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Information-Centric Networking With Edge Computing for IoT: Research Challenges and Future Directions

REHMAT ULLAH[1], SYED HASSAN AHMED[2], (Senior Member, IEEE), AND BYUNG-SEO KIM[3], (Senior Member, IEEE)

[1]Department of Electronics and Computer Engineering, Hongik University, Sejong 30016, South Korea
[2]Department of Computer Science, Georgia Southern University, Statesboro Campus, Statesboro, GA 30460, USA
[3]Department of Software and Communications Engineering, Hongik University, Sejong 30016, South Korea

Corresponding author: Byung-Seo Kim (jsnbs@hongik.ac.kr)

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ABSTRACT Cloud computing is a paradigm that offers storage, computation, and software services on demand in the Cloud and far from end users. These services and computations are then extended to the Edge of the network with the Edge computing paradigm. This paradigm offers computation, data, and application services in close proximity of end users. Future Internet architectures will result in a fast information response time, and low latency will be a main feature of evolving 5th generation (5G) radio networks. To ensure the widespread adoption of 5G applications, low latency, security, mobility, and scalable content distribution support is required. Information-centric networking (ICN) is a newly proposed future Internet paradigm in which communication is based on content names irrespective of their locations. At the same time, ICN promises efficient content delivery, mobility support, scalability, and security for content. The Edge computing and ICN provide an opportunity to reduce latency, support mobility, security, and scalability. In this paper, discussions on Edge computing with ICN are provided. In detail, the Edge computing proposals, use cases, differences among Edge computing proposals and drivers for Edge computing are investigated. The Edge computing standardization, research, and industry/vendors collaboration overview are studied. Applications of ICN integration in Edge computing and their advantages and limitations are highlighted. We conclude our paper by describing potential directions for future research in the field of ICN over Edge computing.

INDEX TERMS Internet of things, Information centric networking, cloud computing, edge computing, caching, naming, ICN-IoT security services, self-certification, location-awareness, offloading, latency.

I. INTRODUCTION

The revolution of mobile services and Cloud Computing (CC) has recently attracted significant attention from both industry and academia. CC provides processing and storage for data in the cloud rather than inside devices of subscribers [1].

CC offers three main service types as shown in Figure 1:

1) *Software as a Service (SaaS)*, which offers access to applications for end users, such as Facebook, Gmail, and Microsoft Office 365;
2) *Platform as a Service (PaaS)*, which offers application programming interface (API) development environments for developers, such as Microsoft Azure and Amazon Web Services (AWS); and
3) *Infra Structure as a Service (IaaS)*, which offers storage and computation services via virtualization using frameworks, such as Amazon Elastic Compute Cloud (AC2).

CC becomes problematic for applications that are latency sensitive and for most of the requirements of novel used cases, CC fall short. To overcome such limitations, an Edge computing paradigm has been introduced. The Edge computing is an abstraction level paradigm that covers many related proposals with same principal and different aspects. The term Edge computing refers to the processing, storage and network optimization at the Edge of networks (fixed and mobile). The Edge could be in the Radio access network (RAN) or in the customer's premises, or at some central location. The journey

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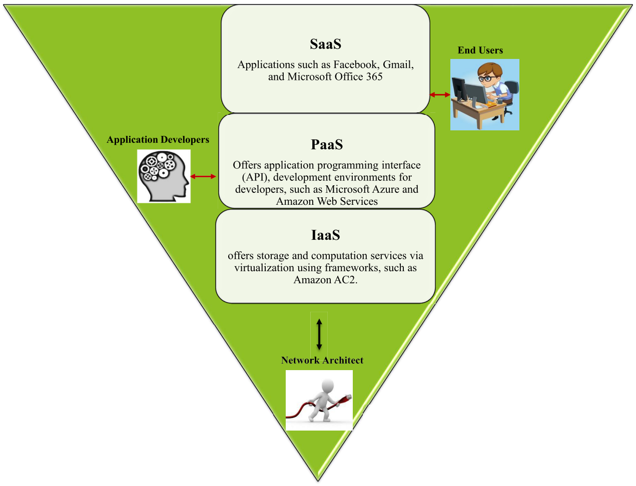


FIGURE 1. **Cloud computing services.**

of Edge computing started due to the rise of Internet of things (IoT) and wearable devices. A huge amount of raw data may be generated in IoT and this may have different requirements. Therefore, to overcome such challenges, different groups come up with several proposals under the same paradigm of Edge computing. However, CC and Edge computing are not independent and have strong correlation. As a result, the paradigm of CC cannot be avoided completely.

Although IoT is advantageous for many applications, however it creates many challenges that cannot be addressed by today's Cloud only model. Industrial IoT (IIoT) such as manufacturing systems, smart grids (to name a few), often demand end-to-end latencies of a few milliseconds between the sensor and the control node. Furthermore, other IoT applications, such as vehicle-to-vehicle communications, drone flight control applications, virtual reality applications, and gaming applications, may require latencies below a few tens of milliseconds. Beside latency the growing number of connected things is generating more data and thus creating bandwidth issues. Therefore, sending all the data to the Cloud will require high network bandwidth. Moreover, mostly IoT devices have resource constrained nature. These devices with limited resources will not be able to fulfill all their computing needs using their own resources. Therefore, they need to offload their computing needs directly to the Cloud which is unrealistic, because such interactions often require resource-intensive processing and complex protocols. At the same time, the increasing number of connected devices also creates a security challenge that how to update the security updates on each device. It is thus impractical to connect every device to the Cloud in order to update its security credentials [2].

Edge computing can provide effective ways to overcome many limitations of the Cloud only model by distributing computing, control, storage, and networking functions closer to end user devices. However, the traditional model (IP approach) is still the dominant solution, where the end-to-end communication is managed between the IoT data sources and fixed purpose-built servers deployed at the network edges [3].

Edge computing is a one of the trending topics which needs further heed and affection. There are different deployment strategies to boost the Edge computing performances such as Software Defined Networking (SDN) and ICN. Edge Computing paradigm is not directly related with the SDN implementations. However, it is noted that SDN has the capability to overcome many challenges of Edge computing through the flexibility of programmable networks [4]. SDN make use of Network Functions Virtualization (NFV) technology which separates the network functions from the hardware and hand them over to a software-based application [5]. In order to enable SDN over Edge computing, related studies should be examined by focusing on the requirements of edge servers and functionalities of SDN. Although SDN is one of the enabling technologies for Edge computing, however, SDN with Edge computing is outside the scope of the present study. Interested readers are referred to [6] for latest research on the proposals for SDN over Edge Computing.

The Edge servers can be better managed through other paradigms, such as ICN integration in Edge computing. In this article, we are focusing specifically on Named Data Networking (NDN) over Edge Computing. However, throughout this article we are using ICN as a general term.

ICN is a promising future Internet paradigm solving the information-dissemination problem through the naming approach. The content is retrieved using the name of the content, not the IP address as in the conventional Internet. We hope that ICN and Edge Computing would be one of the most important paradigms for 5G mobile networks. It will help to reduce the traffic load and latency and will also contribute to energy efficiency in green 5G networks. However, there are several challenges that may result from the combination of ICN and Edge Computing, which are discussed further in this article. Moreover, we studied the Edge computing technologies in depth with supporting use case scenarios.

As a summary, the contributions of this paper are discussed as follows. We:

1) First provide a comprehensive review on the general concept of Cloud computing and Edge computing including the detailed reasons and motivation behind the Edge computing paradigm
2) Survey the Edge computing architectures in detail with targeted use cases (i-e what kind of use-cases can benefit from Edge computing), differences among various Edge computing proposals along with limitations and importance, and drivers for Edge computing
3) Survey the Edge computing standardization activities, the involvement of industry and standard organizations for addressing various research topics in Edge network and specifically ICN
4) Discuss various vendors which are working on the Edge computing solutions and up to date hardware and software solution related to the Edge computing paradigm

5) Introduce ICN as one of the enabling technologies for Edge computing and illustrated how the intrinsic properties of ICN has the potential to support and fulfill the requirements (i-e Mobility, latency and security, heterogeneity etc.) of future networks such as 5G and beyond
6) Discuss recent works and ideas about the integration of ICN and Edge computing
7) Discuss the limitations of both Edge computing and ICN and highlighted the importance of leveraging ICN over Edge Computing
8) Highlight various 5G applications that could be improved by ICN over Edge computing
9) Finally provide future research directions for ICN over Edge computing that could enhance the solution space.

The paper is organized as follows. We present in depth the Edge computing paradigm in the Section 2. In section 3 we present different proposals of Edge computing in detail. In Section 4 we present the difference among all Edge computing proposals. Section 5 consisting of Edge computing novel use cases. Section 6 comprised of Edge computing limitations. In Section 7 we present an overview of ICN paradigm, advantages of leveraging ICN over Edge computing and applications of ICN in Edge computing. Standardization activities and vendor's solution related to Edge computing and ICN are discussed in Section 8 and Section 9 respectively. Finally, we conclude the paper in section 10 and 11, by describing potential benefits and research directions for future research in the area of ICN over Edge computing.

II. EDGE COMPUTING

Due to the evolution of cloud system, most of the functionalities were pushed to the centralized clouds. In this process of virtualization where we got resource enrich platform, we also lost the importance of the location and efficient utilization of resources. It is very true that physical distance increases the latency. The centralized architecture may be easy to manage and handle, however, may not fulfil the requirements of all end users. Many factors can affect the performances such as traffic type, network condition, end user's interests and preferences. Therefore, Edge computing paradigm has been proposed to address such challenges.

The term Edge refers to the computing infrastructure that exists closer to the sources of data. These devices typically reside away from the centralize computing available in the cloud. Edge computing pushes computing power to the Edges of network, instead of centralized cloud. In Edge computing, the data analytics happens very close to the devices and sensors. Therefore, Edge computing thus results in lower delay and high speed of task execution. Moreover, there is need for strong consensus between the vendors and operators to keep a balance between what should be centralized and what should be at the Edge of the network [1].

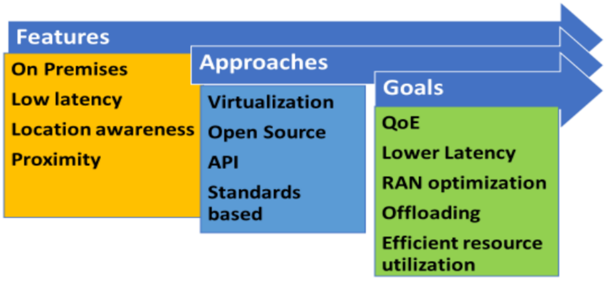


FIGURE 2. Edge computing feature, approaches and goals.

A. WHY EDGE COMPUTING?

In section 1, we explained the Edge computing paradigm that how conventional CC may fall short for fulfilling the requirements of novel use cases. CC is centralized and not compatible with the diverse type of traffic generated by different Edge devices. Hence, bringing servers to the Edge of network becomes necessary. The necessity comes from various factors that drive the evolution of Edge computing paradigm. These factors need to be analyzed as view point of user and operator. Figure 2. illustrates the features, approaches and goals of Edge computing. In the subsequent subsections, we discuss the motivation behind Edge computing paradigm as follows:

1) QoS AND LATENCY

Even though Edge devices are powerful, most of them are lacking enough capacity for fulfilling the delay sensitive requirements. CC provides resource enriched technology infrastructure for constrained devices with huge computation and storage capacity. However, most of the devices in IoT i.e. wearable devices are delay sensitive. In legacy cloud paradigm, the accessibility of all these devices is done via Wide Area Network (WAN), which creates delay, and hence conventional cloud cannot deal with the problems such as the mobility, and real-time requirements. Such latency-sensitive applications demanding computation power and memory resources that cannot be built satisfactorily using cloud services, which can be many network hops away from user locations. Use cases of IoT such as healthcare, needs high QoS requirements [2]. Computation resources is required at the Edge of the network to meet high QoS. As an example, in autonomous vehicles the generated data of camera need to be processed instantly to meet the real-time requirements of QoS [3]. User experience is affected by the centralized servers of cloud due to limited Internet bandwidth and WAN delay. The overall latency can be reduced if the servers is deployed closer to user devices [4]. The benefit of servers closer to the users is the high local-area network (LAN) bandwidth and a smaller number of hopes. An offloading scheme for IoT devices proposed in [5] shows that utilizing servers at the Edge for processing the IoT data provides a high reduction in the latency compared to the cloud servers. Moreover, Edge computing provides caching, storage and computation capabilities in close proximity of

TABLE 1. Terms and abbreviations.

Cloud Computing (CC)	Information Centric Networking (ICN)	Named Data Networking (NDN)
Content Centric Networking (CCN)	Access Point (AP)	Mobile Edge Computing (MEC)
Quality of Service (QoS)	Internet of Things (IoT)	Fifth Generation (5G)
Wide Area Network (WAN)	Local Area Network (LAN)	Quality of Experience (QoE)
European Telecommunications Standards Institute (ETSI)	Internet Service Provider (ISP)	Third Generation (3G)
Worldwide Interoperability for Microwave Access (WiMAX)	Vehicle-to-vehicle (V2V)	Wireless Local Area Network (WLAN)
Body Area Networks (BANs)	Electrocardiogram (ECG)	Advanced Metering Infrastructure (AMI)
Content Store (CS)	Forward Information Base (FIB)	National Science Foundation (NSF)
Internet Engineering Task Force (IETF)	Internet Research Task Force (IRTF)	Information-Centric Networking Research Group (ICNRG)
Code Division Multiple Access (CDMA)	The Alliance for Telecommunications Industry Solutions (ATIS)	Next Generation Mobile Networks (NGMN)
Request for Comments (RFC)	Telecommunication Standardization Sector of the International Telecommunications Union (ITU-T)	Open Edge Computing (OEC)
Platform as a service (PaaS)	Infrastructure as a service (IaaS)	Open Computing Project (OCP)
Software-defined networking (SDN)	Telecom Infra Project (TIP)	PCI Industrial Computer Manufacturers Group (PICMG)
Standardization Group for Embedded Technologies (SGET)	Platforms for Advanced Wireless Research (PAWR)	Name Based Routing (NBR)
User Equipment (UE)	Network attachment Point (NAP)	Vehicular Networks (VNs)
Least frequently used (LFU)	First in first out (FIFO)	Evolved Packet Core (EPC)
Serving Gateway (SGW)	Evolved Node B (eNodeB)	Named Function Networking (NFN)
RAN (Radio Access Network)	Software Defined Networking (SDN)	Fourth Generation (4G)
Mobile Cloud Computing (MCC)	Long-Term Evolution (LTE)	Industry Specification Groups (ISGs)
Pending Interest Table (PIT)	3rd Generation Partnership Project (3GPP)	International Telecommunication Union (ITU)
European Union (EU)	Software as a service (SaaS)	Network functions virtualization (NFV)
PXI Systems Alliance (PXISA)	Look-up based resolution Systems (LRSs)	Least recently used (LRU)
Packet Data Network Gateway (PGW)	Mobility management entity (MME)	Content Delivery Networks (CDNs)
Standardization Group for Embedded Technologies (SGET)	Open Compute Project (OCP)	REST (Representational State Transfer)
Proof of Concept (PoC)	Augmented Reality (AR)	Virtual reality (VR)

end users/devices thereby reduces end to end latency. Edge computing offers such benefits without requiring deployment in the core and remove cloud dependency for content processing.

2) MINIMIZATION OF CORE NETWORK TRAFFIC

In the conventional CC approach, all the traffic flows from devices through core network to reach cloud servers. The content as well as the context require processing and storage which may not achievable on mobile devices. Therefore, it is done on the cloud that result in higher response time and increased backhaul traffic. In case of IoT billions of devices may generate a huge amount of raw data to be processed and stored. According to [11], 15 petabytes of traffic has been generated per month. Sending all the traffic to the cloud servers may result in congestion on cloud servers, since cloud servers have limited capacity. To optimize bandwidth utilization and to reduce traffic on the core network, the traffic should be handled at the Edge servers [12]. Traffic from billions of devices can be handled on Edge servers to prevent congestion and latency problems. Processing data at Edge servers also reduce the demand of computational resources at the cloud data centers such as processing of data generated from IoT sensors and cameras [13]. Therefore, Edge computing paradigm can play a meaningful role in traffic reduction on the core network.

3) SCALABILITY

It is predicated that the end user devices will reach trillion and beyond that may create a serious scalability challenge [13], [14]. Therefore, sending huge amount of data to the centralized servers create a congestion within the datacenters [15]. As a result, CC (centralized) may fall short in the context of scalability for applications and data. The virtualization of Edge servers can bring an opportunity to support scalability [16]. If any of the Edge server becomes congested, then the request can be distributed to other Edge servers in close proximity and so on. The burden on the cloud servers can be reduced by processing data at the Edge servers, since smaller amount of traffic will be forwarded to the cloud servers [17].

In the subsequent section, we discuss the Edge computing drivers with features and goals.

B. DRIVERS FOR EDGE COMPUTING

Centralized topologies fall short and are unable to serve traffic loads with Quality of Experience (QoE) for operators and subscribers. We will discuss some of the key drivers for Edge computing as follows:

1) Continued growth in the user's traffic such as video and interactive applications i-e. games becomes an essential driver for Edge computing. Virtual reality (VR)

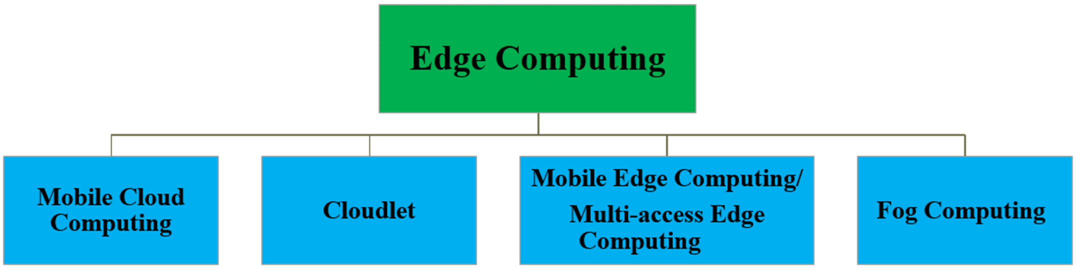


FIGURE 3. Edge computing proposals.

requires increase capacity and lower latency. Edge computing will be useful in reducing the latency which is introduced by the backhaul. Physical distance of backhaul result in high latency. To maximize the utilization of existing resources, Edge computing can play a major role [18].

2) Using Edge computing the operators would move all the centralized hardware near to the end user(s). This would result in the reduction of latency and efficient utilization of bandwidth [18].
3) The benefits such as lower latency, location awareness, security and reduction in the core network traffic can be achieved if the Edge location is chosen appropriately and right content is stored at the Edge. In case these conditions are not met, the cost and complication may be increased with high price.
4) Traffic is increasing day by day specifically video traffic than other traffic. According to Cisco, video traffic is 60% today, and would be 78% by 2021 [19]. According to estimates of Ericsson, the video traffic was 50% in 2016, and would likely increase to 75% in 2022 [20]. Video has become an integral component of social media. The enormous increase and use of video traffic give an important role to latency to showcase the user experience. Therefore, the video traffic has been one of the key drivers for Edge computing

C. IMPORTANCE OF EDGE LOCATION

The most crucial question so far is: where exactly the location of Edge is.? From the Edge, we are meaning that processing, storage, and control units move to the server(s) which are located at the Edge of the network. However, it is very important to determine the potential Edge locations. Edge location can bring performance improvement and financial benefits to the service providers and stakeholders. If the Edge location is too far from the centralized core and too close to the subscriber, the Edge computing may become expensive and complex. Edge location may vary according to application requirements. All the location-based contents should be hosted at some aggregation point. For example, the services providers can choose an Edge location based on the subscriber's interest of videos. All the videos which are highly requested by subscribers should be cached at some specific Edge location near to the subscribers. Applications with highly fluctuating network loads, a mobile Edge will definitely maximize the performance. However, shifting Edge location according to the traffic characteristic is quite difficult to achieve [18].

We explained the Edge computing paradigm so far. Consequently, we will explain different proposals related to the Edge computing paradigm. A taxonomy of Edge computing is shown in Figure 3.

III. EDGE COMPUTING PROPOSALS

In this section, we will discuss in detail about various proposals which comes under the umbrella of Edge computing paradigm. Initially we will discuss about Mobile Cloud Computing (MCC), since it is the first initiatives in Edge computing, and then consequently we will discuss other Edge computing proposals.

A. MOBILE CLOUD COMPUTING

Due to proliferation of the mobile devices, mobile computing terminologies have appeared to provide services to mobile users. Mobile devices have limited resources and cannot provide demanded benefits and services to users. Nowadays, while mobile devices are rich in resources, they cannot still reach to the level of servers [21], [27]. Due to resource-constrained nature, mobile devices need to offload tasks to cloud data centers for empowering various operations. MCC offers offloading mechanism for the mobile devices by integrating mobile Internet, mobile computing, and CC into a combined system [21]. CC is a service model where computing services are delivered over a network on demand independently from device type and location [22]. MCC facilitate the offloading process in a distributed way from a computer to a centralized server. MCC provides resources in terms of storage and computation to mobile users. This goal can be accomplished by bringing resources closer to the proximity of end users [7]. Hence, Edge servers would improve the performance of MCC environments in terms of energy consumption, latency, and congestion. Some of the motivations of MCC are given as follows [23]:

1) To prolong the network life time in term of energy consumption
2) Diverse application services

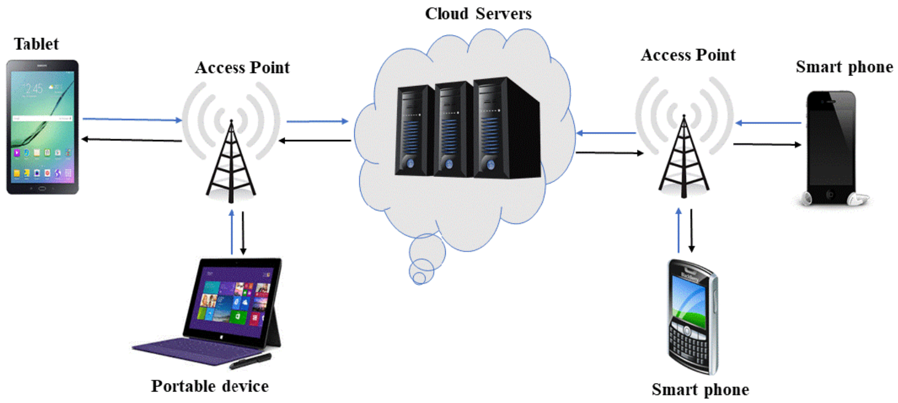


FIGURE 4. Mobile cloud computing architecture.

3) Efficient utilization of resources
4) Virtualization
5) Latency

The major purpose of MCC is offloading tasks from a mobile device to the cloud servers in order to overcome the storage and computation limitation of mobile devices [8]. Moreover, the mobile devices also have the issue of battery drainage. Therefore, the objective of MCC is to save energy and prevent the factors that cause battery drainage [24]. An architecture of MCC is shown in Figure 4.

B. CLOUDLET

Cloudlet [25] has been introduced as an extension of MCC and is considered as one of the keys enabling technologies for MCC [26]. Cloudlet is a part of MCC that overcomes the high WAN latencies. Offloading to the cloud is not always a solution, because of high WAN latencies. Real-time applications need low latency and may not be achieved by offloading tasks to the cloud. Tasks running on mobile devices may require high computation and lower latency. However, the limitation of mobile device cannot fulfil these requirements. Therefore, to provide computation power and to meet lower latency requirements, these tasks can be offloaded to the Cloudlet instead of Cloud servers. Cloudlet is kind of small cloud server located between mobile device and central cloud.

Cloudlets are placed nearby to mobile devices with single-hop proximity and works as virtual-machine (VM). In the initialization phase, the framework requires the cloning (replica) of the mobile device application processing environment to a remote host. The entire application is offloaded using VM as an offloading mechanism. The VM isolates the guest software from the actual Cloudlet environment. The mobile device serves just as user interface, whereas the actual application processing is performed on the Cloudlet infrastructure. Figure 5 illustrates, that Cloudlets are distributed Internet infrastructure components. Instead of accessing the distant cloud servers, the nearby mobile devices can exploit the storage and computation resources of Cloudlets. Such Cloudlets are deployed at public places such as coffee shops.

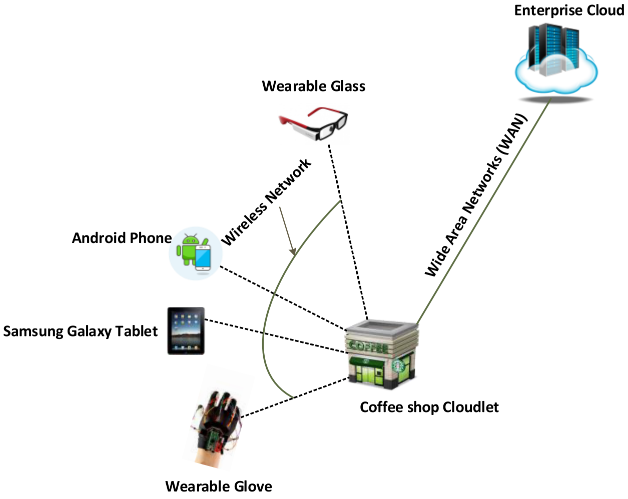


FIGURE 5. An example of Cloudlet [78].

Figure 6 depicts the Cloudlet reference architecture. The main elements of the architecture are Mobile Client and Cloudlet Host. A Discovery Service is a component running in the Cloudlet host and publishes Cloudlet metadata (IP address and port number). The mobile client uses IP address and port number for the specification of Cloudlet and to offload the computation. Once the Cloudlet is determined for offloading, the mobile client sends the application code to the Cloudlet server. The Cloudlet server deploys the application code in the guest VM. Once deployment is done, the execution of the application is launched.

Cloud servers are accessible via WAN technologies that causes the latency issues for some applications. To overcome the latency issue in WANs, Cloudlet can be used by offloading mechanisms to nearby Cloudlet. Moreover, issues like energy can be addressed by Cloudlet [28]. Energy can be saved by offloading all the tasks to nearby resource rich Cloudlet rather than sending to the main cloud. Bandwidth is also a factor of delay. Cloudlet could also help regarding bandwidth because wireless LAN bandwidth is typically two orders of magnitude

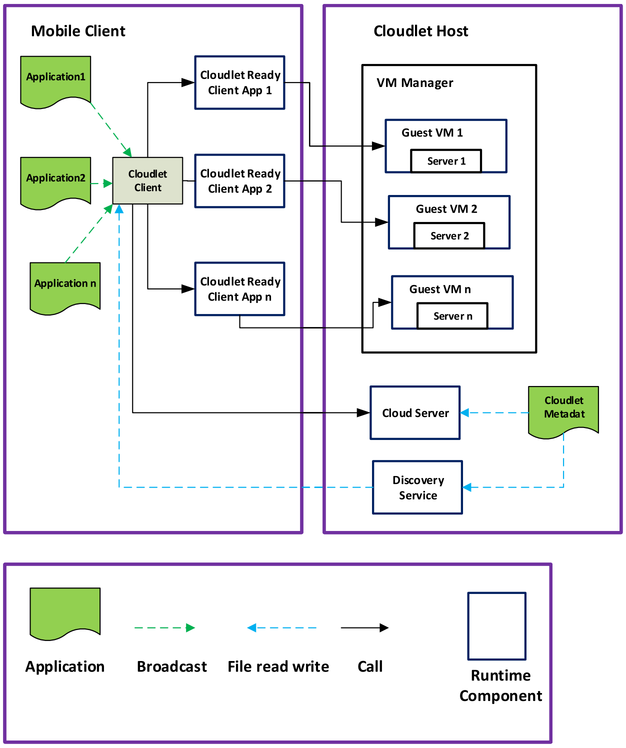


FIGURE 6. A reference Cloudlet architecture [93].

higher than the wireless Internet bandwidth available to a mobile user. Cloudlet is accessible at one hop. Therefore, it can work even if the Internet is not connected for the access of cloud servers [29], [30]. In 2015, the Open Edge Computing (OEC) [31] has been proposed by telecom operators in collaborating with academia with the objective to leverage Cloudlets. For the better services of Cloudlet, the location and user identification of Cloudlet is very important [32]. No standardization effort has been made so far for the deployment of Cloudlets [33].

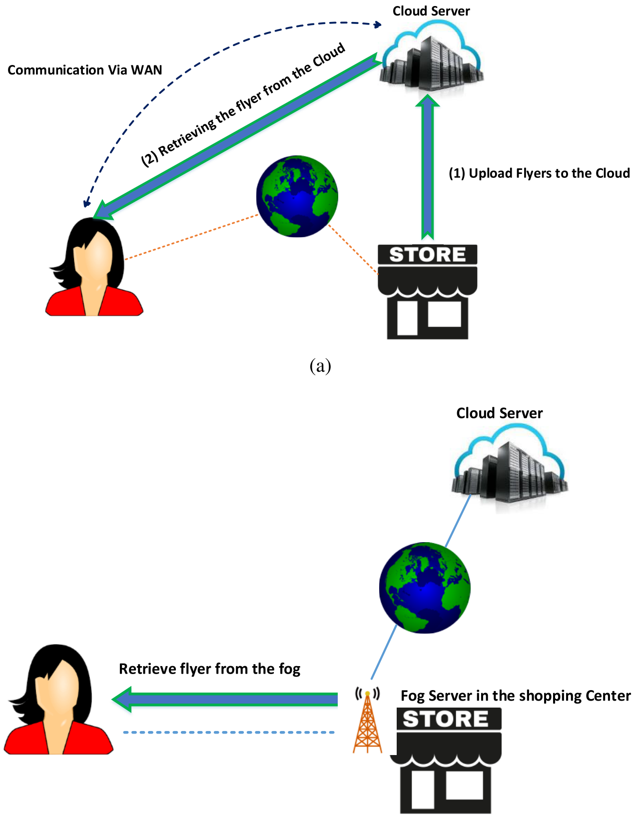
C. FOG COMPUTING

CISCO proposed Fog computing model for the better management of the Clouds by enabling services, applications, and content storage in close vicinity to mobile end users [34]. In the Fog computing paradigm, data processing happens locally rather than being sent to the Cloud servers [35]. Fog servers are located at base stations, streets, parklands, restaurants, and shopping malls [1]. Fog computing supports offloading, caching, location awareness, and mobility information. It has many advantages for applications that are delay sensitive [36]. According to CISCO [37], real-time requirements of IoT devices can be fulfilled by Fog computing paradigm because it provides services like computation, storage, and caching closer to the end user(s) than the conventional CC. Fog computing is a trending topic in industries. The OpenFog Consortium [39] was formed in November 2015 with the objectives to solve the issues related with IoT real-time applications and Tactile Internet whose performances are crucial on latency. This consortium is working on architectural design and testbed cases. There are no restrictions for the contributors/researcher and everyone can contribute irrespective of region and it is a public-private ecosystem. Many use cases have been published such as controlling the drone traffic [40]. Drone traffic can be generated by IoT devices and an instant process may be required which can be provided by Fog computing devices located near to end users. The Fog technology are also commercially available such as IOx and Local Grid [15].

Fog Computing addresses issues in the applications that are distributed instead of centralized cloud architecture [41]. Due to proliferation of smart devices and their requirements, cloud servers cannot be a single solution. Since all data are gathered to one data center and required data are distributed to devices from the center. Therefore, the centralized structure of CC causes a long delay by accessing WAN due to congestion of data, which may create challenges in IoT applications requiring real-time services. For example, Applications such as Augmented Reality (AR) services require minimum latency for accessing computation resources [42]. In addition to the latency issue, many of the devises in IoT are mobile, mobility management for the devices is hard to be supported in conventional cloud architecture because of centralized architecture. On the other hand, Fog computing can be used for localized services according to the application demands [43].

One comparative example of the localized service using Fog computing is illustrated in Figure 7(a) and Figure 7(b). As illustrated in Figure 7(a), a mobile user wants to get flyers of store inside shopping center. However, to retrieve the flyers the mobile user needs to request the remote cloud server. Since the store need to upload flyers on the cloud over Internet. This results in high latency because of long physical distance between the Cloud server and the user. In order to overcome such latency, the flyers should be stored locally inside the shopping center so that user can access directly instead of requesting to remote cloud server. As illustrated in Figure 7(b) the Fog server is deployed inside a shopping center for providing localized services to users. From the example in Figure 7(b), it might be obvious that Fog computing provides better services than cloud computing in term of latency. However, some of the application cannot be satisfied by Fog computing such as smart grid which requires global cloud servers. Therefore, the interaction among cloud and Fog servers should be regulated. Face identification [44] is a use case that utilize both Fog and cloud servers and utilizing benefits from both ends.

Figure 8 illustrates the use case of all the aforementioned services of face identification. When a user requests a service to the Fog server using image as an input, then the subservices i-e face detection and image preprocess is executed by the Fog server. The pattern recognition is the last step and has high computation complexity than the other initial services. Therefore, Fog server offload this task to the cloud server for further processing. When the cloud server processes the task



(a)

(b)

FIGURE 7. Localized services by Fog computing: (a) Retrieving flyers from Cloud, (b) Retrieving flyers from Fog.

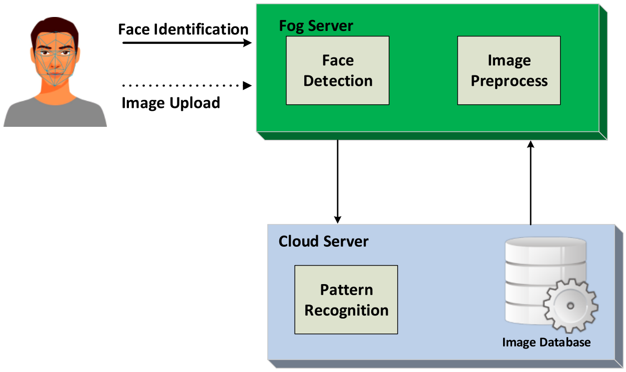


FIGURE 8. Face identification using cloud server and Fog server.

and achieves the face identification, the result is then forward to the Fog server.

D. MOBILE EDGE COMPUTING

The term Mobile Edge Computing (MEC) is coined by European Telecommunications Standards Institute (ETSI) with the aim to push computational power into RAN and to leverage the virtualization of software at the radio Edge. In order to realize the power of location both fixed and mobile networks are accepting MEC. However, initially MEC were intended for mobile networks only. This new paradigm of MEC can accommodate and optimize the performance of many applications.

MEC empowers the Edge of the network to perform in isolated way from the rest of the network and allow access to local resources [34]. The motivation behind MEC is the proliferation of smart phones and the traffic generated from the phones. According ETSI, MEC can reduce the latency and can provide location awareness to mobile users. Requirements such as bandwidth (higher), latency (lower) and mobility should be met in future mobile networks such as 5G and beyond. Therefore, to fulfil such requirements both the RAN and core network should be optimized to serve billion of devices [45]. It is noted that 5G system shall be able to provide end to-end latency less than 10ms and 1ms for some special cases [46]. MEC is the promising paradigm to reduce latency. Furthermore, Edge servers address issue of congestion at the core network. The reason is that most of the traffic is processed locally instead sending to the backbone networks [47]. Providing cloud-resources at the Edge creates issues such as security and privacy [48]. Furthermore, MEC servers could be congested due to loads on MEC servers. Therefore, the non-functioning of MEC servers may result in huge cost for operators [49]. In the following subsection, we discuss the content delivery process in the conventional MEC architectures.

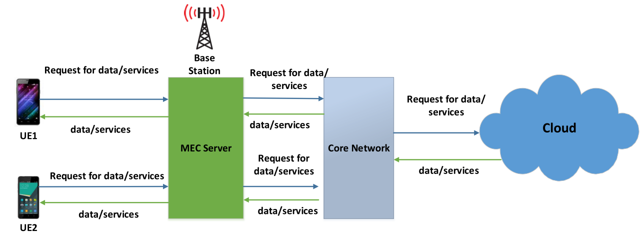


FIGURE 9. Content forward process using MEC server.

E. CONTENT DELIVERY IN MEC

Figure 9 depicts the data/service delivery process in MEC architecture. The architecture consists of User Equipment (UE), base station with MEC server installed, the core network, and the Cloud. First, UE requests some data/service from the MEC server, which is installed at the base station. The first time, the data/services are not found in the MEC server. Therefore, the MEC server forwards the request to provider for requested data/service through the core network. The provider replies with data/service and sends back to the MEC server. The MEC server saves the data as well the service subject to the policy of MEC. Now in the future, whenever UE requests the same data or service, then UE will obtain it from the MEC server instead from the Cloud. This reduces the latency and traffic for future requests. However, without MEC installed at base-station, the user interacts with cloud center via access point and core network. Therefore, it creates an increased data traffic towards cloud and results in

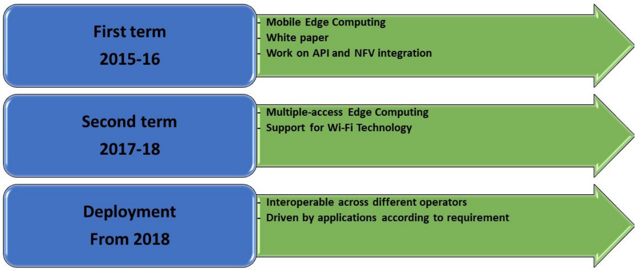


FIGURE 10. **MEC progress.**

delay and high response time. Using Edge computing at base station brings computation capability, and cache capability at the Edge of network in close proximity to end users.

F. NO LONGER MOBILE EDGE COMPUTING

As previously discussed the term MEC was coined by ETSI in 2014 with a white paper authored by Huawei, IBM, Intel, Nokia, NTT DOCOMO, and Vodafone [50]. ETSI main objective is to shift storage, processing, and control to the Edge of network. While the term specifically referred to mobile networks initially, now ETSI's scope covers both mobile and fixed networks. The MEC acronym no longer refers to "*Mobile Edge Computing*" and instead stands for "*Multiple-access Edge Computing*" [18]. The extension includes non-cellular technologies and now Wi-Fi is included within MEC's scope. Most of the mobile operators uses Wi-Fi and most of the traffic accounts for Wi-Fi network on mobile devices. Hence, this is a very good inclusion for mobile networks.

1) MEC PROGRESS SO FAR

The ETSI MEC progress is illustrated in Figure 10. The basic specifications are released by MEC during the first stage (2015-2017). During the second terms (2017-2018) the agenda was to extend it to mobile networks and to strengthen the collaboration with other Edge computing initiatives. Along with the standardization and industry body different business and deployment models should be explored, such a private owners, enterprises, and providers. Enhancements in QoE are very important. From 2018 onwards the ETSI planned to deploy MEC across different operators. However, in practical it shall take time before commercial release [18], [19].

IV. DIFFERENCES BETWEEN EDGE COMPUTING PROPOSALS

In the previous sections, we discussed in detail about Edge computing proposals. Since the vital role of Edge computing is to bring computational resources to the Edge of network. However, implementation specification differs at different aspects for each proposal. In this section, we discuss the key differences among all Edge computing proposals in depth.

The fundamental objective of MEC is exploiting the capacity of conventional cloud at the Edge for accomplishing the operations of mobile network and offloading the subscriber's tasks. MEC provides access within RAN instead of core WAN to minimize latency and to decrease the energy consumption [51]. However, Cloudlets and Fog computing provides the services to offload the subscriber's tasks. Service providers also affect the Edge server operations. Furthermore, mobile network operators maintain the MEC and provide services to a group of subscribers. However, Cloudlet or Fog servers can be deployed with in a private environment such as shopping mall and restaurant etc. [3]. Some of the key aspects of each proposal are discusses as follows:

A. DEPLOYMENT LOCATION

The specifications of MEC states that MEC servers should be co-located with the cellular network base station. On the other hand, Fog servers are generally provided by private environment such as shopkeeper etc. However, they can be deployed as routers and gateways in Internet service provider (ISP) infrastructure. Cloudlet can be deployed in a distributed way. Said otherwise, there is not exact location or vendor for the deployment of Cloudlets. MEC server is reachable via third generation/Long-Term Evolution (3G/LTE) base station. Therefore, MEC has the largest coverage area among the Edge computing proposals. However, Fog servers and Cloudlets are accessible via wireless access point (AP) whose coverage area is much smaller than 3G/LTE. Mostly the Cloudlet study emphasis on Wi-Fi as an access technology. However, Cloudlet is not limited and can be applied in other wireless technologies [50]. Furthermore, Worldwide Interoperability for Microwave Access (WiMAX), is also supported by Cloudlet and may be utilized for communication between Cloudlets [52]. Due to technological enhancement in cellular networks, the operators emphasis on MEC technology. In other words, future cellular networks are more commonly referred to MEC instead of any other Edge Computing proposal. Hence, for cellular networks, MEC is the de-facto Edge computing technology. The reason is that Cloudlet and Fog computing have short range communication such as Bluetooth and Wi-Fi and hence cannot reach to the level of MEC.

B. DEVICES AND USERS

Mostly studies related to Edge computing specifically Fog computing addresses the use cases of IoT and vehicle-to-vehicle (V2V) communication. For this reason, the users and devices in Fog computing is expected higher than the Cloudlet. However, Cloudlet covers the IoT devices but not V2V communication. The users of MEC is much smaller because MEC only focuses on subscribers and providers in cellular environment.

C. TRAFFIC PATTERNS

Due to huge number of users served in IoT and the traffic generated from all the users and diverse devices affect the traffic patterns at the Edge eventually. The traffic or data generated from Fog enabled servers and Cloudlet are continues data generated from sensors while the traffic of MEC servers

TABLE 2. Features comparison of conventional cloud systems and edge computing proposals.

Features	*Cloud Computing*	*MCC*	*Cloudlet*	*MEC*	*Fog Computing*
Latency	High	Low	Low	Low	Low
Network Access Type	WAN	Mostly WAN	Mostly Wifi, WLAN	3G/LTE, Base Station	Wireless access point (AP)
Deployment Location	Centralized such as Amazon etc.	Centralized	In private environment, such as shop, restaurant etc.	Mostly at Base stations, RAN	In private environment, such as shop, restaurant etc.
Mobility Support	No	Yes	Yes	Yes	Yes
Distribution	Centralized	Distributed	Distributed	Distributed	Distributed
User Devices	Computers	Mobile	Mobile	Mobile and Fixed devices	IoT and smart wearable devices
Management	Services provider	Local businesses and service providers	Local business	Local business and services providers	Local business
Conserving Energy	No	Yes	Yes	Yes	Yes
Scalability	Yes	Yes	Yes	Yes	Yes
Distance to users	Large (may across the country border)	Large (may across the country border)	Small	Small (ten to hundreds of meters)	Small (in meters)
Backhaul usage	Frequent use	Frequent use	Infrequent use	Infrequent use	Infrequent use
Applications	Delay tolerant and computation insensitive	Delay tolerant	Latency sensitive	Latency sensitive	Latency sensitive
Ownership	Centralized ownership by amazon, yahoo etc.	IT companies e.g. Google and Amazon	Private business owners	Mobile vendors	Local business owners
Location awareness	No	Yes	Yes	Yes	Yes
Server hardware	Highly capable servers	Highly capable servers	Small scale servers	Small data centers	Small scale servers
Deployment cost	High	High	Low	High	Low (can be adopted from available devices such as router etc.)
Server density	Low	Low	High	Low	High

are intendment and non-continuous. The reason is the pricing polices and targeted use cases of cellular networks [54].

D. DEPLOYMENT COST

Deployment cost is also one of the key factors that varies in each proposal. MEC servers is located at the base stations and the cost of server deployment at the base stations are expensive than Cloudlet. The cost of Fog servers is not higher than MEC because of available devices such as a wireless AP and a router etc. [43]. Therefore, the Fog server(s) result in a minimum deployment cost than other Edge computing proposals.

E. NUMBER OF SERVERS

MEC servers can be installed at the base stations and hence server density is limited to the base stations. While the Cloudlet can be installed at any public place such as coffee shop, shopping mall and restaurants etc. Cloudlets mostly uses wireless local area network (WLAN) as an access technology. Therefore, the density of Cloudlet is much higher than other Edge computing proposals. Fog server(s) deployment is average and cannot be installed everywhere like Cloudlet. The comparison of conventional cloud systems and Edge computing has been shown in Table 2.

In order to enable MEC in innovative use cases, several organizations provide implementations in accordance with ETSI Industry Specification Groups (ISGs)and MEC Proof of Concept (PoC) Framework [55].

Edge computing use cases varies due to users, server deployment and vendors. The main objective of Cloudlet is to reduce the delay for real-time applications such as AR/VR. A set of use cases and scenarios has been introduced by ETSI ISGs in the Group Specification (GS MEC-IEG 004) [49] to showcase the role of MEC for the improvement of QoS.

V. EDGE COMPUTING USE CASES

This section aims at the protentional benefits of Edge servers in real-life implementations. In following subsections, we discuss the use cases given in the Edge computing literature.

A. COGNITIVE ASSISTANCE

Cloudlet is used as an enabler for the real time cognitive assistance applications that runs on wearable devices such as smart glasses [50]. The main objective of Cloudlet in cognitive assistance is to accomplish task with low response time. A Cloudlet framework has been proposed in [57] as a practical implementation.

B. BODY AREA NETWORKS (BANs)

The fundamental role of a BAN is to monitor the collected data with low latency [58]. A huge amount of data is generated in BAN that need storage and computational resources.

Moreover, the data which has been generated in BAN is life critical and need to be monitored in real-time. The collected data can be stored and analyzed with low response time using Cloudlet and Fog computing. A huge amount of data is uploaded by sensors in the case of electrocardiography (ECG). In case of instant processing of ECG data, the Fog servers can be used to process the collected data with low response time. The data is collected by Fog servers and various operations could be performed such as data filtering and data aggregation [59].

C. HOSTILE ENVIRONMENTS

The data generated by sensors in hostile environments such as war can be compromised [60] In order to detect adversaries in hostile environments, Fog servers can be used to analyze the sensed data of sensors with low latency [61].

D. LANGUAGE PROCESSING

Language processing applications required large resources and continues Internet connection for the better processing of real-time processing [62]. Mobile devices are not good enough to provide all these resources because of limited capacity. Cloudlet can be used to lower the load on mobile devices and to provide all the necessary resources. The Cloudlet eliminate the WAN for all Cloudlet enabled applications. An application named Android smartwatch has been implemented which transfers the collected speech data to the Fog servers to be processed [63]. After processing at Fog servers, the data is transferred to the cloud servers for further analysis.

E. SMART GRID NETWORKS

The Edge computing may be used for the smart grid networks. In case of Advanced Metering Infrastructures (AMI) the data may be categorized in different classes such as normal data and real-time data [64]. Normal data is transferred periodically and do not need real-time interactions. In case of real-time situation such as alarming situation in a grid, the data need to be processed with minimum latency in order to prevent the fire hazards. Therefore, the Fog computing may be utilized for load balancing in such cases. Smart grid works on multi-tier architecture and needs both Fog and Cloud architecture [37]. Main Cloud servers provide services for storing the data for months and years and for analyzing large amount of data. Local data can be processed by Fog nodes as well as MEC server(s) [65].

F. WIRELESS SENSOR NETWORKS AND IoT

Wireless sensors are resource constrained in terms of storage and computation resources and unable to perform complex functions except sensing and relaying data [37]. Fog computing can overcome the storage and computation limitations by offloading user's tasks. Moreover, wireless networks have interoperability problems because of heterogenous environments. This problem can also be solved by deploying heterogeneous Fog nodes [66]. CitySee [67] is an environmental monitoring system in which the sensors data are transferred to the sink node(s). The data is processed and then transferred to the Cloudlet. A huge amount of diverse data is generated by IoT devices that need to be aggregated. Cloudlet can be used for IoT environments since Cloudlet services can interact with IoT devices [4].

G. VIDEO ANALYSIS

Low latency and jitter are required mostly in video steaming. This can be achieved by enabling services at the Edge instead of centralized servers to eliminate the WAN congestion. For instance, if Fog server is deployed inside a bus or train then video streaming with low latency can be provided using Wi-Fi [43]. Fog servers are storage capable and have computational resources to analyze video steams [68] . The video processing tasks can be offloaded to the Cloudlet to minimize delay and jitter to a certain threshold. Moreover, Cloudlet can also be used in stadiums to replay the video for audience. In stadium thousands of users request the video at a time and hence resulting in congestion. Therefore, Cloudlet or Fog node can be used to offer video streaming services at the Edge and closer to users to mitigate the congestion.

H. AUGMENTED REALITY

The proliferation of smart phones and wearable devices such as smart glasses boosted the popularity of AR applications [68]. These smart devices are not capable of handling computational complexity. Cloud Computing is better option for providing computational power and storage capacity. However, AR applications are latency sensitive, and traditional cloud systems cannot fulfil the required latency requirements. Therefore, Fog computing can be used to fulfil these requirements such as an increased throughput and lower latency.

Let us take an example scenario which takes inspiration from the pervasive AR scenarios mentioned at [69] and [70]. This example scenario explains the pervasive AR between Carlos and Sally and is discussed as follows.

Carlos is informed by his voice assistant to meet Sally and then he moves towards his self- driving car. His smart glasses mapped the destination map and time of arrival. Upon reaching the destined location, Carlos steps out from his car and entered into a busy market. His face identification application identified Sally in the crowd. Both Carlos and Sally met at a specific location and after meeting their glasses make a visual route towards a nearest cafe. Right at this time, Carlos and Sally both receives an alert message about major earthquake to happen. After the alert message, the most structurally strong spots are highlighted to them within the building, and they run toward nearest spots. As the power goes out and parts of the building collapse, Carlos and Sally get separated, trapped in separate parts of the building. Existing sensors connect with their glasses and now visually displayed as places where first responders can access video and audio feeds. Both Carlos and Sally wait trapped under the rubble for the first responders to arrive [70].

In the above scenario, the services are offered with continuous context changing, from Carlos leaving his home, to getting into the car, to meeting Sally, experiencing the earthquake, and reconnecting with her. In this scenario, when the earthquake occurs, pervasive AR is able to operate even the infrastructure is failed and the local resources has been compromised. Therefore, the key requirement such applications is fast information response time which is unable to achieve with the existing host-oriented approach. Therefore, it is important to introduce emerging and innovative architectural and networking paradigms to accommodate such latency requirements.

I. CONNECTED VEHICLES AND SMART TRAFFIC LIGHTS

High mobility and unreliable wireless connection are the main reasons that affects vehicular communication [70]. The performance can be improved by installing Fog technology for communication between vehicles. Moreover, Fog technology can also be used in smart cities such as smart lights to avoid the accidents by communication with each other [4]. In addition, in road traffic signals scenario a video system can detect an ambulance and can change the traffic lights for opening a way for ambulance. To avoid the road hazards and traffic congestion, an instant communication is needed with the driver of vehicle. Therefore, the MEC technology can be used to provide roadside information to travelers by cooperating with sensors [55]. The sensors at the roadside senses the data and then transfer to MEC servers for further processing. This collected data can be pass on to other vehicles in the range. Using MEC technology the vehicle drivers can be informed of traffic congestion, accidents and other road hazards. Beside advantages of MEC in vehicular communication, there are many security issues such as reporting of fake data by vehicles, trust and user privacy etc. [71], [72]. Therefore, security and privacy should be considered for the protection of user's data [73].

Even though the Edge computing offer better performances than cloud, however there are some limitations that needs to be addressed. In the next section, we will discuss the limitations of Edge computing.

VI. LIMITATIONS OF EDGE COMPUTING

The EC paradigm brings computational resources, storage and services from the cloud to the Edge of the network and therefore closer to the consumers, in order to reduce latency. Examples for such capabilities are resources for computational-intensive and time-sensitive operations or flexible deployment of applications and services. However, the Edge Computing approaches (Specifically Multiple access Edge Computing) is based on virtual machines (VM) and totally based on the host-centric networking model (TCP/IP approach). This creates challenges in data dissemination between the highly mobile users as well as the addressing issues of domain name systems (DNS) due to nodes constantly joining and leaving the network. Exiting TCP/IP-based solutions have some weaknesses when designed to support cloud services at the Edge of network.

Therefore, following are some of the limitations of TCP-IP based solutions for Edge computing and is discussed as follows:

A. LATENCY

TCP-IP-based approach creates unacceptable latency for many latency-critical mobile applications such as autonomous driving, Realtime online gaming, VR, AR, Tactile Internet etc. Such applications may require tactile speed with latency approaching 1ms. Latency cannot be avoided, of course. However, it can be precisely measured, understood, and managed in order to minimize its impact on QoE and network performance [97].

B. LACK OF BUILT-IN MECHANISMS TO DISCOVER POTENTIAL PROVIDERS

TCP-IP-based cloud platforms typically implement a Representational State Transfer (REST) model to access cloud resources through Hyper Text Transfer Protocol (HTTP). HTTP uses Uniform Resource Identifiers (URIs) to identify the resources via Resource Discovery. When the resource discovery servers are not available then multicast DNS can be used for service discovery. The reason is that network layer and transport layer in TCP/IP are unable to autonomously discover the resources defined by the application-layer names and do not allow application semantics into network layer packets. This can be done by moving some of the functionalities implemented at the application layer (e.g., REST-related) to the network layer [98].

C. DYNAMIC PLACEMENT OF APPLICATIONS AT EDGE NODES

Dynamic placement of applications at Edge nodes and resolution of requests to those nodes is a problem in EC. Furthermore, the application software's that run Edge computation must be first downloaded on the Edge-node, while mobile clients request for resources from different locations. Mobility as well as diversity in user demand makes it very difficult to predict which functions would be requested in the future and from where in the network [99].

In recent years ICN was proposed which addresses data directly using content identifiers, instead of addressing the host in the network. This fact allows mobility support by nature, while not maintaining network addresses of hosts. Moreover, it facilitates features such as in-network processing and caching of data. Therefore, to overcome the above-mentioned issues, ICN in Edge computing is promising.

We have discussed Edge computing in depth so far. In the next section, we will discuss the futuristic paradigm called ICN that would be used as deployment strategy for Edge computing.

VII. INFORMATION-CENTRIC NETWORKING

Various ICN architectures have been proposed that share common ideas and principles, such as name-based content retrieval and discovery, content-based security, in-network caching, and connectionless receiver-driven communication models [74]. Interested readers are referred to [75] for more detailed information about such projects and architectures. In the ICN paradigm, a unique name is assigned to content, and that content is retrieved without knowing about the location where it resides unlike traditional IP systems. That name uniquely identifies the content (e.g., a video, a picture, a document, a web page). In this paradigm, the content is secured instead of communication channel/pipe. Connectivity between consumers and producers is not necessary for the exchange of content. Anycast data retrieval is supported, meaning that the router forwards requests to any node holding content. ICN offers flat or hierarchal naming. The former is easier to manage and self-certifying. However, it is not readable to humans. The latter is human-readable and the most usable and backward compatible [76]. Both have pros and cons. If flat names are used, attackers can be avoided because the names are un-readable to humans. If hierarchal names are used, attackers know to attack sensitive data since the information is unveiled to users. However, content-based security is implemented at the packet level rather than at the communication channel/pipe level.

ICN is based on two packet types, Interest and Data. The communication process is as follows:

1) Consumers send Interest packet(s) containing the names of the requested content.
2) Data packet(s) flow back, carrying the named and secured content chunks, by following the same path through which the Interest packets were sent [74].

Each node maintains three types of data structures: (1) a Content Store (CS), which is capable of caching data temporarily; (2) a Pending Interest Table (PIT), which retains the records of unsatisfied Interest packets (3) a Forwarding Information Base (FIB), which traverses Interest packets toward the data providers.

When a consumer node wants to access specific content, it sends an Interest packet containing the name of the content. When some relay node(s) receives the Interest packet, it first checks its own CS for data availability; if match is found, the node sends the data back to the consumer via the same interface from which the interest is received. Otherwise, it checks its PIT. If the entry is found in PIT, the node updates the existing PIT table by adding a new incoming interface entry and discards the Interest for further processing. Otherwise, a new PIT entry is created, and the Interest packet is sent further via interface(s) stored in the FIB. The Simplified procedure when a node receives an Interest packet is shown in Figure 11.

A. WHY ICN IN EDGE COMPUTING?

In the conventional Internet design the communication happens between fixed entities due to host based approach. However, due to rise of IoT and real-time applications such as AR, VR and Tactile Internet, it becomes challenging in terms of mobility, scalability, security and network management.

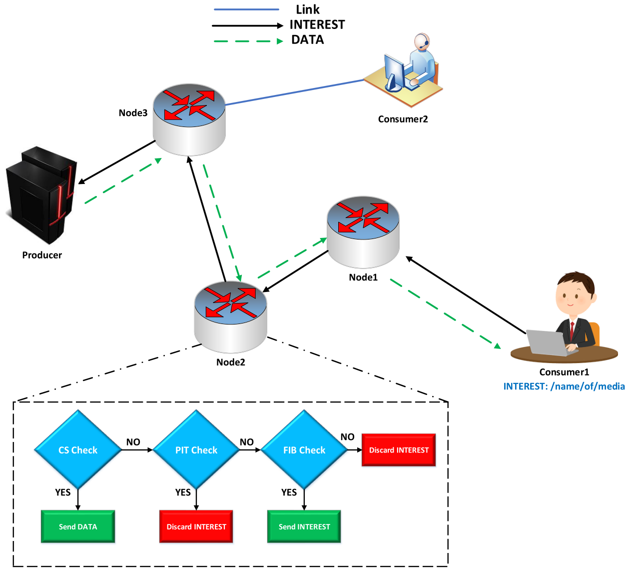


FIGURE 11. Simplified interest packet processing in ICN.

ICN is a promising paradigm that is based on named based communication rather than host based. The first research efforts in ICN was only limited to naming the content and to request on the network layer. However, in today's era the ICN also provides the naming of services with the help of Named Function Networking (NFN) [100]. Therefore, the content and services can be named and requested at the network layer without relying on the fixed communication of IP based approach.

Moreover, Edge computing is able to deploys services on the edge of network. The edge computing provides local computing and storage, thereby reducing latency. In addition, ICN natively supports decentralized caching, self-authentication and multicast that can enable Edge computing deployment. Both ICN and Edge computing has some correlative properties, such as decentralization, local storage etc. Fortunately, edge computing is able to support storage and computing naturally. A combination of both ICN and edge computing could result in better performance gains if paired the features of both together.

There are many expected benefits resulting from the integration of ICN in Edge computing which are described as follows:

1) VIRTUALIZATION OF SERVICES

In the literature, support is available for virtualization of services, such as Docker [101], Amazon Lambda [102] or serverless computing technologies such as unikernels [103]. These technologies are useful for Edge computing. Since it provides encapsulation of functions into self-contained software components, executable on Edge nodes and totally independent of its deployment structure.

Moreover, virtualization technologies are lightweight and efficient, leveraging their benefits to provide improved Edge services in resource constrained environment.

2) FUNCTION NAMING

In NFN [100] ICN function naming has been proposed to identify network resources and to support the execution of network functions. Explicitly named functions can be resolved in network nodes, while network-layer requests (i.e., Interests) can carry input information for Edge-executable functions. Function code can be stored in node caches and migrate across the network following user demand.

These solutions can be enhanced to support Edge computing by making use of ICN technologies to allow devices to express the services they need without having to specify the exact node that could provide those services. They could provide support by: a) route the requests to the best Edge server/device; b) instantiate/migrate the network function to Edge device that is closer to the user.

3) INTEREST AGGREGATION

In ICN over Edge computing, the interests can be aggregated with the same name coming from difference consumers, so that they cannot be duplicated over a given link towards a producer or service executor. However, the legacy IP approach does not allow aggregation of requests [104].

4) CACHING OF RESULT/COMPUTATION FOR REUSE

Nodes in NFN caches the results of functions/services and make them available to other consumers without performing the computation again and again [100]. Moreover, the distance between the Cloud and Edge networks can be several kilometers [87], which may result in a significant delay. ICN over Edge networks can achieve latency requirements by providing data and services that are close to end users via caching the content and results as well.

5) LOCATION-INDEPENDENT NAMING

Hierarchical user-friendly URI-like names uniquely identify a content (e.g., a movie, a picture, a song) as well as context (location, identity etc), independently of the identity/locator (i.e., the IP address) of the node generating/hosting it. Therefore, ICN is not bound to specific address of content, service or context. In ICN those all reflect the named pieces of content and could be requested via name directly at the network layer.

6) NATIVE IN-NETWORK CACHING

By integrating data caching into the forwarding process, NDN makes content delivery more robust against packet losses and improve content availability. Besides content caching it is also useful for function results that are executed in the network. Therefore, ICN not only provides content caching but also functions/code caching in order to avoid re-request the content or re-execute the function/code [69].

7) IN-NETWORK SECURITY

Protection and trust are implemented at the packet level, rather than at the channel level. By design, ICN, offers native support for security, which are still not effectively available in the host-centric paradigm [104].

The self-certify names model of ICN enable to verify the binding between public key and self-certify name in distributed system without relying on a third party. This can reduce the security risk of involving a third party. However, it is difficult to maintain the centralized key management infrastructures such as Central Authority (CA), especially in the constrained IoT. The reason is large communication and computational overheads incurred due to complex trust chain of certificate verifications. The problem was solved by Zhong et al., with a distributed key management scheme adopting identity-based public key cryptography (IB-PKC) [119] to avoid the problems of single location. However, it suffers the key-escrow problem and single point of failure. To solve the key-escrow problem and single point of failure, Al-Riyami et al., introduced a certificate-less public key cryptography (CLPKC) [120]. In this scheme, the private key is eventually generated by users and key generation center together, and the attacker is not able to acquire the private key of any users even when Key generation center has been compromised.

Recently Jun Wu et al., propose an anonymous distributed key management scheme based on CL-PKC specifically for Space Information Network (SIN) in order to overcome the security issues [121]. Authors designed a distributed key management system model for key exchange services. Since authors scheme is based on the certificateless public key cryptosystem, therefore, it can avoid the problems of complicated certificate management and key escrow. Furthermore, implementation methods have been provided for the generating and updating of key pairs. The security analysis and comparison of computational overhead confirms it's security and less computing cost as well. However, this was specifically designed for SIN, and may be used for NDN based Edge computing.

Liu *et al.* [122] proposed a scheme for information-centric social networks (ICSN) and claimed that the existing schemes for the conventional social networks cannot fulfill the requirements of ICSN. Therefore, a fog computing-based content-aware filtering method for security services, FCSS, is proposed in information centric social networks. They introduced fog computing in IC-SN, and the content aware filtering scheme is proposed for security services. Such Edge computing based ICN solutions can be introduced in many NDN-based Edge computing applications which are detailed in Section VIII. Moreover, CL-PKC is one of the areas to be explored for NDN based Edge computing applications.

8) BANDWIDTH UTILIZATION

Storage and bandwidth can be efficiently utilized due to ICN multi-point delivery mechanism. The content will be sent to a group of users and will not be unicasted. With growth of users the bandwidth will not be affected too much unlike unicasting. Therefore, using ICN over Edge computing we could utilize the bandwidth affectively.

9) BUILT-IN MOBILITY SUPPORT

Consumer Mobility is a built-in feature of ICN due to receiver driven and connectionless data communication nature. When an end device moves to a new location, it simply needs to re-express request for its interested data. However, support for producer mobility is still a research problem in ICN.

Some networks are highly mobile, such as vehicular networks (VNs). Therefore, if mobile users can only receive the content from the provider (original server), then the connection can be lost during the mobility of users. Due to interruptions in connectivity, users will re-request the content from original server. In ICN the mobility feature is inherently supported. The devices can directly communicate using service names instead of specific host such as Netflix.com or Youtube.com. Services are provided by the network and does not rely on end to end communication. ICN caching provides a copy of the content to all users and hence mobile users no longer make requests of the original server. Therefore, if the mobile users keep moving in network as in VN, then content can be obtained from the nearest cache instead of going to the original server. Hence, a reduction in delay and support for mobility is achieved. Moreover, ICN offers heterogeneous wireless support where mobile devices should be able to transparently use a variety of communication technologies [105].

B. FEASIBILITY OF ICN DEPLOYMENT ON EDGE

The traditional Internet is based on TCP/IP (host oriented) network model. Therefore, to replace the TCP/IP model with ICN is impractical. However, there is a way to deploy the ICN partially or overlay such as ICN over IP or IP over ICN. Deploying ICN on edge service not only can help to mitigate the ICN whole-network deployment complexity, but also makes the network model more flexible. The combination of ICN and EC is able to offer a great combo and such approach may result in maximum performance.

C. RELATED WORKS ABOUT ICN OVER EDGE COMPUTING

There has been no focused attempt to adjust existing proposals for Information-Centric Networks to support edge computing with the exception of few related works which are discussed as follows.

Sifalakis *et al.* [100] proposed a pioneering scheme call ‘‘Named Function Networking’’ (NFN) for the extension of NDN to the edge computing. In NFN, the name field of interest packet carry the name of the content as well as expressions for named functions. The network is in-charge of computing the result and resolving the forwarding plane of NDN. However, NFN is constrained by the number of services/functions it can support. In many scenarios, nodes require more sophisticated processing, custom code and libraries, which is difficult to express only through simple expressions and acquiring additional function code.

In [123], Named Function as a Service (NFaaS) has been proposed that supports more sophisticated processing with lightweight virtual machines in the form of named unikernels. The unikernels are actually the functions/codes. In NDN the content is cached in the Content Store. However, in NFaaS an additional data structure call Kernel store has been introduced. Every node contains Kernel Store that stores the unikernels. The Kernel store is responsible not only for storing functions, but also for making decisions on which functions to run locally. Since the Kernel Store has lots of functions and which functions to download locally to the node is calculated by score function. The score function score all the popular function that is requested more frequently and the main goal of score function is to identify the unikernels/functions that are worth downloading locally into the node’s memory.

Amade *et al.* [2] extended the NDN architecture to turn the network edge into a dynamic computing in the IoT domain. The proposed scheme performs distributed in-network IoT data processing at the network edge, by relying on NDN augmentation and named computations. This scheme also performs the dynamic execution of services, according to the interests popularity function. In the proposed scheme authors have performed minor modification of legacy NDN and used a naming scheme that identifies IoT contents and services without affecting the NDN routing.

Amadeo *et al.* [125] proposed an NDN based scheme call NDNe (NDN at the edge) that supports cloudification at the edge. In NDNe the existing NDN packet is extended and names are used to address, not only ‘‘contents’’, but also to identify different types of cloud service (e.g., storage, computation, etc.)

VIII. APPLICATIONS OF ICN INTEGRATION IN EDGE COMPUTING

Future networks such as 5G will result in data rates of multi gigabits per second and will support the scalability of devices. 5G systems will support real-time networks to deliver real-time controls. Latency is the fundamental unit of 5G systems, and thus the target is to enable low-latency applications such as Tactile Internet, autonomous driving, industrial robotics, and VR/AR applications. All these requirements cannot be fulfilled by the existing TCP/IP approach due to host-oriented approach and fall short for such applications. Indeed, ICN principles can directly address the above challenges. In ICN network, the content is cached along the path. Therefore, the requested content can be from the source node or the other content caching nodes thereby reducing latency. Instead of binding security to host node, ICN advocates the security model for the content. This model focuses more on securing the content not the channel. Moreover, consumer mobility is natively supported in ICN architecture. In 5G application it is possible to have frequent handover events. Since ICN can natively support mobility through its content-centric design and stateful forwarding plane, Therefore, an ICN solution for consumer mobility would be more appropriate. In addition, 5G networks are expected to utilize multiple interfaces. ICN offers heterogeneous wireless support where mobile devices should be able to transparently use a variety of communication technologies simultaneously.

Following subsections details some of the 5G applications as follows:

A. TACTILE INTERNET

Low latency and the highest reliability of data with more security for real-time systems, such as real-time gaming, industrial automation etc., will be provided by Tactile Internet [12]. 5G wireless solutions will fulfil the requirements of wireless communication for 2020 and beyond. Therefore, 5G is predictable to support the Tactile Internet at the Edge of wireless networks. To reduce the latency and bandwidth requirements, content will need to be either localized or pushed to the Edge of networks [86].

B. INDUSTRIAL AUTOMATION

Various control processes exist and require different data rates, reliability, security, and latency [87]. Automation industry applications will be driven by 5G systems. Currently, the wired industrial Ethernet is used to control processes. Wireless systems adoption is necessary for flexible production, which requires guaranteed reliability and low latency [88].

C. AUTONOMOUS DRIVING

Within the context of 5G, autonomous driving is discussed as a new phase in mobility. Today's applications require latency to be less than 10ms for vehicle safety to avoid collisions. Therefore, if the bi-directional data exchange for the movement in autonomous driving is considered, a latency of millisecond will likely be desired [87]. Highly reliable and proactive behavior is thus needed in future 5G communication systems. However, ICN with Edge computing could solve the issue of latency and mobility for autonomous driving.

D. INDUSTRIAL ROBOTICS

Autonomous robotics may react in an irregular manner if real-time communication fails. Therefore, it may lead to an unwanted behavior. There are many scenarios in the manufacturing of robotics that necessitate a maximum delay target of 100μ s and round-trip reaction time of 1ms [88]. In order to provide such latency, it is of upmost importance to bring the content and resources closer to the user. Moreover, integration of ICN with Edge computing is a promising approach for providing real-time communication.

E. VIRTUAL AND AUGMENTED REALITY

Tactile Internet can prove helpful for VR and AR applications. Many users mutually perform tasks by perceiving objects using simulation tools in VR. On the other hand, in AR, dynamic content is visualized compared with today's static augmentation [87].

The existing AR applications are built upon TCP/IP protocol stack and rely on cloud computation. To enable pervasive AR applications, it is important to explore new computing paradigms, new approaches such as ICN to network communications. Though the existing AR applications bring utility in specific domains, their reliance on cloud service may limit the potentials of AR [89]. Therefore, Edge computing paradigms, within physical vicinity, could achieve the required low latency while protecting user privacy. Edge computing paradigms are important in accomplishing pervasive AR. To support Edge computing, ICN, can be introduced that how ICN could address the requirements of resource discovery, multicast support for context-content exchange, and experimentation with user experience.

These applications will drive the ICN and Edge computing design in terms of latency, performance, and scalability and would prove the importance of ICN in Edge computing. The ICN naming mechanism may result in lower signaling costs in content retrieval [89].

This article intends to show ICN as an important deployment strategy for the utilization of ICN mechanisms and their key benefits in such environments of Edge computing. ICN can be beneficial, allowing new concepts to be developed based on named requests, caching, any-casting, and new applications to be created, as a true future Internet paradigm.

IX. STANDARDIZATION ACTIVITIES

Many academic, industry and standard organizations are working to address various research topics in Edge networks and ICN. In the United States, these programs come under the National Science Foundation (NSF) Future Internet Architecture initiative (e.g., CCN, NDN, Mobility First, Xia). In Europe, they are under the European Union (EU) Framework programs (through H2020).

ETSI plays a vital role in the development and implementation of telecommunication standards. ETSI is currently working on the development of standards relating to cloud. The work of ETSI MEC aims to provide IT and CC capabilities within the RAN. MEC shall enable applications and services to be hosted on the base station. These applications and services can benefit from being in close proximity to the customer and from receiving local radio-network contextual information [2].

The ETSI MEC ISG was founded in December 2014 and the purpose of the ISG is to create a standardized, open environment which will allow the efficient and seamless integration of applications from vendors, service providers, and third-parties across multi-vendor MEC platforms.

MEC ISG has been published the following specifications so far [56]:

1) Foundation specification GS MEC 001 MEC Terminology (2016-03)
2) Foundation specification GS MEC 002 MEC; Technical Requirements (2016-03)

3) Foundation specification GS MEC 003 MEC; Framework and Reference Architecture (2016-03)
4) GS MEC-IEG 004 MEC; Service Scenarios (2015-11)
5) GS MEC-IEG 005 MEC; Proof of Concept Framework (2015-08)

In [79] and [80], Edge computing is demonstrated using OpenStack to bring the cloud closer to the mobile Edge. The Open Edge Computing project [31] was created in 2015 to facilitate prototyping applications that can take advantage of Edge computing and engaging with relevant development communities.

Open Fog Consortium (OpenFog) is founded in November 2015 by a major industry movers and leading academic institutions. The OpenFog Consortium [40] was founded by the following technology industry leaders: ARM, Cisco, Dell, Intel, Microsoft and Princeton University in order to solve the bandwidth, latency and communications challenges associated with the IoT, Artificial Intelligence, Robotics, the Tactile Internet and other advanced concepts. 3rd Generation Partnership Project (3GPP) [80] recently started the NextGen study item, which aims at defining the 5G system architecture. ICN is not yet being explicitly addressed as a dedicated payload type in the 3GPP system. This is partly due to the fact that the related work on defining the ICN protocol and the related mechanisms in Internet Research Task Force (IRTF) and Internet Engineering Task Force (IETF) are still ongoing.

The key enabler for many ICN use cases is the ability to deploy ICN routers close to the radio network. Information-Centric Research Group (ICNRG) was formed to identify outstanding research challenges for ICN, and to couple ongoing ICN research with solutions that are relevant and appropriate for evolving the Internet at large [81]. The work in the ICNRG (in the form of Informational Request for comments (RFCs), meeting contributions, etc.) is completely documented and accessible through its website at https://trac.tools.ietf.org/group/irtf/trac/wiki/icnrg.

ITU Telecommunication Standardization Sector (ITU-T) created a group IMT-2020 [82] to study how emerging 5G technologies will interact in future networks. This group also included studies on high-level network architecture. The Alliance for Telecommunications Industry Solutions (ATIS) board initiated a committee to investigate the Evolution to Content Optimized Networks (eCON) [83]. Although not exclusively focused on ICN, most work addressed the overall ICN opportunity space from a network operator's perspective. 5G Americas present a 5G white paper [84] which describes some detail ICN architecture, along with ICN benefits and use cases. ICN is presented as a potential technology for consideration as 5G. The paper suggests that 5G should be based on new network architectures and protocols designed specifically, with support for mobility, security and content caching as fundamental design criteria. ICN as realized in the NDN and Content-Centric Networking (CCNx) programs is described as a leading architecture that can meet such design criteria.

Next Generation Mobile Networks (NGMN) published a 5G white paper [85] in March 2015. The paper provides requirements for 5G and encourages the adoption of new emerging technologies. ICN is one of the technology building blocks considered by NGMN. ICN is described as having the potential to migrate from a host-centric and node centric model to a content-centric, data-oriented and information-centric model with an intrinsic focus on named information objects in network caching and name-based routing.

X. VENDOR SOLUTIONS

In this section, we will discuss about vendors which are working on the Edge computing solutions. This subsection explains the up to date hardware and software solution related to the Edge computing paradigm so far at the time of writing this survey paper.

A. ADLINK TECHNOLOGY

ADLINK technology [106] is working towards hardware solutions for Edge devices which are capable of Fog computing and MEC features. Recently a product has been launched by ADLINK called SETO-1000 [96] which is a part of the MEC architecture. SET0-1000 is designed with the aim to provide networking solutions in extreme outdoor environment. It is providing CC features within the RAN closer to mobile users. The platform consisting of storage capacity, accessibility to real-time radio and network information. Moreover, it reduces the backhaul cost and increase network efficiency in terms of delay and bandwidth since the data is processed at the Edge.

ADLINK is a Premier Member of the Intel Internet of Things Solutions Alliance. Moreover, ADLINK is contributing in many standardization projects, including Open Compute Project (OCP), ETSI MEC , Network function virtualization (NFV), OpenFog Consortium, Telecom Infra Project (TIP), the PCI Industrial Computer Manufacturers Group (PICMG), the PXI Systems Alliance (PXISA) and the Standardization Group for Embedded Technologies (SGET).

B. ADVANTECH

Advantech [107] enables MEC and OpenFog deployments by providing hardware solutions at the outer Edge, and pushes the processing, storage to the far Edge. Recently, Packetarium XLc, which is a virtualized platform has been introduced by Advantech for Edge-computing deployments. Moreover, it offers solution for 5G networks based on open architectures and industry standards. According to [107] Packetarium XLc is installed far from centralized data centers, and it can support 9 slots, up to 288 Intel Xeon processor cores. Advantech along with Vasona, Brocade, GigaSpaces and Saguna Networks takes part in an ETSI MEC PoC, "*Multi-Service MEC Platform for Advanced Service Delivery*". The PoC illustrates how the infrastructure between a Network Function Virtualization (NFV) and a cloud system can simultaneously support many MEC platforms and applications.

The MEC platform offers operators optimization of RAN performance, particularly, to minimize latency.

C. ARTESYN

Artesyn [108] focuses on virtualized solutions in the RAN as well as in the core network. Artesyn is also designing the hardware for next generation networks to facilitate the transition to 5G. The MaxCore platform has been developed for Edge computing. Artesyn, with the support of MaxCore platform, offers a power efficient, scalable and flexible fully integrated suite of cloud-based products.

MaxCore is mainly focusing on optimizing performance in terms of latency and bandwidth, for the environments where the subscribers and traffic is in high density. Artesyn has worked on many use cases such as Known-location services (for government, retail, education and health), IoT applications (for smart cities) and AR.

D. INTERDIGITAL

In order to enable ultra-low latency, real-time and location-specific traffic optimization and context awareness, Interdigital [109] is working towards MEC, to bring storage and Processing at the far Edge of user devices. Interdigital actively takes part not only in the ETSI MEC i-e the Open Fog Consortium, open-edge initiatives, groups (for example 3GPP), but also in advanced wireless research (PAWR) platforms such as NSF's Platform and European Commission's Horizon 2020. Furthermore, in collaboration with University of Essex and Intracom, Interdigital also gets involved in an ETSI MEC PoC. Interdigital integrates ICN and SDN. According to Interdigital, the paradigm shift of networking away from host-to-host communications, to content- and name-based addressing by ICN, is mandatory to satisfy the requirements of 5G's latency. Furthermore, Interdigital keeps focusing on its development and research, to combine the services and network infrastructure, such as converge of NFV, MEC and SDN with the evolution of 4G and the development of 5G.

E. QWILT

Qwilt [110] was established in 2010, to facilitate the broadband fixed and wireless services. Qwilt offers optimization both in terms of latency requirements and capacity of high video traffic loads to enhance the QoE.

In order to optimize the video delivery and to facilitate real-time applications such as VR and AR, Open Edge Cloud platform offers content delivery solutions and open caching to service providers at the network's Edge. To minimize latency, the Edge Cloud platform enables the storage capabilities and computation as much as possible to the Edge of the network.

The main purpose of Qwilt's Edge Cloud solution is to extend the Content Delivery Networks (CDNs) and content providers to reduce the costs of transport for efficient delivery. To use the network infrastructure more efficiently, Open Caching software integrates open caching with analytics and media delivery, which allows them efficiently to manage the rate and distribution of traffic (over time). The great advantage of open caching, data which is frequently in use, can be accessed without requesting any action from CDNs, content providers or subscribers, since it is stored at the Edge of network.

F. VASONA NETWORKS

Vasona Networks [111] is working towards Edge computing to manage the traffic at the Edge between the mobile core and the RAN, to optimizing RAN performance and QoE. The main aim of this technique is to assist mobile operators by providing them better end-user quality and efficient use of network resources.

Initial solutions by Vasona, focused on the challenges of video traffic and the requirements of its latency, that mobile operators have to suffer. Standards-based software platforms has been developed by Vasona for MEC that could be placed at an aggregation point between the mobile core and the RAN. Typically, a thousand or more cells can be covered by locating the MEC functionality in an aggregation point.

Today, Vasona has two products (i.e. Smart AIR and Smart VISION):

1) Smart AIR is referred as an Edge application controller developed at the individual cell level. In the case when RAN is overflowed, SmartAIR works to control the individual traffic flows at real time to overcome latency and offers efficient network utilization.
2) SmartVISION is described as to assist operators to analyze RAN performance, by providing them real-time and historical data. SmartVISION has an ability to obtain information on user activity, content usage and application, for every cell sector. The optimization and planning for network performance and expansion can be done based on this information.

XI. FUTURE RESEARCH DIRECTIONS FOR ICN OVER EDGE COMPUTING

In this section our aim is to direct the researchers for the enhancement of ICN and Edge computing. Although ICN paradigm promises to provide the required features currently not addressed by the existing 5G research. Therefore, the following question arises: How can ICN be enabled in Edge computing? How can ICN be combined and co-optimized with these networks? Several few issues are described as follows:

A. MORPHING (IN-NETWORK DATA MANIPULATION)

The Internet of Things (IoT) promises to connect billions of objects to the Internet. It needs to support 50-100 Billion networked objects, many of which are mobile. A large amount of data will be generated by things and many applications will be deployed at the Edge to consume these data. IoT is compatible with Edge networks because of its IP nature. However, ICN is not compatible with Edge networks, and hence it is a very challenging task to handle IoT devices and data at the Edge of network using ICN. There are many potential challenges

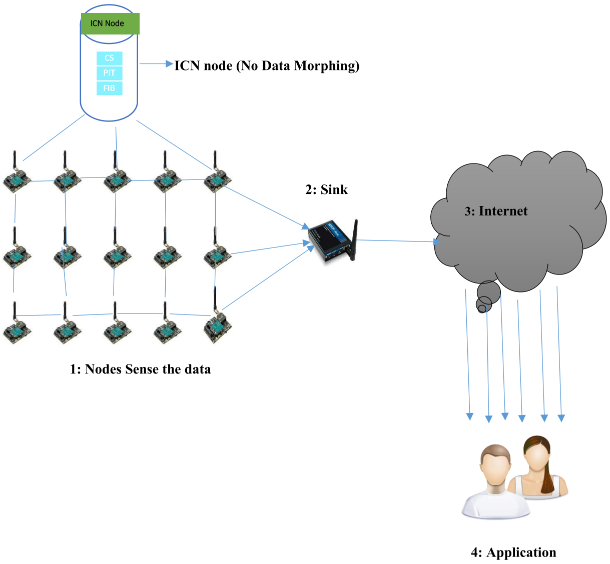


FIGURE 12. **Morphing in ICN enabled networks.**

due to ICN integration in Edge networks, as discussed above. However, on the other hand, ICN in Edge networks can be beneficial for IoT to support seamless mobility, security, and efficient content and service delivery.

As discussed in [91], applications in IoT will be deployed at the Edge, and there are no compatibility issues. By compatibility, we mean that the Edge networks and IoT are both IP-based (host-centric) unlike ICN. Therefore, Edge networks and IoT can co-exist. To handle a huge amount of raw data in the network of IoT, morphing is a strong concept. These raw data create congestion and delay in the network, resulting in various issues. Before going into detail of these issues, we will first explain what morphing is? Morphing is a concept used for in-network data manipulation/filtering. Data inside the network are filtered by some intermediate nodes and then sent to the sink node. In this approach, only filtered data that are meaningful are sent to the sink node instead of sending all the raw data. This filtering of raw data results in low power consumption, low traffic, and fewer transmissions, improving the bandwidth and lifetime of the network. Hence, only manipulated data are sent to the sink. A consumer is only interested in processed data rather than raw data. Therefore, we are directing interested researchers to perform morphing in ICN-enabled Edge networks. However, there are some pros and cons that may result due to ICN integration. First, the ICN node does not provide any data transformation (e.g., filtering, aggregation) [91]. However, ICN could enable lightweight in-network data manipulation at intermediate nodes by embedding semantics awareness at the network layer, as shown in Figure 13.

Second, issues may result such as increased complexity and function overloading inside the network if transformation is performed. There is space to think about morphing in ICN-enabled Edge networks. Therefore, the requester can retrieve aggregated data from the best node in the network. Note that data morphing should be carefully applied at specific locations in the network to ensure a trade-off between effectiveness and computational resource demands.

B. CACHING

Caching is very beneficial to increase the availability of data and to speed up data retrieval. The cache everything everywhere approach is not useful, resulting in the wastage of cache resources and creating a considerable amount of redundant data in the network. Data replacement policies that will behave according to the behavior of the content and interest are needed [92].

Caching creates the following three main questions:

1) WHAT TO CACHE?

It is useless to cache all the content in the network. Therefore, it is necessary to consider the popularity of content and determine what content to cache. Many users request the same content, and therefore unpopular content has a negative impact on the utilization of caching.

2) HOW TO CACHE?

It is necessary to evaluate the reputation of content rather than applying traditional caching policies, such as the least recently used (LRU), least frequently used (LFU), and first in first out (FIFO).

3) WHERE TO CACHE?

Integrating ICN in Edge computing creates another challenge for the deployment of caching. In current cellular networks, caches are deployed at two places, evolved packet core (EPC) and at the radio access network (RAN). EPC consist of packet data network gateway (P-GW), serving gateway (S-GW) and mobility management entity (MME) in Long Term Evolution (LTE). In 3G networks, RAN consists of NodeBs and evolved NodeBs (NodeBs) in 4G LTE networks [93]. It is unclear whether to store in a MEC server or ICN node or both.

Moreover, to execute functions there is a strong need of data availability. Since ICN provides in-network caching capabilities, therefore, proactive caching strategies needs to be investigated for prefetching data as well as functions to speed up computation of service/function results on the Edge devices.

C. DEPLOYMENT STRATEGIES AND ORCHESTRATION

Cloud technologies such as unikernels simplify the deployment of functions and services and therefore provide efficient data processing and dissemination [112]. The loosely coupled addressing concept of ICN simplifies both the access to and the placement of functions and services in the network. This is due to the fact that addresses of physical components need not be maintained and well-known by consumers as it is required in today's host-centric networks.

However, resource allocation and management of functions and services defines a new research problem. There is a need of distribution strategies for functions and resources are unnecessarily occupied and thus decreases network efficiency. That means that most of the resources in the network are underutilized. For efficient data dissemination such information needs to be transferred from one service instance to another according to the mobility model of the mobile node. Such mechanisms need to be supported by QoS mechanisms, required to differentiate between different types of data and services and to ensure efficient data dissemination. Additionally, such strategies/policies must ensure fairness among the different consumers and providers of the services.

D. SECURITY

In ICNs, security features are directly introduced as part of the content itself instead of the transport layer as given in today's IP networks. Enabling ICN in Edge networks creates many issues for security and privacy. ICN over Edge will share data with all users because the ICN node has the capability of any casting. Due to the anycasting feature of ICN, data will be sent to all future interested users [91].

Moreover, due to network caching, security is increased by the fact that data is expected to stay within untrusted caching nodes [69]. This also includes privacy concerns while requesting customized service results. In recent years, mechanisms are proposed that are showing security features. However, such mechanisms are not addressing the requirements of mobile scenarios. The question is how to exchange encryption related information across fast changing networks. Moreover, in case of constrained network, it become very difficult to implement complex security mechanism. Open research challenges are the design of schemes that would deal with powerful and also constrained devices in order to ensure privacy and integrity.

E. NAMING

Naming is also an open issue for ICN over Edge networks. The use of ICN in Edge computing creates issues, since ICN access the data and services by name. There is a need to introduce the design of novel naming schemes that support both Edge and ICN to handle mobility, security, and scalability. To be more specific, content and context-based Naming Schemes could be designed for ICN based Edge systems [112]. Where context-based naming means the information on the context i-e location (where are the users) identity (who are the users), neighbors (who are near them) and what are the content choices and so on. In ICN the location, identity, neighbor etc) could be named and signed pieces of content that will reflect that local context. The named content could be relevant object(s) that may be needed sooner or later.

In addition, from a consumer perspective, there are multiple options to request for data such as query for data objects or chunks using their name or sequence number. When talking about services, querying for results (e.g. function results) becomes difficult. Customized information or parameters need to be provided by a consumer, for example as part of the naming scheme such as the NFN approach. Research activities need to investigate the options to querying the network for computational expensive and context-sensitive service results [69]. Furthermore, mechanisms such as name-based routing and forwarding should cope with the mobility of network participants.

F. DISCOVERY AND DELIVERY

Name-based routing (NBR) or look-up-based resolution systems (LRSs) are used for content discovery and delivery in ICN. With NBR, the interest packet is sent in a manner of hop-by-hop transmission by forwarding node(s) by looking up a name match into their FIB. Once the content is found, it follows the reverse path back. With LRS, the interest packet is sent to a resolution system, which may vary subject to the ICN architecture. Different architectures may have different resolution systems depending on the implementation of architecture [21]. Therefore, how data could be discovered and delivered in paradigm of ICN over the Edge computing? Hence, a new resolution system may be designed to discover and deliver data and resources in ICN over the Edge computing approach.

The resource discovery could be of two types 1) Services discovery: (that means which service(s) are running on the Edge node and what are the capabilities of each Edge node. 2) Resource availability: (that means, what is the current load on the Edge nodes and which Edge node is the best node for task execution in terms of central processing unit (CPU), random access memory (RAM), Graphics Processing Unit (GPU) etc.) [69].

G. MOBILITY

The architecture for ICN based Edge computing should support consumer mobility and producer mobility as well. Since the consumer mobility is inherently supported in ICN, however, there is much work needed for the producer mobility. Only limited number of works is available dealing with producer mobility such as [114]–[116]. However, most of these works cover fixed networks. Producer mobility needs to be addressed for Edge computing, since in ICN based Edge system, the mobile users themselves might be publishers to a local audience, supported by Edge nodes for storage and computing capacity. Therefore, those mobile devices may behave like a publisher/producer and may move in the entire network. Mechanisms are required to address the producer mobility of ICN based Edge system.

H. NETWORK HETEROGENEITY

Future networks will support numerous wireless technologies and types of devices. Therefore, a mobile user can move across diverse networks. However, this mobility will result in handoff delay, packet loss, packet duplication, or packet reordering for the period of handoff. This handoff is an issue in such heterogeneous networks. Future networks such as 5G and beyond will need a minimum handoff delay whenever mobile users move across different networks. Therefore, ICN over Edge computing is an efficient approach to deal with such issues. Now the question arises: How ICN over Edge computing can be an efficient solution? To answer this, we explain features of each paradigm and how they will help to solve these issues. In Edge computing, data processing is pushed from the Cloud to the Edge of the network to achieve minimum latency. Thus, Edge computing offers less delay than the Cloud. 5G networks basic requirement is a minimum delay, Therefore, this delay can be reduced more if we apply ICN in Edge computing. How can ICN help? First, ICN is receiver-driven in nature and supports consumer-mobility: unsatisfied requests will be re-issued whenever consumers move. Second, host multi-homing is also supported by ICN. Therefore, content requests and data delivery can use any of the interface(s) available at the device [78]. Due to the disconnection of consumers and producers, self-consistent content, any casting, and in-network-caching, ICN thus proves to reconnect services and devices in heterogeneous networks [21], [69]. In addition, function in ICN is named that could be requested at the network layer. Explicitly named functions can be resolved in network nodes, while network-layer requests (i.e., Interests) can carry input information for Edge-executable functions [118]. We explained the features of both ICN and Edge computing above; therefore, joint optimization will solve the issues of network heterogeneity, mobility, and so on.

I. LOAD BALANCING STRATEGIES FOR REQUESTS ON MULTI-INTERFACES

For an efficient content retrieval in ICN based Edge computing, the network stack must transparently support simultaneous use of multiple interfaces. In TCP/IP this is done via multipath TCP [117], [118]. The problem in multipath TCP is that we should know in advance that on how many paths we want to load balance our requests. However, ICN provides native support for multi-interface communication. Therefore, load balancing strategies are required for ICN based Edge computing that would try to minimize the congestion over the entire network. Moreover, how to tune the request on different interfaces without degrading the user experience is an issue in ICN based Edge computing.

J. INFRASTRUCTURE AND ARCHITECTURE

We believe that the combination of ICN and Edge computing will speed up content retrieval. However, ICN in Edge networks poses many challenges to network's infrastructure and architecture. The issue arises because of two different architectures. How will ICN and Edge computing co-exist with each other? Inter-networking schemes with existing architecture of Edge computing are necessary to make both paradigms interoperable. The interoperability of ICN with Edge networks is an open challenge to researchers that should be addressed.

XII. CONCLUSION

A migration of IP addresses and the use of naming mechanisms for content, context and services/functions shall contribute to the optimal performance for future networks. ICN over Edge computing is an efficient technique to ensure a shorter response time. It will help to solve the problems of big data management, mobility, naming, latency, and security. In this article, we provided a comprehensive survey of ICN over Edge computing for future networks. The contributions are multi-fold. First, the Edge computing concepts, drivers, proposals, limitations and use cases has been provided. Second, ICN is highlighted for Edge computing which includes an overview of ICN and motivations to leverage the ICN for Edge computing. In addition, various standardization efforts and software and hardware vendor solutions are presented. Finally, future research directions are provided for ICN over Edge computing. We believe this survey will stimulate the research community and pave the way towards the empowerment of future networks in order to achieve the fast response time.

REFERENCES

[1] A. U. R. Khan, M. Othman, S. A. Madani, and S. U. Khan, "A survey of mobile cloud computing application models," *IEEE Commun. Surveys Tuts.*, vol. 16, no. 1, pp. 393–413, 1st Quart., 2013.

[2] M. Amadeo, C. Campolo, A. Molinaro, and G. Ruggeri, "IoT data processing at the edge with named data networking," in *Proc. Eur. Wireless Conf.*, May 2018, pp. 1–6.

[3] G. Li, J. Wu, J. Li, K. Wang, and T. Ye, "Service popularity-based smart resources partitioning for fog computing-enabled industrial Internet of Things," *IEEE Trans. Ind. Informat.*, vol. 14, no. 10, pp. 4702–4711, Oct. 2018.

[4] J. Wu, M. Dong, K. Ota, J. Li, and Z. Guan, "Big data analysis-based secure cluster management for optimized control plane in software-defined networks," *IEEE Trans. Netw. Serv. Manage.*, vol. 15, no. 1, pp. 27–38, Mar. 2018.

[5] G. Li, J. Wu, J. Li, T. Ye, and R. Morello, "Battery status sensing software-defined multicast for V2G regulation in smart grid," *IEEE Sensors J.*, vol. 17, no. 23, pp. 7838–7848, Dec. 2017.

[6] A. C. Baktir, A. Ozgovde, and C. Ersoy, "How can edge computing benefit from software-defined networking: A survey, use cases, and future directions," *IEEE Commun. Surveys Tuts.*, vol. 19, no. 4, pp. 2359–2391, 4th Quart., 2017.

[7] M. Ahmadi, N. Khanezaei, S. Manavi, F. F. Moghaddam, and T. Khodadadi, "A comparative study of time management and energy consumption in mobile cloud computing," in *Proc. IEEE 5th Control Syst. Graduate Res. Colloq.*, Aug. 2014, pp. 199–203.

[8] B. Zhou, A. V. Dastjerdi, R. N. Calheiros, S. N. Srirama, and R. Buyya, "A context sensitive offloading scheme for mobile cloud computing service," in *Proc. IEEE 8th Int. Conf. Cloud Comput.*, New York, NY, USA, Jun. 2015, pp. 869–876.

[9] Y. Li, L. Sun, and W. Wang, "Exploring device-to-device communication for mobile cloud computing," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Sydney, NSW, Australia, Jun. 2014, pp. 2239–2244.

[10] K. Ha *et al.*, "The impact of mobile multimedia applications on data center consolidation," in *Proc. IEEE Int. Conf. Cloud Eng. (IC2E)*, Redwood City, CA, USA, Mar. 2013, pp. 166–176.

[11] M. T. Beck *et al.*, "ME-VoLTE: Network functions for energy-efficient video transcoding at the mobile edge," in *Proc. 18th IEEE Int. Conf. Intell. Next Generat. Netw.*, Paris, France, Apr. 2015, pp. 38–44.

[12] T. J. Barnett, A. Sumits, S. Jain, and U. Andra, "Cisco visual networking index: Global mobile data traffic forecast update, 2016–2021," Cisco Syst., Inc., San Jose, CA, USA, White Paper 1454457600, Mar. 2017. [Online]. Available: http://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/mobile-white-paper-c11-520862.html

[13] M. T. Beck *et al.*, "Mobile edge computing: A taxonomy," in *Proc. 6th Int. Conf. Adv. Future Internet*, Lisbon, Portugal, 2014, pp. 48–54.

[14] M. Satyanarayanan, "The emergence of edge computing," *Computer*, vol. 50, no. 1, pp. 30–39, Jan. 2017.

[15] F. Bonomi, R. Milito, P. Natarajan, and J. Zhu, "Fog computing: A platform for Internet of Things and analytics," in *Big Data and Internet of Things: A Roadmap for Smart Environments*. Springer, Mar. 2014, pp. 169–186. [Online]. Available: https://link.springer.com/chapter/10.1007/978-3-319-05029-4_7

[16] D. Thomas, "Cloud computing—Benefits and challenges!" *J. Object Technol.*, vol. 8, no. 3, pp. 37–41, Jun. 2009.

[17] L. Gao, T. H. Luan, B. Liu, W. Zhou, and S. Yu, "Fog computing and its applications in 5G," in *5G Mobile Communications*. Cham, Switzerland: Springer, 2017, pp. 571–593. [Online]. Available: https://doi.org/10.1007/978-3-319-34208-5_21

[18] Y. Yu, "Mobile edge computing towards 5G: Vision, recent progress, and open challenges," *China Commun.*, vol. 13, no. 2, pp. 89–99, 2016.

[19] M. Paoloni, "Power at the edge: Processing and storage move from Central core to the network edge," Greater Seattle Area, Senza Fili Consulting, Tech. Rep., Feb. 2017. [Online]. Available: http://www.senzafiliconsulting.com

[20] (Jun. 2017). *Ericsson Mobility Report, SE-164 80 Stockholm, Sweden*. [Online]. Available: https://www.ericsson.com/en/mobility-report

[21] K. Gai, M. Qiu, H. Zhao, L. Tao, and Z. Zong, "Dynamic energy-aware cloudlet-based mobile cloud computing model for green computing," *J. Netw. Comput. Appl.*, vol. 59, pp. 46–54, Jan. 2016.

[22] S. Marston, Z. Li, S. Bandyopadhyay, J. Zhang, and A. Ghalsasi, "Cloud computing—The business perspective," *Decision Support Syst.*, vol. 51, no. 1, pp. 176–189, 2011.

[23] M. Rahman, J. Gao, and W.-T. Tsai, "Energy saving in mobile cloud computing," in *Proc. IEEE Int. Conf. Cloud Eng. (IC2E)*, San Francisco, CA, USA, Mar. 2013, pp. 285–291.

[24] Z. Sanaei, S. Abolfazli, A. Gani, and R. Buyya, "Heterogeneity in mobile cloud computing: Taxonomy and open challenges," *IEEE Commun. Surveys Tuts.*, vol. 16, no. 1, pp. 369–392, Feb. 2014.

[25] M. Satyanarayanan *et al.*, "Edge analytics in the Internet of Things," *IEEE Pervasive Comput.*, vol. 14, no. 2, pp. 24–31, Feb. 2015.

[26] R. Roman, J. Lopez, and M. Mambo, "Mobile edge computing, Fog *et al.*: A survey and analysis of security threats and challenges," *Future Generat. Comput. Syst.*, vol. 78, pp. 680–698, Nov. 2016. [Online]. Available: https://doi.org/10.1016/j.future.2016.11.009

[27] M. Satyanarayanan, Z. Chen, K. Ha, W. Hu, W. Richter, and P. Pillai, "Cloudlets: At the leading edge of mobile-cloud convergence," in *Proc. 6th Int. Conf. Mobile Comput., Appl. Services*, Austin, TX, USA, Nov. 2014, pp. 1–9.

[28] U. Shaukat, E. Ahmed, Z. Anwar, and F. Xia, "Cloudlet deployment in local wireless networks: Motivation, architectures, applications, and open challenges," *J. Netw. Comput. Appl.*, vol. 62, pp. 18–40, Feb. 2016.

[29] B. Li, Y. Pei, H. Wu, and B. Shen, "Heuristics to allocate high-performance cloudlets for computation offloading in mobile ad hoc clouds," *J. Supercomput.*, vol. 71, no. 8, pp. 3009–3036, 2015.

[30] X. Guo, L. Liu, Z. Chang, and T. Ristaniemi, "Data offloading and task allocation for cloudlet-assisted ad hoc mobile clouds," *Wireless Netw.*, vol. 24, no. 1, pp. 79–88, Jan. 2018, doi: 10.1007/s11276-016-1322-z.

[31] *Open Edge Computing*. Accessed: May 11, 2017. [Online]. Available: http://openedgecomputing.org/index.html

[32] A. Ceselli, M. Premoli, and S. Secci, "Cloudlet network design optimization," in *Proc. IFIP Netw. Conf. (IFIP Netw.)*, Toulouse, France, May 2015, pp. 1–9.

[33] *European Telecommunications Standards Institute*. Accessed: Sep. 10, 2018. [Online]. Available: http://www.etsi.org/

[34] M. R. Rahimi, J. Ren, C. H. Liu, A. V. Vasilakos, and N. Venkatasubramanian, "Mobile cloud computing: A survey, state of art and future directions," *Mobile Netw. Appl.*, vol. 19, no. 2, pp. 133–143, 2014.

[35] W. Shi, J. Cao, Q. Zhang, Y. Li, and L. Xu, "Edge computing: Vision and challenges," *IEEE Internet Things J.*, vol. 3, no. 5, pp. 637–646, Oct. 2016.

[36] B. Ahlgren, C. Dannewitz, C. Imbrenda, D. Kutscher, and B. Ohlman, "A survey of information-centric networking," *IEEE Commun. Mag.*, vol. 50, no. 7, pp. 26–36, Jul. 2012.

[37] F. Bonomi, R. Milito, J. Zhu, and S. Addepalli, "Fog computing and its role in the Internet of Things," in *Proc. 1st Ed. MCC Workshop Mobile Cloud Comput.*, Helsinki, Finland, 2012, pp. 13–16.

[38] I. Stojmenovic and S. Wen, "The Fog computing paradigm: Scenarios and security issues," in *Proc. Federated Conf. Comput. Sci. Inf. Syst.*, Warsaw, Poland, Sep. 2014, pp. 1–8.

[39] OpenFog Consortium, Fremont, CA, USA. *An Open, Interoperable Fog Computing Architecture*. Accessed: May 5, 2017. [Online]. Available: https://www.openfogconsortium.org/about-us/

[40] C. Byers. *OpenFog Consortium—Out of the Fog: Use Case Scenarios*. Accessed: May 5, 2017. [Online]. Available: https://www.openfogconsortium.org/wp-content/uploads/OpenFog-Transportation-Drone-Delivery-Use-Case.pdf

[41] M. Aazam and E.-N. Huh, "Fog computing and smart gateway based communication for cloud of things," in *Proc. IEEE Int. Conf. Future Internet Things Cloud*, Barcelona, Spain, Aug. 2014, pp. 464–470.

[42] M. Firdhous, O. Ghazali, and S. Hassan, "Fog computing: Will it be the future of cloud computing?" in *Proc. 3rd Int. Conf. Inform. Appl.*, Kuala Terengganu, Malaysia, 2014, pp. 8–15.

[43] T. H. Luan, L. Gao, Z. Li, Y. Xiang, G. Wei, and L. Sun. (2015). "Fog computing: Focusing on mobile users at the edge." [Online]. Available: https://arxiv.org/abs/1502.01815

[44] P. Hu, H. Ning, T. Qiu, Y. Zhang, and X. Luo, "Fog computing based face identification and resolution scheme in Internet of Things," *IEEE Trans. Ind. Informat.*, vol. 13, no. 4, pp. 1910–1920, Aug. 2017.

[45] E. Cau *et al.*, "Efficient exploitation of mobile edge computing for virtualized 5G in EPC architectures," in *Proc. 4th IEEE Int. Conf. Mobile Cloud Comput., Services, Eng. (Mobile Cloud)*, Oxford, U.K., Mar./Apr. 2016, pp. 100–109.

[46] M. Agiwal, A. Roy, and N. Saxena, "Next generation 5G wireless networks: A comprehensive survey," *IEEE Commun. Surveys Tut.*, vol. 18, no. 3, pp. 1617–1655, 3rd Quart., 2016.

[47] S. Nunna *et al.*, "Enabling real-time context-aware collaboration through 5G and mobile edge computing," in *Proc. 12th Int. Conf. Inf. Technol.-New Generat.*, Las Vegas, NV, USA, Apr. 2015, pp. 601–605.

[48] D. Satria, D. Park, and M. Jo, "Recovery for overloaded mobile edge computing," *Future Generat. Comput. Syst.*, vol. 70, pp. 138–147, May 2017.

[49] *European Telecommunications Standards Institute Industry Specifications Group, Mobile-Edge Computing—Service Scenarios*. [Online]. Available: http://www.etsi.org/deliver/etsi_gs/MEC-IEG/001_099/004/01.01.01_60/gs_MEC-IEG004v010101p.pdf

[50] M. Satyanarayanan *et al.*, "An open ecosystem for mobile-cloud convergence," *IEEE Commun. Mag.*, vol. 53, no. 3, pp. 63–70, Mar. 2015.

[51] A. Ahmed and E. Ahmed, "A survey on mobile edge computing," in *Proc. 10th IEEE Int. Conf. Intell. Syst. Control ISCO*, Coimbatore, India, Jan. 2016, pp. 1–8.

[52] M. Quwaider and Y. Jararweh, "Cloudlet-based efficient data collection in wireless body area networks," *Simul. Model. Pract. Theory*, vol. 50, pp. 57–71, Jan. 2015.

[53] S. Yi, Z. Hao, Z. Qin, and Q. Li, "Fog computing: Platform and applications," in *Proc. 3rd IEEE Workshop Hot Topics Web Syst. Technol. (HotWeb)*, Washington, DC, USA, Nov. 2015, pp. 73–78.

[54] P. Du and A. Nakao, "Application specific mobile edge computing through network softwarization," in *Proc. 5th IEEE Int. Conf. Cloud Netw. (Cloudnet)*, Pisa, Italy, Oct. 2016, pp. 130–135.

[55] *European Telecommunications Standards Institute Industry Specifications Group, MEC Proofs of Concept*. Accessed: May 15, 2017. [Online]. Available: http://www.etsi.org/technologies-clusters/technologies/mobile-edge-computing/mec-poc

[56] *European Telecommunications Standards Institute, PoC Edge Video Orchestration and Video Clip Replay*. Accessed: May 15, 2017. [Online]. Available: http://mecwiki.etsi.org/index.php?title=PoC_2_Edge_Video_Orchestration_ and _Video_Clip_Replay_via_MEC

[57] K. Ha, Z. Chen, W. Hu, W. Richter, P. Pillai, and M. Satyanarayanan, "Towards wearable cognitive assistance," in *Proc. 12th Annu. Int. Conf. Mobile Syst., Appl., Services*, New York, NY, USA, 2014, pp. 68–81.

[58] O. Arias, J. Wurm, K. Hoang, and Y. Jin, "Privacy and security in Internet of Things and wearable devices," *IEEE Trans. Multi-Scale Comput. Syst.*, vol. 1, no. 2, pp. 99–109, Apr./Jun. 2015.

[59] M. Quwaider and Y. Jararweh, "Cloudlet-based for big data collection in body area networks," in *Proc. 8th Int. Conf. Internet Technol. Secured Trans.*, London, U.K., Dec. 2013, pp. 137–141.

[60] Y. Shi, G. Ding, H. Wang, H. E. Roman, and S. Lu, "The fog computing service for healthcare," in *Proc. 2nd Int. Symp. Future Inf. Commun. Technol. Ubiquitous HealthCare (Ubi-HealthTech)*, Beijing, China, May 2015, pp. 1–5.

[61] Q. Yaseen, F. AlBalas, Y. Jararweh, and M. Al-Ayyoub, "A fog computing based system for selective forwarding detection in mobile wireless sensor networks," in *Proc. IEEE 1st Int. Workshops Found. Appl. Self* Syst. (FAS*W)*, Augsburg, Germany, Sep. 2016, pp. 256–262.

[62] M. Satyanarayanan, G. Lewis, E. Morris, S. Simanta, J. Boleng, and K. Ha, "The role of cloudlets in hostile environments," *IEEE Pervas. Comput.*, vol. 12, no. 4, pp. 40–49, Oct. 2013.

[63] V. S. Achanta, N. T. Sureshbabu, V. Thomas, M. L. Sahitya, and S. Rao, "Cloudlet-based multi-lingual dictionaries," in *Proc. 3rd Int. Conf. Services Emerg. Markets*, Mysore, India, Dec. 2012, pp. 30–36.

[64] R. Ullah, Y. Faheem, and B. S. Kim, "Energy and congestion-aware routing metric for smart grid ami networks in smart city," *IEEE Access*, vol. 5, pp. 13799–13810, 2017, doi: 10.1109/ACCESS.2017.2728623.

[65] I. Stojmenovic, "Fog computing: A cloud to the ground support for smart things and machine-to-machine networks," in *Proc. Austral. Telecommun. Netw. Appl. Conf. (ATNAC)*, Southbank, VIC, Australia, Nov. 2014, pp. 117–122.

[66] Y. Jararweh, A. Doulat, O. AlQudah, E. Ahmed, M. Al-Ayyoub, and E. Benkhelifa, "The future of mobile cloud computing: Integrating cloudlets and mobile edge computing," in *Proc. 23rd Int. Conf. Telecommun. (ICT)*, Thessaloniki, Greece, May 2016, pp. 1–5.

[67] M. Aazam and E.-N. Huh, "Fog computing: The cloud-IoT/IoE middleware paradigm," *IEEE Potentials*, vol. 35, no. 3, pp. 40–44, May/Jun. 2016.

[68] Y. Liu, X. Mao, Y. He, K. Liu, W. Gong, and J. Wang, "CitySee: Not only a wireless sensor network," *IEEE Netw.*, vol. 27, no. 5, pp. 42–47, Oct. 2013.

[69] L. Soh, J. Burke, and L. Zhang, "Supporting augmented reality: Looking beyond performance," in *Proc. Morning Workshop Virtual Reality Augmented Reality Netw. (VR/AR Netw.)*, New York, NY, USA, 2018, pp. 7–12, doi: 10.1145/3229625.3229627.

[70] J. Grubert, T. Langlotz, S. Zollmann, and H. Regenbrecht, "Towards pervasive augmented reality: Context-awareness in augmented reality," *IEEE Trans. Vis. Comput. Graphics*, vol. 23, no. 6, pp. 1706–1724, Jun. 2017.

[71] G. Karagiannis *et al.*, "Vehicular networking: A survey and tutorial on requirements, architectures, challenges, standards and solutions," *IEEE Commun. Surveys Tuts.*, vol. 13, no. 4, pp. 584–616, Nov. 2011.

[72] M. Amadeo, C. Campolo, and A. Molinaro, "Information-centric networking for connected vehicles: A survey and future perspectives," *IEEE Commun. Mag.*, vol. 54, no. 2, pp. 98–104, 4th Quart., 2016.

[73] M. Kaur, J. Martin, and H. Hu, "Comprehensive view of security practices in vehicular networks," in *Proc. Int. Conf. Connected Vehicles Expo (ICCVE)*, Seattle, WA, USA, Sep. 2016, pp. 19–26.

[74] A. Osseiran *et al.*, "Scenarios for 5G mobile and wireless communications: The vision of the METIS project," *IEEE Commun. Mag.*, vol. 52, no. 5, pp. 26–35, May 2014.

[75] M. F. Bari, S. R. Chowdhury, R. Ahmed, R. Boutaba, and B. Mathieu, "A survey of naming and routing in information-centric networks," *IEEE Commun. Mag.*, vol. 50, no. 12, pp. 44–53, Dec. 2012.

[76] G. Xylomenos *et al.*, "A survey of information-centric networking research," *IEEE Commun. Surveys Tuts.*, vol. 16, no. 2, pp. 1024–1049, 2nd Quart., 2014.

[77] C. Fang, F. R. Yu, T. Huang, J. Liu, and Y. Liu, "A survey of green information-centric networking: Research issues and challenges," *IEEE Commun. Surveys Tuts.*, vol. 17, no. 3, pp. 1455–1472, 3rd Quart., 2015.

[78] M. Amadeo, C. Campolo, and A. Molinaro, "Information-centric networking for connected vehicles: A survey and future perspectives," *IEEE Commun. Mag.*, vol. 54, no. 2, pp. 98–104, Feb. 2016.

[79] M. Satyanarayanan, P. Bahl, R. Caceres, and N. Davies, "The case for VM-based cloudlets in mobile computing," *IEEE Pervasive Comput.*, vol. 8, no. 4, pp. 14–23, Oct./Dec. 2009.

[80] *Cloudlet-based Edge Computing*. Accessed: May 17, 2017. [Online]. Available: http://elijah.cs.cmu.edu/

[81] *3rd Generation Partnership Project (3GPP)*. [Online]. Available: http://www.3gpp.org/

[82] *Information-Centric Networking Research Group ICNRG*. [Online]. Available: https://irtf.org/icnrg

[83] *SG13: Future Networks, With focus on IMT-2020, Cloud Computing and Trusted Network Infrastructures*. [Online]. Available: http://www.itu.int/en/ITU-T/studygroups/2017-2020/13/Pages/default.asp

[84] *Alliance for Telecommunications Industry Solutions*. Accessed: May 15, 2017. [Online]. Available: https://www.atis.org/

[85] M. Recchione, "Understanding information centric networking and mobile edge computing," 5G Americas, Vicki Livingston, White Paper 3330, Dec. 2016. [Online]. Available: http://www.5gamericas.org/files/3414/8173/2353/Understanding_Information_Centric_Networking_and_Mobile_Edge_Computing.pdf

[86] R. El Hattachi and J. Erfanian, "A Deliverable by NGMN (Next Generation Mobile Networks)," NGMN 5G, Frankfurt, Germany, White Paper, Feb. 2015, pp. 1–125.

[87] E. Bastug, M. Bennis, and M. Debbah, "Living on the edge: The role of proactive caching in 5G wireless networks," *IEEE Commun. Mag.*, vol. 52, no. 8, pp. 82–89, Aug. 2014.

[88] M. Simsek, A. Aijaz, M. Dohler, J. Sachs, and G. Fettweis, "5G-enabled tactile Internet," *IEEE J. Sel. Areas Commun.*, vol. 34, no. 3, pp. 460–473, Mar. 2016.

[89] O. Galinina, A. Pyattaev, S. Andreev, M. Dohler, and Y. Koucheryavy, "5G multi-RAT LTE-WiFi ultra-dense small cells: Performance dynamics, architecture, and trends," *IEEE J. Sel. Areas Commun.*, vol. 33, no. 6, pp. 1224–1240, Jun. 2015.

[90] M. Amadeo *et al.*, "Information-centric networking for the Internet of Things: Challenges and opportunities," *IEEE Netw.*, vol. 30, no. 2, pp. 92–100, Mar./Apr. 2016.

[91] D. Trossen, M. J. Reed, M. Georgiades, N. Fotiou, and G. Xylomenos. (2015). "IP over ICN–The better IP? An unusual take on information-centric networking." [Online]. Available: https://arxiv.org/abs/1507.04221

[92] M. Amadeo *et al.*, "Information-centric networking for the Internet of Things: Challenges and opportunities," *IEEE Netw.*, vol. 30, no. 2, pp. 92–100, Mar./Apr. 2016.

[93] W. Shi, J. Cao, Q. Zhang, Y. Li, and L. Xu, "Edge computing: Vision and challenges," *IEEE Internet Things J.*, vol. 3, no. 5, pp. 637–646, Oct. 2016.

[94] X. Wang, M. Chen, T. Taleb, A. Ksentini, and V. C. M. Leung, "Cache in the air: Exploiting content caching and delivery techniques for 5G systems," *IEEE Commun. Mag.*, vol. 52, no. 2, pp. 131–139, Feb. 2014.

[95] G. A. Lewis, S. Echevería, S. Simanta, B. Bradshaw, and J. Root, "Cloudlet-based cyber-foraging for mobile systems in resource-constrained edge environments," in *Proc. 36th Int. Conf. Softw. Eng.*, Hyderabad, India, May/Jun. 2014, pp. 412–415.

[96] Extreme outdoor Server. *ADLINK Technologies*. Accessed: Jul. 15, 2018. [Online]. Available: http://www.adlinktech.com/PD/web/PD_detail.php?cKind=&pid=1573&utm_source

[97] M. Paolini and S. Fili, "How to control latency and benefit from it: An expanded role for latency," Greater Seattle Area, Senza Fili Consulting, White Paper, 2018, [Online]. Available: http://www.senzafiliconsulting.com

[98] D. Grewe, M. Wagner, M. Arumaithurai, I. Psaras, and D. Kutscher, "Information-centric mobile edge computing for connected vehicle environments: Challenges and research directions," in *Proc. Workshop Mobile Edge Commun. (MECOMM)*, New York, NY, USA, 2017, pp. 7–12, doi: 10.1145/3098208.3098210.

[99] N. Fotiou, V. A. Siris, G. Xylomenos, G. C. Polyzos, K. V. Katsaros, and G. Petropoulos, "Edge-ICN and its application to the Internet of Things," in *Proc. IFIP Netw. Conf. (IFIP Netw.) Workshops*, Stockholm, Sweden, Jun. 2017, pp. 1–6, doi: 10.23919/IFIPNetworking.2017.8264880.

[100] M. Sifalakis, B. Kohler, C. Scherb, and C. Tschudin, "An information centric network for computing the distribution of computations," in *Proc. 1st ACM Conf. Inf.-Centric Netw. (ACM-ICN)*, New York, NY, USA, 2014, pp. 137–146, doi: 10.1145/2660129.2660150.

[101] Docker Inc. (2017). *The Docker Project Page*. [Online]. Available: https://www.docker.com/

[102] Amazon Web Services, Inc. (2017). *Amazon Lambda Project Page—Run Code, Not Servers—Serverless Computing*. [Online]. Available: https://aws.amazon.com/lambda/

[103] A. Madhavapeddy, "Unikernels: Library operating systems for the cloud," *SIGARCH Comput. Archit. News*, vol. 41, no. 1, pp. 461–472, 2013.

[104] W. Shang *et al.*, "Named data networking of things (invited paper)," in *Proc. IEEE 1st Int. Conf. Internet-Things Design Implement. (IoTDI)*, Berlin, Germany, Apr. 2016, pp. 117–128, doi: 10.1109/IoTDI.2015.44.

[105] M. Mukherjee, D. Wang, and L. Shu, "Survey of fog computing: Fundamental, network applications, and research challenges," *IEEE Commun. Surveys Tuts*, vol. 20, no. 3, pp. 1826–1857, 3rd Quart., 2018.

[106] *ADLINK Technology*. Accessed: Jul. 15, 2018. [Online]. Available: https://www.adlinktech.com

[107] *Advantech*. [Online]. Available: www.advantech.com/nc

[108] *Artesyn*. [Online]. Available: https://www.artesyn.com/

[109] *Interdigital*. [Online]. Available: http://www.interdigital.com/

[110] *Qwilt*. [Online]. Available: https://www.qwilt.com/

[111] *Vasona Networks*. Accessed: Jul. 15, 2018. [Online]. Available: https://www.vasonanetworks.com/

[112] K. Zhang, Y. Mao, S. Leng, Y. He, and Y. Zhang, "Mobile-edge computing for vehicular networks: A promising network paradigm with predictive off-loading," *IEEE Veh. Technol. Mag.*, vol. 12, no. 2, pp. 36–44, Jun. 2017.

[113] S. Arshad, B. Shahzaad, M. A. Azam, J. Loo, S. H. Ahmed, and S. Aslam, "Hierarchical and flat-based hybrid naming scheme in content-centric networks of things," *IEEE Internet Things J.*, vol. 5, no. 2, pp. 1070–1080, Apr. 2018.

[114] T. Refaei, J. Ma, S. Ha, and S. Liu, "Integrating IP and NDN through an extensible IP-NDN gateway," in *Proc. ACM ICN*, vol. 3, 2017, pp. 224–225,

[115] J. Augé, G. Carofiglio, G. Grassi, L. Muscariello, G. Pau, and X. Zeng, "MAP-Me: Managing anchor-less producer mobility in content-centric networks," *IEEE Trans. Netw. Serv. Manage.*, vol. 15, no. 2, pp. 596–610, Jun. 2018, doi: 10.1109/TNSM.2018.2796720.

[116] Y. Zhang, A. Afanasyev, J. Burke, and L. Zhang, "A survey of mobility support in named data networking," in *Proc. 3rd Workshop Name-Oriented Mobility, Architect., Algorithms Appl. (NOM)*, Apr. 2016, pp. 83–88.

[117] Z. Zhu, R. Wakikawa, and L. Zhang, *A Survey of Mobility Support in the Internet*. document RFC 6301.IRTF, 2011.

[118] C.-A. Sarros *et al.*, "Connecting the edges: A universal, mobile-centric, and opportunistic communications architecture," *IEEE Commun. Mag.*, vol. 56, no. 2, pp. 136–143, Feb. 2018.

[119] X. Chen, L. Jiao, W. Li, and X. Fu, "Efficient multi-user computation offloading for mobile-edge cloud computing," *IEEE/ACM Trans. Netw.*, vol. 24, no. 5, pp. 2795–2808, Oct. 2016.

[120] Z. Yantao and M. Jianfeng, "A highly secure identity-based authenticated key-exchange protocol for satellite communication," *J. Commun. Netw.*, vol. 12, no. 6, pp. 592–599, Dec. 2011.

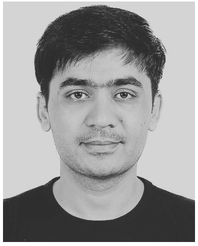
[121] S. S. Al-Riyami and K. G. Paterson, "Certificateless public key cryptography," in *Advances in Cryptology—ASIACRYPT*, vol. 2894. Berlin, Germany: Springer-Verlag, 2003, pp. 452–473.

[122] J. Wu, M. Dong, K. Ota, J. Li, and Z. Guan, "FCSS: Fog computing based content-aware filtering for security services in information centric social networks," *IEEE Trans. Emerg. Topics Comput.*, to be published, doi: 10.1109/TETC.2017.2747158.

[123] Y. Liu, A. Zhang, J. Li, and J. Wu, "An anonymous distributed key management system based on CL-PKC for space information network," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Kuala Lumpur, Malaysia, May 2016, pp. 1–7, doi: 10.1109/ICC.2016.7510841.

[124] M. Król and I. Psaras, "NFaaS: Named function as a service," in *Proc. ACM Conf. Inf.-Centric Netw.*, Berlin, Germany, 2017, pp. 134–144.

[125] M. Amadeo, C. Campolo, and A. Molinaro, "NDNe: Enhancing named data networking to support cloudification at the edge," *IEEE Commun. Lett.*, vol. 20, no. 11, pp. 2264–2267, Nov. 2016.



REHMAT ULLAH received the B.S and M.S degrees (major in wireless communications and networks) in computer science from COMSATS University Islamabad, Islamabad, Pakistan, in 2013 and 2016, respectively. He is currently pursuing the Ph.D. degree in computer engineering with the Broadband Convergence Networks Laboratory, Department of Electronics and Computer Engineering, Hongik University, South Korea. His major interests are in the field of information-centric networking (specifically wireless content-centric/named data networking), edge computing, low power and lossy networks (LLN), IoT, 5th Generation (5G), and future internet architectures. Moreover, he is an ACM member and serves as a Reviewer for the *IEEE Wireless Communications Magazine*, the *IEEE Communications Magazine*, *Transactions on Emerging Telecommunications Technologies*, *Future Generation Computer Systems* (Elsevier), the IEEE ACCESS Journal, and various International Conferences and Workshops, including ACM MobiHoc (Los Angeles, CA, USA), IEEE CCNC (Las Vegas, NV, USA), and VTC2018-Spring (Porto, Portugal).

SYED HASSAN AHMED (S'13–M'17–SM'18) received the B.S. degree in computer science from the Kohat University of Science and Technology, Pakistan, and the master's combined Ph.D. degree from the School of Computer Science and Engineering (SCSE), Kyungpook National University (KNU), South Korea. In 2015, he was a Visiting Ph.D. Student at Georgia Tech, Atlanta, GA, USA. He is currently an Assistant Professor with the Computer Science Department, Georgia Southern University (GSU), Statesboro, GA, USA. Before starting at GSU, he was a Post-Doctoral Fellow with the Department of Electrical and Computer Engineering, University of Central Florida, Orlando, FL, USA. He has authored/co-authored over 100 international publications, including journal articles, conference proceedings, book chapters, and three books. His research interests include sensor and ad hoc networks, cyber-physical systems, vehicular communications, and future Internet. He is an ACM Professional Member. From 2014 to 2016, he consequently received the Research Contribution Awards by SCSE and KNU. In 2016, his work on robust content retrieval in future vehicular networks leads him to receive the Qualcomm Innovation Award at KNU.

BYUNG-SEO KIM (M'02–SM'17) received the B.S. degree in electrical engineering from Inha University, Incheon, South Korea, in 1998, and the M.S. and Ph.D. degrees in electrical and computer engineering from the University of Florida in 2001 and 2004, respectively. His Ph.D. study was supervised by Dr. Y. Fang. From 1997 to 1999, he was at Motorola Korea Ltd., Paju, South Korea, as a Computer Integrated Manufacturing Engineer in Advanced Technology Research and Development. From 2005 to 2007, he was at Motorola Inc., Schaumburg Illinois, as a Senior Software Engineer in Networks and Enterprises. His research focuses in Motorola Inc. were designing protocol and network architecture of wireless broadband mission critical communications. From 2012 to 2014, he was the Chairman with the Department of Software and Communications Engineering, Hongik University, South Korea, where he is currently a Professor. His work has appeared in around 167 publications and 22 patents. His research interests include the design and development of efficient wireless/wired networks, including link-adaptable/cross-layer-based protocols, multi-protocol structures, wireless CCNs/NDNs, mobile edge computing, physical layer design for broadband PLC, and resource allocation algorithms for wireless networks. He was also served as the member of Sejong-city Construction Review Committee and the Ansan-city Design Advisory Board. He served as the General Chair for 3rd IWWCN 2017, and a TPC member for the IEEE VTC 2014-Spring and the EAI FUTURE2016, and ICGHIC in 2016 and 2019 conferences. He served as the Guest Editor of special issues for the *International Journal of Distributed Sensor Networks* (SAGE), the IEEE ACCESS, and the *Journal of the Institute of Electrics and Information Engineers*. He is an Associate Editor of the IEEE ACCESS.

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