. These requirements are different from traditional cloud computing where the use cases are well defined and most hardware and software frameworks are compatible.

4.3. Security and Privacy

One of the major challenges in deployment and adoption of edge computing paradigm is privacy and security. Edge computing implementations in terms of size and investments are way smaller than cloud infrastructure and way more in terms of number and granularity. The organizations offering small edge computing solutions belonging to small businesses are less interested in investing in security and privacy infrastructure [138]. Moreover, at the core of the edge computing are the enabling technologies, such as peer-to-peer systems, wireless networks, distributed systems, IoT, and virtualization platforms. To secure edge, all the aforementioned technologies must be secured while keeping in consideration that the interoperability and integration of devices should not be compromised. Addressing the security of cloud is comparatively easier than edge because of the centralized nature and a single controlling authority of cloud paradigm. In edge, the services migrating from one device to other, or from one edge to another edge deployed by different vendors can create vulnerabilities, and security provisions in this regard are not widely studied. All the privacy concerns related data transfer from user to edge and from edge to cloud must be taken into account. The user devices may not be resourceful enough to run complex cryptography algorithms to encrypt the data. Similarly, the edge devices may consist of micro servers (e.g., fog made of raspberry pi computers), which may take longer to encrypt data, thus increasing the latency. More importantly, most of the end users usually are not aware of privacy and security, so there must be some automatic mechanisms ensuring run-time privacy of user data. For instance, in a survey, it was revealed that 80% of Wi-Fi users have their wireless routers set on default password out of 439 million subscribers, and 49% user networks are unsecured [7]. Moreover, 89% of public Wi-Fi hotspots are unsecured [7]. It is reported in [9] that by year 2020, 10% of all the attacks will target IoT systems. It is also critical to isolate a userôs private data from other data collected by third party applications. For instance, an activity tracking application should not be able to access the electricity usage data of a user [7]. The specific data control access mechanisms should be implemented on edge frameworks to ensure data privacy.

Edge computing can also act as a middleware to secure the data at edge before sending it out to the Internet and cloud [65]. IoT devices being lightweight with limited battery, processing, and storage, are not suitable to perform security related tasks, such as encryption. However, security and privacy being one of the utmost concerns in Cloud of Things (CoT) paradigm, edge computing inherently can offer a middle tier to secure the data before sending to cloud, offering a convenient solution to resource constrained devices. Stojmenovic *et al.* [139] discussed the security and privacy issues of fog computing. The authors studied the effects of man-in-the-middle attack on fog computing, and discussed the consequences of this attack on CPU and memory consumption of fog devices. Rodrigo *et al.* [140] presented a detailed survey on security threats and challenges on mobile edge, and fog computing. LocalGridôs fog computing platform provides standardizations and secured end-to-end data communications from edge devices to cloud [141].

4.4. Scalability

Cloud computing utilizes resource from multiple data centers with tens to hundreds of thousands of serves. However, edge technologies are very high in number, and possess small number of computation and storage resources. Resource overprovisioning is infeasible because of the cost and energy concerns. Therefore, scalability and rapid resource provisioning is of significant importance. Considering the limited resources and delay sensitive services in edge computing domain, timely provisioning of resource to service the request is vital. In case of non-availability of resources, time critical applications, specifically services related to healthcare and emergency evacuation may have catastrophic impact. Similarly, user interactive and multimedia related applications cannot tolerate extra delay for waiting or request forwarding to nearest edge service. Therefore, necessary resource provisioning strategies, and priority based provisioning are required to be discussed by research community.

4.5. Data abstraction

One of the important challenges of edge computing is data abstraction. Data abstraction is the preprocessing and trimming of data at edge before sending the data to cloud. The IoT devices produce huge volumes of data. Sending such large datasets to cloud will lead to the congestion of both the backbone network and overburdening of datacenters.

Table 4: Summary of edge computing work in various areas as presented in Section 4.

Area/Application	Ref	Idea presented
Resource Management	[117]	A comparison of computation and communication latency is presented. It has been observed that computational latency may increase based on the current load of the fog server. Therefore, appropriate resource management and allocation is a key.
	[157]	A cost efficient resource management scheme is presented for fog computing supported medical cyber physical systems (FC-MCPS). The base station association, task distribution, and virtual machine placement is investigated jointly. Problem is formulated into a mixed-integer non-linear programming and linearized to mixed integer linear programming.
	[158]	A hierarchical game framework for resource management in fog computing is proposed. A three-layer hierarchical game framework to solve challenges in fog computing is designed. Stackelberg sub-game is used for interaction between data server operators and fog networks. Matching sub-game is used for the interaction between fog networks and authorized data service subscribers.
	[159]	A fog computing structure presented along with crowd-funding algorithm to integrate spare resources in the network. Incentives mechanisms are implemented to encourage owners to share their resources.
General Purpose Computing	[160]	Designed SONM'S secure and cost efficient fog supercomputer for general purpose computing, from mobile app hosting to video rendering and DNA analysis. Users all over the world can leverage their idle computer power to become part of SONM network.
Security	[161]	Proposed a security technique called Encrypted Data Flow Mechanism (EDFM) based on the concept of Fog computing to secure cloud storage from unauthorized/illegal access. The simulated environment utilizes a fog data center called Broker to hide the actual cloud storage underneath it.
	[162]	Proposed various potential threats to IoT fog, and existing security measures to mitigate those threats.
Scalability	[163]	The paper proposed a fog computing paradigm that utilizes busesô network for service offloading. The bus based fog servers provide fog services to passengers, as well as perform computation offloading to road side cloudlets. Allocations are performed using genetic algorithm (GA).
Data abstraction	[121]	Azam et al. proposed a smart gateway architecture for cloud computing. The gateway performs data collection, preprocessing, filtering, and reconstruction of data into useful form, and uploads only necessary data to the cloud.

The data should be preprocessed and filtered at edge device to remove noise, low quality data, and for privacy protection (by truncating the unauthorized data). However, the data abstraction impose several challenges. If too much trimming of data is performed, this may result in the loss of some useful information, thereby reducing the precision/accuracy of data. If data is subjected to less trimming, unwanted data may also be sent towards cloud causing extra burden on resources. Azam *et al.* [121] proposed a smart gateway architecture for cloud computing. The smart gateway can either be directly connected with the IoT devices using single-hop link, or multiple IoT devices are connected with base stations and sink nodes, which in turn are connected with gateway. The gateway performs data collection, preprocessing, filtering, and reconstruction of data into useful form, and uploads only necessary data to the cloud.

4.6. Fault Tolerance and Quality of Service

Maintaining acceptable levels of QoS and fault tolerance is an important issue in edge computing. Due to distributed nature of edge, the existing methods of fault tolerance in cloud will not be applicable to edge computing. The edge is primarily designed for real-time applications, so the fault tolerance should be proactive and there must be automatic recovery from faults. The edge devices should not be overburdened so that the minimum level of QoS must be maintained. Therefore, a proper monitoring mechanism should be deployed that inspect the peak hour usage of edge nodes, thereby facilitating the task partitioning and scheduling in flexible manner. Another challenge in maintaining QoS in edge computing is when multiple edges are involved in collaboration, also known as collaborative edge [7]. For instance, such scenario may occur when a user moves from the area of coverage of one edge to another edge. In this case, the user data must be available on the other edge node. A solution to this issue is to cache user data on multiple edges in collaboration. However, this will raise the issue of increased traffic among participating edges. Therefore, optimal data placement and replication strategies needs to be designed that reduce the latency and traffic, within minimum acceptable thresholds of QoS.

5. CONCLUSIONS

This survey discussed in detail the emerging technologies and the state-of-the-art in edge computing and its various applications. With the multifold increase in IoT enabled devices and their applications, especially those that require near real-time response, the traditional cloud computing paradigm faces numerous challenges in terms of latency, scalability, and computation. The cloud data centers are deployed at far places due to which response time could be a few milliseconds to few seconds. Moreover, the user application may be generating large volumes of data to be sent to cloud that may cause significant overhead on backbone network. Edge computing is solution to the aforementioned problems, as it brings the computational and storage resources closer to the end user devices, and reduce burden on cloud. The edge computing technologies discussed in the survey are: fog, cloudlets, micro datacenters, and mobile edge. The aforementioned technologies have some basic differences, but they are all based on the same idea having similar objectives, i.e., to bring the computation and storage resources at the edge of the network near the end users. As a key contribution, a comprehensive list of the potentials, applications, architectures, and evaluations are also presented in the survey, along with the state of the art in the aforementioned. In the end, some of current challenges of edge computing are discussed.

As a future work, we aim to develop a simulator for edge computing that will allow users to model the three layers: (a) IoT layer, consisting of heterogeneous IoT devices, (b) edge layer, consisting of networked edge servers, and (c) cloud layer, connected with edge and backbone network. The users will be able to test their applicationsô efficiency in terms of response time, energy consumption, latency, and computational resources usage. We also aim to design and integrate a billing model with the simulator that will allow researchers to design and test their applications that generate maximum revenues at service providerôs end with reduced price for customer without compromising the QoS parameters and given set of constraints.

Acknowledgement

This publication was made possible by NPRP grant # [8-519-1-108] from the Qatar National Research Fund (a member of Qatar Foundation). Samee U. Khan's work was supported by (while serving at) the National Science Foundation. The findings achieved herein are solely the responsibility of the author[s].

References:

[1] K. Bilal, S. U. R. Malik, S. U. Khan, and A. Y. Zomaya, ñTrends and Challenges in Cloud Data Centers,ò *IEEE Cloud Computing*, vol. 1, no. 1, pp. 10-20, 2014.

[2] K. Bilal, S. U. R. Malik, O. Khalid, A. Hameed, E. Alvarez, V. Wijaysekara, R. Irfan, S. Shrestha, D. Dwivedy, M. Ali, U. S. Khan, A. Abbas, N. Jalil, and S. U. Khan**,** ñA Taxonomy and Survey on Green Data Center Networks,ò *Future Generation Computer Systems*, vol. 36, pp. 189-208, 2014.

[3] K. Bilal, S. U. Khan, and A. Y. Zomaya, ñGreen Data Center Networks: Challenges and Opportunities,ò in *11th IEEE International Conference on Frontiers of Information Technology (FIT)*, Islamabad, Pakistan, December 2013, pp. 229-234.

[4] K. Bilal, S. U. Khan**,** S. A. Madani, K. Hayat, M. I. Khan, N. Min-Allah, J. Kolodziej, L. Wang, S. Zeadally, and D. Chen, ñA Survey on Green Communications using Adaptive Link Rate,ò *Cluster Computing*, vol. 16, no. 3, pp. 575-589, 2013.

[5] Z. Chen, L. Jiang, W. Hu, K. Ha, B. Amos, P. Pillai, A. Hauptmann, M. Satyanarayanan, ñEarly Implementation Experience with Wearable Cognitive Assistance Applicationsò *Proceedings of WearSys 2015*, Florence, Italy, May 2015

[6] O. Fratu, C. Pena, and R. Craciunescu, ñFog Computing System for Monitoring Mild Dementia and COPD Patients,ò *12th International Conference on Telecommunication in Modern Satellite, Cable and Broadcasting Services (TELSIKS)*, pp: 123ï128, 2015

[7] W. Shi, J. Cao, Q. Zhang, Y. Li, and L. Xu, ñEdge Computing: Vision and Challenges,ò *IEEE Internet of Things Journal*, vol. 3, no. 5, pp. 637-646, 2016

[8] IDC FutureScape: Worldwide Internet of Things 2016 Predictions, ñhttps://www.idc.com/research/viewtoc.jsp?containerId=259856ò accessed on January, 2017.

[9] IDC FutureScape: Worldwide Internet of Things 2017 Predictions [online]. Available: https://www.idc.com/research/viewtoc.jsp?containerId=US40755816, Accessed: January, 2017.

[10] Cisco Global Cloud Index: Forecast and Methodology, 2015ï2020, ñhttp://www.cisco.com/c/dam/en/us/solutions/collateral/service-provider/global-cloud-index-gci/white-paper-c11-738085.pdf,ò accessed on January, 2017.

[11] 4 Vs of Big Data, [online] Available: http://www.ibmbigdatahub.com/sites/default/files/infographic_file/4-Vs-of-big-data.jpg, Accessed: January, 2017

[12] E. Borcoci, ñFog Computing, Mobile Edge Computing, Cloudlets - which one?ò *2016 Conference SoftNet*, Rome, August 21, 2016

[13] F. Bonomi, R. Milito, J. Zhu, S. Addepalli, ñFog computing and its role in the internet of things,ò *Proceedings of the first edition of the MCC workshop on Mobile cloud computing*, Helsinki, Finland, pp. 13-16, 2012

[14] F. Bonomi, R. Milito, P. Natarajan, and Jiang Zhu, ñFog Computing: A Platform for Internet of Things and Analytics,ò Book Chapter, *Big Data and Internet of Things: A Roadmap for Smart Environments*, Volume 546 of the series Studies in Computational Intelligence, Springer, pp 169-186, March 2014

[15] M. T. Beck, M. Werner, S. F. L. Maximilian, T. Schimper, ñMobile Edge Computing: A Taxonomy,ò *The Sixth International Conference on Advances in Future Internet*, 2014.

[16] G. I. Klas, ñFog Computing and Mobile Edge Cloud Gain Momentum,ò *Open Fog Consortium,* ETSI MEC and Cloudlets,ò 2015

[17] V. Avelar, Practical Options for Deploying Small Server Rooms and Micro Data Centers, Revision 1, White Paper [online] Available: http://www.datacenterresearch.com/whitepaper/practical-options-for-deploying-small-server-rooms-and-micro-9014.html, Accessed: January, 2017

[18] B. Brown Microsoft researcher: Why Micro Datacenters really matter to mobile's future, [online] Available: http://www.networkworld.com/article/2979570/cloud-computing/microsoft-researcher-why-micro-datacenters-really-matter-to-mobiles-future.html, Accessed: January, 2017

[19] M. Satyanarayanan, P. Bahl, R. Cáceres, N. Davies, and L. University, ñThe Case for VM-Based Cloudlets in Mobile Computing,ò *IEEE Pervasive Computing*, vol. 8, no. 4, DOI: 10.1109/MPRV.2009.82, 2009

[20] Cloudlet-based Mobile Computing [online]. Available: http://elijah.cs.cmu.edu/, Accessed: January, 2017

[21] V. Valancius, N. Laoutaris, L. Massouli®, and P. Rodriguez, ñGreening the Internet with Nano Data Centers,ò *Proceedings of the 2009 ACM Conference on Emerging Networking Experiments and Technology, CoNEXT*, Rome, Italy, DOI: 10.1145/1658939.1658944, 2009

[22] Content Delivery Networks Interconnection (cdni), [online] Available: https://datatracker.ietf.org/wg/cdni/charter/, Accessed: January, 2017

[23] Final Version of NIST Cloud Computing Definition Published, October 25, 2011. [online] Available: https://www.nist.gov/news-events/news/2011/10/final-version-nist-cloud-computing-definition-published, Accessed: February, 2017

[24] P. G. V. Naranjo, M. Shojafar, L. Vaca-Cardenas, C. Canali, R. Lancellotti, and E. Baccarelli, ñBig Data Over SmartGrid - A Fog Computing Perspective,ò *24th International conference on software, telecommunications, and computer networks*, 2016

[25] S. Sarkar and S. Misra, ñTheoretical modelling of fog computing: a green computing paradigm to support IoT applications,ò *IET Networks*, Volume: 5, Issue: 2, pp: 23-29, 2016

[26] M. Aazam and E. Huh, ñDynamic Resource Provisioning Through Fog Micro Datacenter,ò *The 12th IEEE International Workshop on Managing Ubiquitous Communications and Services*, pp: 105-110, 2015

[27] M. Aazam, E. Huh, and K. Hee, ñFog Computing Micro Datacenter Based Dynamic Resource Estimation and Pricing Model for IoT,ò *IEEE 29th International Conference on Advanced Information Networking and Applications*, 2015.

[28] T. H. Luan, L. Gao, Z. Li, Y. Xiang, and L. Sun, ñFog computing: Focusing on mobile users at the edge,ò [online] arXiv:1502.01815, 2015

[29] I. Stojmenovic, S. W. X. Huang, and H. Luan, ñAn overview of Fog computing and its security issues,ò *Concurrency Computation Practices and. Experience.* DOI: 10.1002/cpe.3485, (2015)

[30] S. Yi, C. Li, Q. Li, ñA Survey of Fog Computing: Concepts, Applications and Issues,ò *Proceedings of the 2015 Workshop on Mobile Big Data*, Hangzhou, China, pp 37-42, 2015

[31] A. Ahmed and E. Ahmed, ñA Survey on Mobile Edge Computing,ò *10th IEEE International Conference on Intelligent Systems and Control*, DOI: 10.1109/ISCO.2016.7727082, 2016

[32] M. Aazam, E. Huh , M. St-Hilaire, C. Lung, and I. Lambadaris, ñCloud of Things: Integration of IoT with Cloud Computing,ò Book Chapter, *Robots and Sensor Clouds*, Volume 36 of the series Studies in Systems, Decision and Control, Springer, pp 77-94, August 2015

[33] A. V. Dastjerdi and R. Buyya, ñFog Computing: Helping the Internet of Things Realize Its Potential,ò *IEEE Computer Society*, Issue No. 08, vol. 49, pp: 112-116, 2016

[34] V. Dastjerdi, H. Gupta, R. N. Calheiros, S. K. Ghosh, R. Buyya, ñFog Computing: principles, architectures, and applications,ò in *Internet of Things Principles and Paradigms*, R. Buyya and A. V. Dastjerdi, Eds., Elsevier, USA, 2016, ISBN: 978-0-12-805395-9, Chapter 4.

[35] B. Varghese, N. Wang, S. Barbhuiya, P. Kilpatrick, and D. S. Nikolopoulos, ñChallenges and Opportunities in Edge Computing,ò *IEEE International Conference on Smart Cloud (SmartCloud)*, pp. 18-20, 2016

[36] 5 Ways Netflix is Changing Telecom Networks, [online] Available: https://www.linkedin.com/pulse/5-ways-netflix-changing-telecom-networks-avi-dorfman-1, Accessed: December, 2016.

[37] E. Nygren, R. K. Sitaraman, and J. Sun, ñThe Akamai Network: A Platform for High-Performance Internet Applications,ò *ACM SIGOPS Operating Systems*, Issue 3, vol. 44, pp: 2-19, July 2010.

[38] K. Ha, P. Pillai, G. Lewis, S. Simanta, S. Clinch, N. Davies, and M. Satyanarayanan, ñThe impact of mobile multimedia applications on data center consolidation,ò *2013 IEEE International Conference on Cloud Engineering (IC2E)*, pp. 166ï176, March 2013.

[39] Green Clouds, [online] Available: http://www.greenclouds.in/resources/, Accessed: January, 2017

[40] A. Giordano and G. Spezzano ñSmart Agents and Fog Computing for Smart City Applications,ò *Smart Cities*, DOI: 10.1007/978-3-319-39595-1_14, pp 137-146, 2016.

[41] S. Agarwal, M. Philipose, P. Bahl, ñVision: the case for cellular small cells for cloudlets,ò *Proceedings of the fifth international workshop on Mobile cloud computing & services*, pp. 1-5, 2014.

[42] T. Maqsood, O. Khalid, R. Irfan, S. A. Madani, and S. U. Khan, ñScalability Issues in Online Social Networks,ò *ACM Computing Surveys*, 2016

[43] Foursquare by the numbers [online]. Available: http://venturebeat.com/2015/08/18/foursquare-by-the-numbers-60m-registered-users-50m-maus-and-75m-tips-to-date/, Accessed: January, 2017

[44] Foursquare Aims [online]. Available: https://techcrunch.com/2013/03/16/foursquare-aims-at-a-moving-target-as-it-tries-to-close-another-round-of-funding/, Accessed: January, 2017

[45] Nike+ sports tracking [online]. Available: http://nikeplus.nike.com, Accessed: January, 2017

[46] Runtastic sports tracking [online]. Available: https://www.runtastic.com/, Accessed: January, 2017

[47] Runkeeper sports tracking [online]. Available: http://runkeeper.com, Accessed: January, 2017

[48] Endomondo sports tracking [online]. Available: http://www.endomondo.com, Accessed: January, 2017

[49] R. Cortesa, X. Bonnaireb, O. Marina, and P. Sensa, ñStream processing of healthcare sensor data: studying user traces to identify challenges from a big data perspective,ò *The 4th International Workshop on Body Area Sensor Networks (BASNet-2015), Procedia Computer Science, 52*, pp. 1004ï1009, 2015

[50] D. Costenaro and A. Duer, ñThe Megawatts behind Your Megabytes: Going from Data-Center to Desktop,ò *ACEEE Summer Study on Energy Efficiency in Buildings*, 2012

[51] F. Jalali, *Energy consumption of cloud computing and fog computing applications*, PhD Thesis, The University of Melbourne [online]. Available: http://hdl.handle.net/11343/58849, 2015.

[52] Data Never Sleeps 2.0 [online]. Available: https://www.domo.com/learn/data-never-sleeps-2, Accessed: January, 2017

[53] Cisco Data in Motion [online] Available: https://developer.cisco.com/site/data-in-motion/discover/overview/, Accessed: January, 2017

[54] K. Ha, Z. Chen, W. Hu, W. Richter, P. Pillai, and M. Satyanarayanan, ñTowards Wearable Cognitive Assistance,ò *Proceedings of the Twelfth International Conference on Mobile Systems, Applications and Services (MobiSys 2014)*, Bretton Woods, NH, June 2014.

[55] D. Ye, M. Wu, S. Tang, and R. Yu, ñScalable Fog Computing with Service Offloading in Bus Networks,ò *2016 IEEE 3rd International Conference on Cyber Security and Cloud Computing (CSCloud)*, pp: 247-251, 2016

[56] Cisco Unified Computing System [online] Available: http://www.cisco.com/c/en/us/products/servers-unified-computing/index.html, Accessed: January, 2017

[57] VxBlock and Vblock Systems [online] Available: https://www.emc.com/en-us/converged-infrastructure/converged-systems.htm#collapse=, Accessed: January, 2017

[58] Dell Active System Manager [online] Available: http://www.dell.com/learn/us/en/05/large-business/solution-converged-infrastructure-asim, Accessed: January, 2017

[59] Schneider Electrics Microdata centers [online] Available: https://www.schneider-electric.com/b2b/en/solutions/system/s4/data-center-and-network-systems-micro-data-center, Accessed: January, 2017

[60] DX Raser [online] Available: https://www.ellipticalmobilesolutions.com/raserdx.html, Accessed: January, 2017

[61] MicroDC Solution [online], Available: http://e.huawei.com/en/solutions/industries/retail/shoppingmall/medium-sized-store, Accessed: January, 2017

[62] Mobile edge computing [online] Available: http://www.etsi.org/technologies-clusters/technologies/mobile-edge-computing, Accessed: January, 2017

[63] Mobile edge computing, Nokia [online], Available: https://networks.nokia.com/solutions/multi-access-edge-computing, Accessed: January, 2017

[64] S. Agarwal, M. Philipose, and P. Bahl, ñVision: The Case for Cellular Small Cells for Cloudlets,ò *in Proceedings of the International Workshop on Mobile Cloud Computing & Services*, 2014, pp. 1ï5.

[65] M. Aazam and E. Huh, ñFog computing: The cloud-IoT/IoE middleware paradigm,ò *IEEE Potentials*, pp: 40-44, 2016

[66] S. Sarkar, S. Chatterjee, and S. Misra, ñAssessment of the Suitability of Fog Computing in the Context of Internet of Things,ò *IEEE Transactions on Cloud Computing*, DOI 10.1109/TCC.2015.2485206

[67] Boeing 787s to create half a terabyte of data [online] Available: http://www.computerworlduk.com/data/boeing-787s-create-half-terabyte-of-data-per-flight-says-virgin-atlantic-3433595/, Accessed: January, 2017

[68] Self-driving Cars Will Create 2 Petabytes Of Data, [online] Available: https://datafloq.com/read/self-driving-cars-create-2-petabytes-data-annually/172, Accessed: January, 2017

[69] The Internet of Things in Smart Commercial Buildings 2016 to 2021, MARKET PROSPECTS, IMPACTS & OPPORTUNITIES [online] Available: http://www.memoori.com/portfolio/internet-things-smart-commercial-buildings-2016-2021/, Accessed: January, 2017

[70] Gooee enterprise IoT lighting and ecosystem [online] Available: https://gooee.com/, Accessed: January, 2017

[71] PointGrab, [online] Available: http://www.pointgrab.com/about, Accessed: January, 2017

[72] IoT Partnership for Smart Building Lighting [online] https://www.senseware.co/smart-building-solutions-integration-key/, Accessed: January, 2017

[73] Christine Boles, Intel IoT Solutions Transforming Smart Buildings from the Ground Up [online] Available: http://blogs.intel.com/iot/2016/06/07/intel-iot-solutions-transforming-smart-buildings-ground/, Accessed: January, 2017

[74] Saving Energy with Intel and AVOB | Smart Building Management [online]. Available: http://www.intel.com/content/www/us/en/internet-of-things/solution-briefs/avob-smart-building-management-brief.html, Accessed: January, 2017

[75] S. K. Datta, C. Bonnet, and J. Haerri, ñFog Computing Architecture to Enable Consumer Centric Internet of Things Services,ò *EURECOM*, Biot, France

[76] L. A. Tawalbeh, W. Bakheder, and H. Song, ñA Mobile Cloud Computing Model Using the Cloudlet Scheme for Big Data Applications,ò In *Connected Health: Applications, Systems and Engineering Technologies (CHASE), 2016 IEEE First International Conference on*, pp. 73-77. IEEE, 2016.

[77] R. Brzoza-Woch, M. Konieczny, P. Nawrocki, T. Szydlo, and K. Zielinski, ñEmbedded systems in the application of fog computing ï levee mon0069cFDtoring use case,ò *2016 11th IEEE Symposium on Industrial Embedded Systems (SIES)*, pp: 1-6, 2016.

[78] White paper: Cisco Visual Networking Index: Forecast and Methodology, 2015ï2020, 2015-2020, Document ID:1465272001663118

[79] N. Chen, Y. Chen, Y. You, H. Ling, P. Liang, R. Zimmermann, ñDynamic Urban Surveillance Video Stream Processing Using Fog Computing,ò *2016 IEEE Second International Conference on Multimedia Big Data*, pp: 105-112, 2016

[80] K. Bilal and A. Erbad, ñImpact of Multiple Video Representations in Live Streaming: A Cost, Bandwidth, and QoE Analysis,ò *IEEE International Conference on Cloud Engineering (IC2Eô17)*, Vancouver Canada, April 2017.

[81] F. Chen, C. Zhang, F. Wang, J. Liu, X. Wang and Y. Liu, "Cloud-Assisted Live Streaming for

Crowdsourced Multimedia Content," in *IEEE Transactions on Multimedia*, vol. 17, no. 9, pp. 1471-1483, Sept. 2015.

[82] K. Pires and G. Simon, ñYouTube live and Twitch: a tour of user-generated live streaming systems,ò *Proceedings of the 6th ACM Multimedia Systems Conference (MMSys '15)*, New York, 2015.

[83] Akamai, Akamaiôs State of the Internet Q1 2014 report | volume 7 number 1, [online] Available: https://www.akamai.com/uk/en/multimedia/documents/state-of-the-internet/akamai-state-of-the-internet-report-q4-2014.pdf

[84] Akamai, Akamaiôs State of the Internet Q1 2016 report | volume 9 number 1, [online] Available: https://www.akamai.com/es/es/multimedia/documents/state-of-the-internet/akamai-state-of-the-internet-report-q1-2016.pdf

[85] Amazon CloudFront Pricing [online] Available: https://aws.amazon.com/cloudfront/pricing, Accessed: January, 2017

[86] Twitch, the 2015 retrospective [online] Available: https://www.twitch.tv/year/2015, Accessed: January, 2017

[87] A. Hamza and M. Hefeeda, ñAdaptive streaming of interactive free viewpoint videos to heterogeneous clients,ò *7th International Conference on Multimedia Systems (MMSys '16)*, New York, 2016.

[88] S. Banerjee and D.O. Wu, ñFinal Report from the NSF Workshop on Future Directions in Wireless Networking,ò National Science Foundation, Nov. 2013.

[89] M. Satyanarayanan, P. Simoens, Y. Xiao, P. Pillai, Z. Chen, K. Ha, W. Hu, B. Amos, ñEdge Analytics in the Internet of Thingsò *IEEE Pervasive Computing*, Volume 14, Number 2, April-June 2015

[90] M. Mukerjee, D. Naylor, J. Jiang, S. Seshan, and H. Zhang, ñPractical, Real-time Centralized Control for CDN-based Live Video Delivery,ò *SIGCOMM Comput. Commun. Rev*. vol. 45, no. 4, 2015, pp 311-324.

[91] P. Simoens, , Y. Xiao, , P. Pillai, Z. Chen, , K. Ha, , M. Satyanarayanan, ñScalable Crowd-Sourcing of Video from Mobile Devices,ò *Proceedings of the Eleventh International Conference on Mobile Systems, Applications and Services* (MobiSys 2013), Taipei, Taiwan, June 2013

[92] M. Ramon, S. Caharel, and B. Rossion. ñThe speed of recognition of personally familiar faces,ò *Perception*, vol. 40, issue. 4, pp. 437-449, 2011

[93] C. Wei, V. C. Leung, and L. Hu, ñA cloudlet-assisted multiplayer cloud gaming system,ò *Mobile Networks and Applications*, vol. 19, no. 2, pp.144-152, 2014

[94] S. J. R. M®ndez, Y. Wang, T. R. Mullen, and T. Jung, ñAugmented Brain Computer Interaction Based on Fog Computing and Linked Data,ò *2014 International Conference on Intelligent Environments (IE),* 2014

[95] headit [online] Available: http://headit.ucsd.edu/, Accesses: January, 2017

[96] PhysioNet [online] Available: https://www.physionet.org/, Accessed: January, 2017

[97] BrainMap [online] Available: http://www.brainmap.org/, Accessed: January, 2017

[98] T. Soyata, R. Muraleedharan, C. Funai, M. Kwon, and W. Heinzelman, ñCloud-Vision: Real-time face recognition using a mobile-cloudlet-cloud acceleration architecture.ò *2012 IEEE Symposium on Computers and Communications (ISCC)*, pp. 59-66., 2012.

[99] F. Jalali, K. Hinton, R. Ayre, T. Alpcan, and R. S. Tucker, ñFog Computing May Help to Save Energy in Cloud Computing,ò DOI 10.1109/JSAC.2016.2545559, *IEEE Journal on Selected Areas in Communications*, 2015.

[100] K. Gai, M. Qiu, H. Zhao, L. Tao, and Z. Zong, ñDynamic energy-aware cloudlet-based mobile cloud computing model for green computing,ò *Journal of Network and Computer Applications* vol. 59, pp. 46-54, 2016

[101] X. Sun and N. Ansari, ñGreen Cloudlet Network: A Distributed Green Mobile Cloud Network,ò *arXiv preprint arXiv:1605.07512* (2016).

[102] J. Li, J. Jin, D. Yuan, M. Palaniswami, and K. Moessner, ñEHOPES: Data-centered Fog Platform for Smart Living,ò *2015 International Telecommunication Networks and Applications Conference (ITNAC)*, pp: 308 ï 313, 2015.

[103] M. Sneps-Sneppe and D. Namiot, ñOn Mobile Cloud for Smart City Applications,ò *arXiv preprint arXiv:1605.02886*, 2016

[104] T. Tarik, S. Dutta, A. Ksentini, M. Iqbal, and H. Flinck, ñMobile Edge Computing Potential in Making Cities Smarter,ò *IEEE Communications Magazine*, 2016.

[105] A. Ksentini, T. Taleb, and F. Messaoudi, ñA LISP-based Implementation of Follow Me Cloud,ò in IEEE Access, Vol 2, Oct. 2014. pp. 1340 ï 1347

[106] T. Taleb and A. Ksentini, ñAn analytical model for Follow Me Cloud,ò *in Proc. IEEE Global Communications Conference (GLOBECOM),* Atlanta, GA, USA, Dec. 2013

[107] M. U. S. Khan, O. Khalid, Y. Huang, F. Zhang, R. Ranjan, S. U. Khan, J. Cao, K. Li, B. Veeravalli, and A. Zomaya, ñMacroServ: A Route Recommendation Service for Large-Scale Evacuations,ò *IEEE Transactions on Services Computing.* (Accepted and to appear.)

[108] O. Khalid, M. U. S. Khan, Y. Huang, S. U. Khan, and A. Y. Zomaya, ñEvacSys: A Cloud-based Service for Emergency Evacuation,ò *IEEE Cloud Computing*, vol. 3, no. 1, pp. 60ï68, 2016.

[109] Towards applications of fog computing for designing smart city verticals [online] Available: http://www.telxperts.com/fog/towards-applications-fog-computing-designing-smart-city-verticals/, Accessed: January, 2017

[110] Y. Yan and W. Su, ñA Fog Computing Solution for Advanced Metering Infrastructure,ò *2016 IEEE/PES Transmission and Distribution Conference and Exposition (T&D)*, Pages: 1 - 4, DOI: 10.1109/TDC.2016.7519890, 2016.

[111] M. Saleem, H. Nazmudeen, A. T. Wan, S. M. Bukhari, ñImproved throughput for Power Line Communication (PLC) for Smart Meters using Fog Computing based Data aggregation approach,ò *2016 IEEE International Smart Cities Conference (ISC2)*, DOI: 10.1109/ISC2.2016.7580841, 2016

[112] Y. Cao, S. Chen, P. Hou, and D. Brown, ñFAST: A Fog Computing Assisted Distributed Analytics System to Monitor Fall for Stroke Mitigation,ò *2015 IEEE International Conference on Networking, Architecture and Storage (NAS)*, DOI: 10.1109/NAS.2015.7255196, 2015

[113] X. Masip-Bruin, E. Marín-Tordera, A. Alonso, and J. Garcia, ñFog-to-cloud Computing (F2C): the key technology enabler for dependable e-health services deployment,ò *Ad Hoc Networking Workshop (Med-Hoc-Net), 2016 Mediterranean*, DOI: 10.1109/MedHocNet.2016.7528425, 2016

[114] M. Quwaider and Yaser Jararweh, ñCloudlet-based for big data collection in body area networks,ò *IEEE 8th International Conference for Internet Technology and Secured Transactions (ICITST), 2013*, pp. 137-141, 2013.

[115] A. E. Amraoui and K. Sethom, ñCloudlet Softwarization for Pervasive Healthcare,ò *2016 30th International Conference on Advanced Information Networking and Applications Workshops (WAINA)*, Crans-Montana, pp. 628-632, 2016

[116] Q. Althebyan, Q. Yaseen, Y. Jararweh, and M. Al-Ayyoub, ñCloud support for large scale e-healthcare systems,ò *Annals of Telecommunications* pp. 1-13, 2016

[117] K. Intharawijitr, K. Iida, and H. Koga, ñAnalysis of Fog Model Considering Computing and Communication Latency in 5G Cellular Networks,ò *IEEE International Conference on Pervasive Computing and Communications Work in Progress*, 2016.

[118] M. Peng, S. Yan, K. Zhang, and C. Wang, ñFog Computing based Radio Access Networks: Issues and Challenges,ò *IEEE Network*, Vol. 30, Issue. 4, pp. 46-53, 2016

[119] S. Nunna, A. Kousaridas, M. Ibrahim, M. Dillinger, C. Thuemmler, H. Feussner, and A. Schneider, ñEnabling real-time context-aware collaboration through 5g and mobile edge computing,ò In *IEEE 2015 12th International Conference on Information Technology-New Generations (ITNG)*, pp. 601-605, 2015.

[120] H. Zhang, Y. Xiao, S. Bu, D. Niyato, R. Yu, and Z. Han, ñFog Computing in Multi-Tier Data Center Networks: A Hierarchical Game Approach,ò *IEEE ICC 2016 SAC Cloud Communications and Networking,* 2016.

[121] M. Aazam and E. Huh, ñFog computing and smart gateway based communication for cloud of things,ò in *Proc. IEEE Future Internet of Things and Cloud (FiCloud)*, Barcelona, Spain, 27ï29 Aug., 2014, pp. 464ï470

[122] H. Yin, X. Zhang, H. H. Liu, Y. Luo, C. Tian, S. Zhao, and F. Li ñEdge Provisioning with Flexible Server Placement,ò DOI: 10.1109/TPDS.2016.2604803, *IEEE Transactions on Parallel and Distributed Systems,* 2016

[123] C. Do, N. H. Tran, and C. Pham, ñA Proximal Algorithm for Joint Resource Allocation and Minimizing Carbon Footprint in Geo-distributed Fog Computing,ò *International Conference on Information Networking (ICOIN),* pp: 324-329, 2015

[124] Accelerating Innovation and Collaboration for the Next Stage [online], Available: http://www.ntt.co.jp/news2013/1311ehzt/pdf/xgxf131108d_all.pdf, Accessed: January, 2017

[125] J. Zhu, D. S. Chan, and M. S. Prabhu, ñImproving Web Sites Performance Using Edge Servers in Fog Computing Architecture,ò *IEEE Seventh International Symposium on Service-Oriented System Engineering,* 2013

[126] D. Zeng, L. Gu, S. Guo, Z. Cheng, and S. Yu, ñJoint Optimization of Task Scheduling and Image Placement in Fog Computing Supported Software-Defined Embedded System,ò *IEEE Transactions on Computers,* DOI 10.1109/TC.2016.2536019, 2015.

[127] Z. Shelby, K. Hartke, and C. Bormann, ñThe Constrained Application Protocol (CoAP),ò RFC 7252 (Proposed Standard), Internet Engineering Task Force, Jun. 2014. [Online]. Available: http://www.ietf.org/rfc/rfc7252.txt

[128] E. H. Butterfield, ñFog Computing with Go: A Comparative Studyò, CMC Senior Theses. Paper 1348. http://scholarship.claremont.edu/cmc_theses/1348, 2016

[129] S. Cirani, G. Ferrari, N. Iotti, and M. Picone, ñThe IoT Hub: a Fog Node for Seamless Management of Heterogeneous Connected Smart Objects,ò *2015 12th Annual IEEE International Conference on Sensing, Communication, and Networking - Workshops (SECON Workshops),* DOI: 10.1109/SECONW.2015.7328145, 2016

[130] H. Gupta, A. V. Dastjerdi, S. K. Ghosh, and R. Buyya, ñiFogSim: A Toolkit for Modeling and Simulation of Resource Management Techniques in Internet of Things, Edge and Fog Computing Environments,ò *technical report CLOUDS-TR-2016-2,* Cloud Computing and Distributed Systems Laboratory, Univ. of Melbourne, 2016; http://cloudbus.org/tech_reports.html

[131] U. U. Rahman, O. Hakeem, M. Raheem, K. Bilal, S. U. Khan, and L. T. Yang, ñNutshell: Cloud Simulation and Current Trends,ò in *IEEE International Conference on Smart City (SmartCity)*, Chengdu, China, December 2015.

[132] G. Orsini, D. Bade, and W. Lamersdorf, ñComputing at the Mobile Edge: Designing Elastic Android Applications for Computation Offloading,ò *8th IFIP Wireless and Mobile Networking Conference (WMNC),* 5-7 Oct. 2015

[133] Cisco ParStream [online] Available: http://www.cisco.com/c/en/us/products/analytics-automation-software/parstream/index.html, Accessed: January, 2017

[134] Vortex [online] Available: http://www.prismtech.com/vortex, Accessed: January, 2017

[135] Cisco IOx [online] Available: http://www.cisco.com/c/en/us/products/cloud-systems-management/iox/index.html, Accessed: January, 2017

[136] Amazon EMR Pricing, [online] Available: https://aws.amazon.com/emr/pricing/, Accessed: January, 2017

[137] MEC - Applications at the network edge, [online] Available: http://networks.nokia.com/portfolio/solutions/mobile-edge-computing#tab-highlights, Accessed: January, 2017

[138] U. Shaukat, E. Ahmed, Z. Anwar, and F. Xia, ñCloudlet deployment in local wireless networks: Motivation, architectures, applications, and open challenges,ò *Journal of Network and Computer Applications,* vol. 62, pp. 18-40, 2016

[139] I. Stojmenovic, S. Wen, X. Huang, and H. Luan, ñAn overview of Fog computing and its security issues,ò *Concurrency and Computation: Practice and Experience,* DOI: 10.1002/cpe.3485View, 2015

[140] R. Romana, J. Lopeza, and M. Mambob ñMobile edge computing, Fog et al.: A survey and analysis of security threats and challenges, Future Generation Computer Systems,ò *Future Generation Computer Systems,* DOI: http://dx.doi.org/10.1016/j.future.2016.11.009, 2016

[141] LocalGrid Fog Computing Platform, [online] Available: http://www.localgridtech.com/, Accessed: January, 2017

[142] Akamai, [online] Available: https://blogs.akamai.com/2016/07/portugal-france-sets-live-sports-streaming-record-on-akamai.html

[143] Internet of Everything (IoE) [online] Available: https://newsroom.cisco.com/ioe, Accessed: February, 2017

[144] Heterogeneous Network (Hetnet) [online] Available: https://www.ericsson.com/br/res/thecompany/docs/press/media_kits/hetnet_infographic_vertical_04.pdf, Accessed: February, 2017

[145] M. Wang, P. P. Jayaraman, R. Ranjan, K. Mitra, M. Zhang, E. Li, S. Khan, M. Pathan, and D. Georgeakopoulos, ñAn Overview of Cloud Based Content Delivery Networks: Research Dimensions and State-of-the-Art,ò Book Chapter, *Transactions on Large-Scale Data- and Knowledge-Centered Systems,* Volume 9070 of the series Lecture Notes in Computer Science pp 131-158, March 2015

[146] W. Chu, L. Wang, H. Xie, Z. Zhang, and Z. Jiang, ñNetwork delay guarantee for differentiated services in content-centric networking,ò *Computer Communications*, vol. 76, pp. 54ï66, 2016

[147] R. Wang, X. Peng, J. Zhang, and K. B. Letaief, ñMobility-Aware Caching for Content-Centric Wireless Networks: Modeling and Methodology,ò *IEEE Communications Magazine*, pp. 77-83, 2016

[148] S. H. Ahmed, S. H. Bouk, and D. Kim, *Content-Centric Networks An Overview, Applications and Research Challenges,* Springer Briefs in Electrical and Computer Engineering, ISBN: 978-981-10-0064-5, 2016

[149] Twitch Tv [online] Available: https://www.twitch.tv/, Accessed: February, 2017

[150] YouTube Live [online] Available: https://www.youtube.com/live, Accessed: February, 2017

[151] Periscope [online] Available: https://www.periscope.tv/, Accessed: February, 2017

[152] YouNow Broadcast Live [online] Available: https://www.younow.com/, Accessed: February, 2017

[153] Livestream [online] Available: https://livestream.com/, Accessed: February, 2017

[154] Amazon Web Services [online] Available: https://aws.amazon.com/, Accessed: February, 2017

[155] C. Brennand, F. Cunha, and G. Maia, ñFOX: A traffic management system of computer-based vehicles FOG,ò *2016 IEEE Symposium on Computers and Communication (ISCC),* DOI: 10.1109/ISCC.2016.7543864, 2016

[156] Demand for Mayweather-McGregor fight crashed pay-per-view servers [online] https://www.engadget.com/2017/08/27/mayweather-mcgregor-fight-crashes-ppv-servers/, Accessed: September, 2017

[157] L. Gu, D. Zeng, S. Guo, A. Barnawi, and Y. Xiang, ñCost Efficient Resource Management in Fog Computing Supported Medical Cyber-Physical System Sign In or Purchase,ò *IEEE Transactions on Emerging Topics in Computing,* Volume: 5, Issue: 1, Jan.-March 2017

[158] H. Zhang, Y. Zhang, Y. Gu, D. Niyato, and Z. Han, ñA Hierarchical Game Framework for Resource Management in Fog Computing,ò *IEEE Communications Magazine*, Volume: 55, Issue: 8, 2017, pp. 52-57

[159] Y. Sun and N. Zhang, ñA resource-sharing model based on a repeated game in fog computing,ò *Saudi Journal of Biological Sciences*, Volume 24, Issue 3, March 2017, Pages 687-694

[160] SONM Aplha, https://sonm.io/, accessed on September, 2017

[161] K. Garg and J. Singh, ñA Proposed Technique for Cloud Computing Security,ò *Innovations in Computer Science and Engineering*, pp 89-95, June 2017

[162] K. Lee, D. Kim, D. Ha, U. Rajput, and H. Oh, ñOn security and privacy issues of fog computing supported Internet of Things environment,ò *2015 6th International Conference on the Network of the Future (NOF)*, 30 Sept.-2 Oct. 2015

[163] D. Ye, M. Wu, S. Tang, and R. Yu, ñScalable Fog Computing with Service Offloading in Bus Networks,ò *2016 IEEE 3rd International Conference on Cyber Security and Cloud Computing (CSCloud)*, 25-27 June 2016.

[164] Y. Gao, W. Hu, K. Ha, B. Amos et al., ñAre cloudlets necessary?ò *School of Computer Science Carnegie Mellon University Pittsburgh*, (2015).

[165] K. Zhang, Y. Mao, S. Leng, Q. Zhao, L. Li, X. Peng, L. Pan, S. Maharjan, Y. Zhang, ñEnergy-efficient offloading for mobile edge computing in 5G heterogeneous networks,ò *IEEE Access*. J. 4 (2016) 5896-5907.

[166] C. You, K. Huang, H. Chae, B.H. Kim, ñEnergy-Efficient Resource Allocation for Mobile-Edge Computation Offloading,ò *IEEE Transactions on Wireless Communications*. 16 (2017) 1397ï1411.

[167] S. Sardellitti, G. Scutari, S. Barbarossa, ñJoint optimization of radio and computational resources for multi-cell mobile-edge computing,ò *IEEE Transactions on Signal Inf. Process. over Networks.* 1 (2015) 89ï103.

[168] R. Deng, R. Lu, C. Lai, T.H. Luan, and H. Liang, ñOptimal Workload Allocation in Fog-Cloud Computing Toward Balanced Delay and Power Consumption,ò in *IEEE Internet of Things*, 2016: pp. 1171ï1181.

[169] K. Bilal and A. Erbad, ñEdge computing for interactive media and video streaming,ò in *IEEE Conference on Fog and Mobile Edge Computing (FMEC)*, pp. 68-73, 2017.

[170] G. Paschos, E. Bastug, I. Land, G. Caire, and M. Debbah, ñWireless caching: Technical misconceptions and business barriers,ò *IEEE Communications Magazine*, vol. 54, no. 8, pp. 16-22, 2016.

Kashif Bilal is a postdoc researcher at Qatar University, Qatar. He received his PhD from North Dakota State University, USA in 2014. He is an Assistant Professor at COMSATS Institute of Information Technology, Pakistan. He was awarded NDSU CoE Researcher of the Year 2014 and COMSATS CS Researcher of the year 2016 awards. His research interests include cloud computing, edge technologies, data center networks, and multimedia in cloud.

Aiman Erbad is an Assistant Professor and Director of Research Support at Qatar University. Dr. Erbad obtained a Ph.D. in Computer Science from the University of British Columbia, a Master of Computer Science in Embedded Systems and Robotics from the University of Essex and a Bachelor of Science in Computer Engineering from the University of Washington. His research interests span cloud computing, distributed systems and multimedia networking and systems.

Osman Khalid completed his Ph.D. in 2014 at the North Dakota State University, Fargo, USA. His area of research includes opportunistic networks, recommendation systems, and trust and reputation systems. He is an Assistant Professor at COMSATS Institute of Information Technology, Pakistan.

Samee U. Khan is a Program Director at the National Science Foundation, where he is responsible for the Smart & Autonomous Systems program, Critical Resilient Interdependent Infrastructure Systems and Processes program, and Computer Systems Research cluster. He also is a faculty at the North Dakota State University. He is an ACM Distinguished Speaker, an IEEE Distinguished Lecturer, a Fellow of the IET, and a Fellow of the BCS. Samee's research interests include optimization, robustness, and security of computer systems. He is an associate editor of the IEEE Access, IEEE Communications Surveys and Tutorials, IET Wireless Sensor Systems, Scalable Computing and Communications, IET Cyber-Physical Systems, and IEEE IT Pro.