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Fog computing: from architecture to edge computing and big data processing

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Abstract
Cloud computing plays a vital role in processing a large amount of data. However, with the arrival of the Internet of Things, huge data are generated from these devices. Thus, there is the need for bringing characteristics of cloud closer to the request generator, so that processing of these huge data takes place at one-hop distance closer to that end user. This led to the emergence of fog computing with the aim to provide storage and computation at the edge of the network that reduces network traffic and overcomes many cloud computing drawbacks. Fog computing technology helps to overcome challenges of big data processing. The paper discusses the taxonomy of fog computing, how this is different from cloud computing and edge computing technologies, its applications, emerging key technologies (i.e., communication technologies and storage technologies) and various challenges involved in fog technology.

Keywords Cloud computing · Fog computing · Fog network · Fog node · Architecture

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1 Introduction to fog computing

The emergence of Internet of Things (IoT) technology leads to the development of a wide variety of IoT devices. Smart home applications, tablets, smartphones, edge routers, cellular base stations, smart traffic systems, smart energy meters, connected vehicles, smart building controllers, etc. all use IoT devices. The rapid increase in these varieties of network edge devices results in huge data transmission on a continual fashion within a short span of time. These raw data need to be processed and respond quickly.

Cloud computing consists of cloud data centers that are centrally deployed on a global scale. Without fog computing technology, these data centers need to process huge data coming from IoT devices. In addition, as the physical distance between the cloud and the user increases, transmission latency and response time increase with it. Users might become exhausted with the services provided [1–4]. The processing speed in such a large environment is mostly dependent on the performance of the user device. The approachable solution to these problems is the fog computing.

CISCO developed fog computing or fogging in 2014 [5]. This is also known as fogging. Fog computing consists of multiple fog nodes arranged in a network which are placed at just one hop from the user. Due to the placement of these multiple fog nodes very close to the user, the data are processed locally inside fog nodes rather than migrating the data to cloud server placed far away from the user [6,7]. Dastjerdi et al. [8] defined fog computing to be as the distributed computing environment extending the services of cloud computing to one-hop distance from the user. Fog computing technology provides networking, computation, storage and management services between the end-users (edges) and the cloud data centers [9,10]. This supports protocols for communication, mobility, resources to perform computing, distributed analysis of data and integration of cloud for addressing latency-sensitive applications that need minimum delay. In Marin-Tordera et al. [11], fog node is defined as a device where the fog computing is deployed.

Figure 1 represents the transformation of cloud computing to the fog computing with adding functionalities with change of technology. Initially, users' data were directly processed by the cloud data centers. But with the emergence of fog computing, latency-sensitive applications are processed by the fog nodes and latency in-sensitive applications are processed directly by the cloud data centers.

Figure 2 represents fog nodes in a distributed arrangement within a fog network. Fog network consists of multiple fog nodes, each communicating with one another and also in sync with the cloud data center. Fog computing and cloud computing work together to enhance quality and performance of any system.

In today's era of computing, huge data are increasingly generated by the proliferating IoT devices at the core network. These large quantity raw data are initially processed by the fog networking or fog computing technology. Fog computing comprises of microclouds (fog nodes) that are placed at the edge of the data originator. These microclouds have the mechanism how the data are to be processed before going on to the network. Hence, fog computing structure is useful in big IoT data analytics. This is on emerging phase and requires research initiatives on how effective knowledge can be obtained for smart decisions [12].

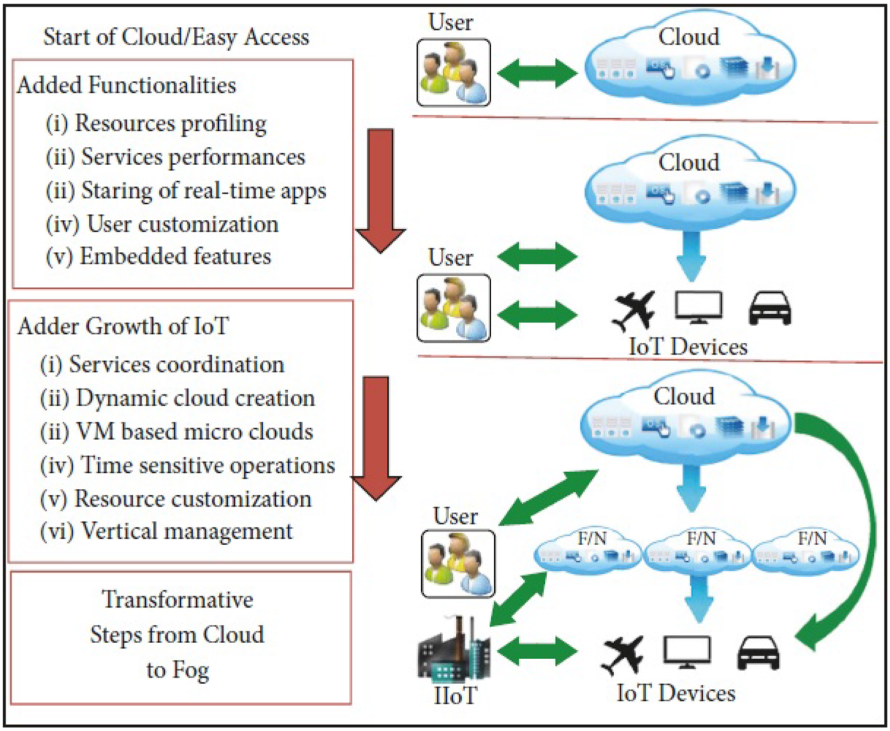


Fig. 1 Transformation era from cloud computing to fog computing [12]

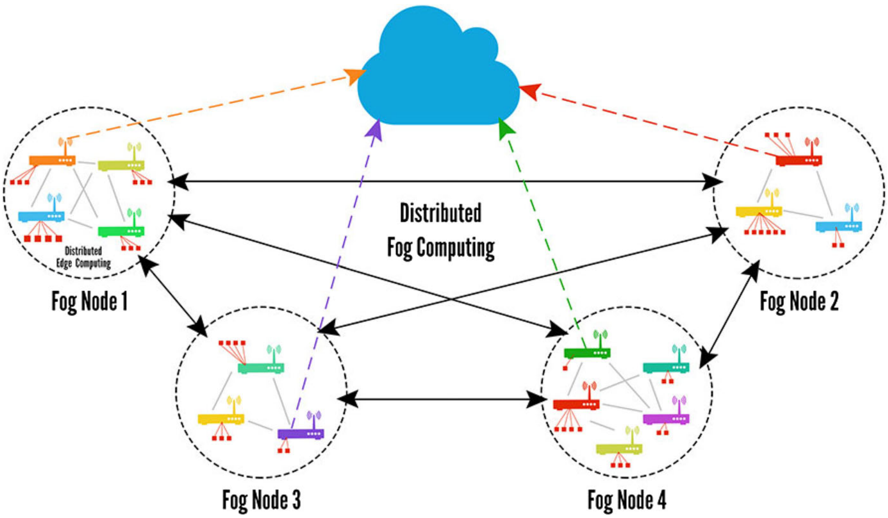


Fig. 2 Working of fog computing

Continuously, huge data are generated by the IoT devices. According to the CISCO estimation report, 847 zettabytes (ZB) of data will be generated by IoT devices by 2021 [13]. All these data are not useful and need to be mined. Fog computing overcomes this processing of data at the edge of the network. As a result, fog computing overcomes some of emerging big data problems [14].

Organization of the paper is as follows: This survey discusses fog computing technology with the introduction in the first part (Sect. 1) and related work in the second part (Sect. 2). Section 1 explains the concept of fog computing. Section 2 discusses the emergence of fog computing, its role in related technologies and how this technology is useful to the researchers in their areas. This section covers the description about this technology stating how and in what all emerging fields this technology is useful. Section 4 discusses the architecture of fog computing. Sections 5 and 6 discuss the comparison of fog computing with different technologies, i.e., cloud computing and edge computing. Section 7 explains key technologies in fog computing. Section 8 discusses the advantages of fog computing. Sections 9 and 10 present the applications and challenges in fog computing.

Finally, Sect. 11 presents the conclusion and future scope of the paper.

2 Related work

Chiang and Zhang [15] discussed fog computing as a provider of various services at the edge of the network making them closer to the user. They summarized new challenges and opportunities of fog computing and focused on how widely IoT network can use fog computing platform and why there was a need for this new architecture. They also discussed how various gaps in the technology can be filled with fog computing architecture, which leads to increase in new business opportunities. Latency constraints, network bandwidth constraints, resource constraints were some challenges for fog computing cited in their work. Stojmenovic and Wen [6] discussed privacy and security issues in fog computing. Study of man-in-the-middle attack was performed considering the CPU and consumption of memory parameters. Dastjerdi et al. [8] discussed the emergence of fog computing along with its key characteristics. They presented a reference architecture and discussed the recent developments and applications. They categorized various research challenges like resource management and energy minimization that were still in need for solutions in their work. They discussed about the IoT, commercial products and the case study of the smart city as use case for the Internet of Things.

An approach was discussed by Kukreja and Sharma [16] about the scalable distributed computing paradigms: fog, cloud and dew computing. They explained dew computing as a novel structural layer in the available distributed computing hierarchy. This was placed as the base level for the fog computing and cloud computing paradigms. From the cloud computing, the various divisions: hierarchical, vertical and complementary to dew computing fulfilled the requirements of low and high-end computing needs in day-to-day work and life. These novel computing paradigms decreased the cost and enhanced the performance, specifically for applications and concepts, i.e., the Internet of Things (IoT) and Internet of Everything (IoE). More [17] defined fog computing as a model in which various applications along with the data were stored in devices which were placed at the edge nearer to the user rather than storing in the existing cloud. They described fog computing as cloud computing extension along with the various services of cloud computing that extends the computing to the user edge. They discussed differences between cloud computing and the fog computing.

Tordera et al. [11] conveyed that fog computing was a "mini-cloud" on its first attempt, which was using lots of edge node devices through wireless connections. They surveyed and analyzed the role that edge devices play in the fog computing definition, and later they summarized their lessons with the implementation. They focused on core aspects of fog node and major research challenges toward fog nodes in the future. They mentioned the location where these fog nodes are located. Table 1 describes their findings.

Mahmud and Buyya [29] discussed the fog computing environment along with challenges in fog computing. They discussed five types of fog nodes, their configuration and resource/service provisioning metrics. Security challenges in fog computing were explained in their work. Saharan and Kumar [30] discussed the main characteristics of this technology. They discussed the advantages along with various distinguish parameters of the cloud computing and the fog computing. They analyzed its applications for IoT. Their approach conveyed that better QoS considering parameters as delay and consumption of energy on the Internet, which is possible by this technology. Yi et al. [31] discussed the unsolved cloud computing issues such as latency and location awareness, etc. and suggested fog computing as a solution to these issues. They discussed the fog computing definition and various issues that might originate during design and implementation of fog technology and highlighted the issues related to resource management, privacy, QoS, security and interfacing. Yi et al. [32] in another paper discussed the various challenges in fog computing platform and presented several application examples to explain the platform design. A prototype for fog computing platform is implemented and evaluated for smart home applications.

Razouk et al. [33] discussed fog computing and proposed middleware architecture from security point of view to solve the issues in cloud computing. Their architecture acted as the smart gateway, which performed analytics at the edge of the network. Yet another privacy and security issues were discussed by Alrawais et al. [34] and they proposed techniques that helped fog computing to improve distribution of certificate revocation information among the IoT devices. Using the proposed technique, their model enhanced the security of entire system.

Roman et al. [35] discussed security aspects of edge computing. They shared various research challenges in their work. Another work by Zhao et al. [36] focused Radio Access Network (RAN) that exists between the traditional services and mobile edge computing. Many researchers [37–40] discussed their work on edge computing.

Table 1 Fog node location [11]

Gateways	[18–21]
Intermediate computing node	[22–25]
Networking elements such as switches and routers	[5,23–28]

Fog computing technology was used in almost every field including health care. Rahmani et al. [41] presented an IoT-based remote health monitoring system that implements prototype of Smart e-Health Gateway called UT-GATE and implemented an IoT-based Early Warning Score (EWS) for health monitoring. They showed the improvement in efficiency of their system using EWS. Vora et al. [42] proposed Fog computing based patient monitoring system for Ambient Assisted Living (FAAL). They also presented clustering algorithm which they used for data transmission that helps in reduction in the communication infrastructure load.

Our work discusses fog computing and various new technologies that are emerging with this technology. Applications, advantages and real- time usage of fog computing are discussed. The paper also explains various challenges in the technology that leads the way for researchers to work in those directions as a future research prospective.

3 Scope and motivation of work

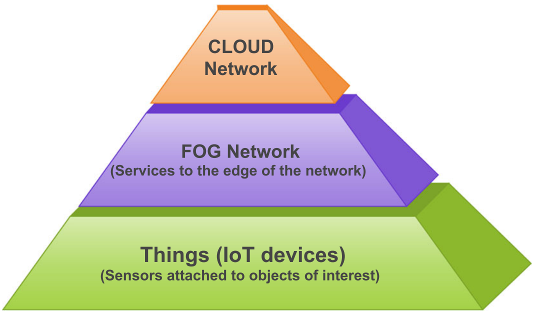
Fog computing works by allowing some application processing to be performed at the users' end. The processing is performed with the fog server (fog node), which is placed between the cloud and the user. This is mainly in a location physically closer to the user. This allows some workloads of users devices be offloaded from the cloud at a location that is closer to the user for processing. This speeds up applications processing time that requires the low latency response. Thus, performance of the system is enhanced.

4 Fog computing architecture

Fog computing architecture is the arrangement of logical and physical software, network elements and hardware for the implementation of useful network like IoT network. The important architectural decisions include the positioning of the fog nodes, their links capacities, topologies in which they are arranged, data bandwidth available and their consumption. How the fog nodes are used and managed is also important architectural decision.

Fog computing, together with the cloud computing, forms three layer architecture [32,43] as described in Fig. 3:

Fig. 3 Basic architecture of fog computing



i. Cloud (top most) layer: Cloud services and resources are contained in the top most layer. It consists of the cloud server having huge storage capacity.
ii. Fog network (middle) layer: The middle layer consists of the fog network, comprising of the fog nodes connected to each other in the network. Fog nodes consist of various networking devices like gateways, routers, switches.
iii. Things (bottom most) layer: The bottom most layer consists of the IoT devices (things) consisting of sensors, smartphones, tablets and computers.

The bottom layer captures raw data in a continuous manner from the user end and simultaneously transfers these data to the edge node. These raw data are reached at the edge node which is closest to the user. These raw data are processed, and computation on these raw data is performed at the fog node. These fog nodes are placed in the middle layer. Analytics is performed at the fog computing network with the help of active fog nodes. This analytics is performed near to the user, and response is sent for further processing immediately, thus reducing latency in transmission, and provides quick response. The results after computation and corresponding action are updated to the cloud on the top most layer. Thus, fog computing helps to reduce the packets transmitted on the network between the fog and the cloud. This helps in improving bandwidth, better performance and faster transmission of packets over the network.

Marin-Tordera et al. [11] conveyed this architecture as a three fog computing layers for analysis of big data in smart cities. According to them, the first fog layer is the intermediate computing node that comprises of computers having efficient computing power. The second layer is termed as edge computing nodes that contain tiny computing nodes like the mobile phones. The last and the third layer is called as the lowest fog layer that comprises of sensors that have sensing capabilities. Taneja and Davy [44] described the basic architecture as the tier division. Their tier division is shown in Fig. 4. They described the fog computing architecture using tier division as represented in Fig. 5.

5 Differentiating cloud and fog computing: analysis

The cloud computing has large data centers each having an infinite storage space that can be used to store large amount of data [45]. Data follow the path on the Internet to reach to the cloud server as cloud services are provided by the third party vendors to the end-users. Thus, migrating data to the cloud server and then receiving the response and vice versa consume much amount of time; especially, this is important when the case of real-time applications is considered, where the response is required within a fraction of a second. Cloud computing takes an interminable time to response as the request has to

Tier 3	Cloud Intelligence : Cloud Layer
Tier 2	Edge intelligence / Fog intelligence : Fog Layer
Tier 1	(End point) Sensor Data : Terminal nodes/ IoT Device Layer

Fig. 4 Tier division [44]

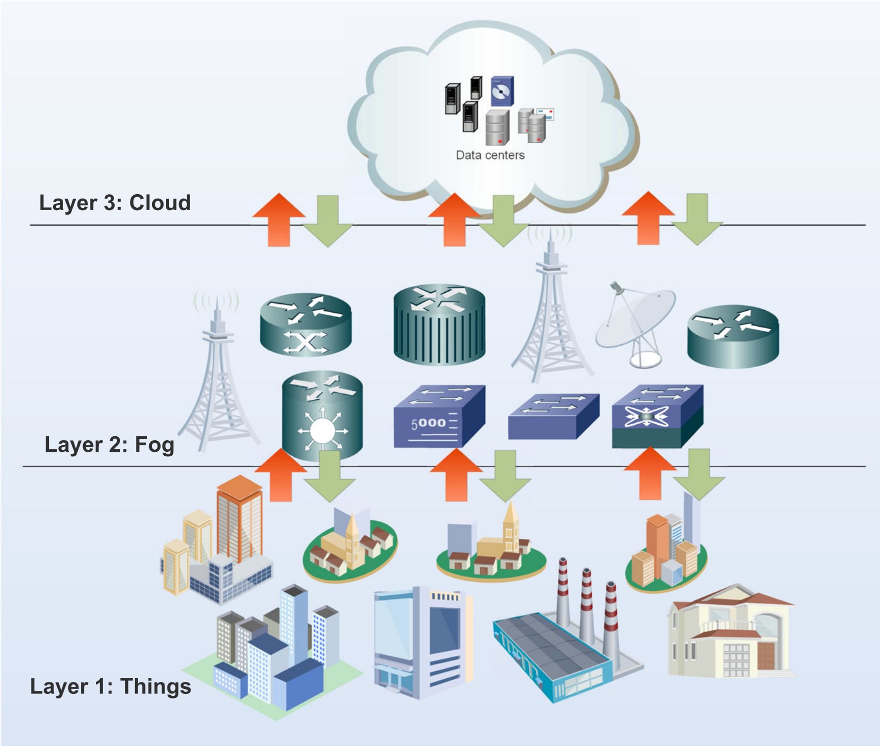


Fig. 5 Architecture of fog computing

cover through a large network of connecting devices like routers, gateways, repeaters. This shortcoming of cloud computing is overcome by fog computing [46–50].

Figure 6 represents the fog computing in comparison with cloud computing. Fog computing is cloud placed near to the user, which has a low computational capacity and small storage space. Fog network is composed of fog devices like routers, gateways, repeaters [51–53]. All the request from the end-users come to these fog devices initially. Computations are performed on the fog devices and are communicated with request–response cycle. The requests which do not require a rapid response can be sent to cloud for handling. Hence, fog computing and cloud computing are two different technologies, but they work together to provide greater response time, higher efficiency and better performance. The comparing parameters between the cloud computing and the fog computing considering various characteristics are described in Table 2.

6 Differentiating edge and fog computing: analysis

Edge computing pushes localized processing in the advanced manner, i.e., closer to the data source. For attaining this, the connection between Programmable Automation Controllers (PAC) and the sensors is made. These PACs handle all the processing and communications. Table 3 shows the characteristics of fog and edge computing.

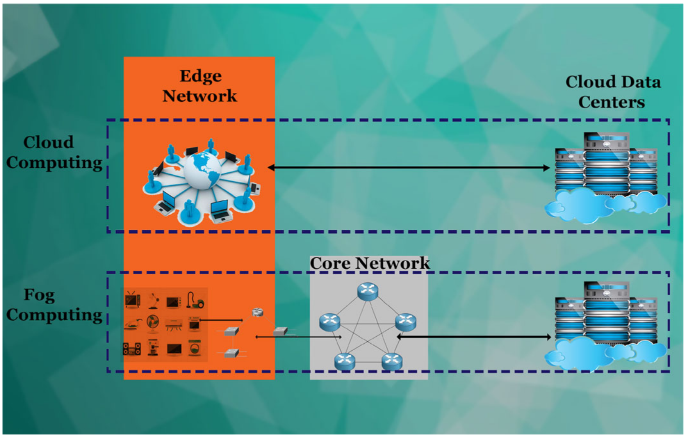


Fig. 6 Fog computing and cloud computing

Table 2 Difference between cloud computing and fog computing [17,30,54]

Characteristics	Fog computing	Cloud computing
Latency	Low	High
Delay	Very low	High
Server nodes location	Edge of network (local)	In-between the internet
Security	Can be defined	Undefined
Client and server distance	One hop	Multiple hops
Location awareness	Yes	No
Prone to attacks on data in transmission	Very less probability	High probability
Geographical distribution	Distributed	Centralized
Mobility	Supports mobility	Limited
Server nodes count	Very large	Few
Interactions in real time	Supports	Supports

Table 4 shows difference between the fog computing and edge computing. The venn diagram showing the comparison between these technologies is shown in Fig. 7.

7 Key technologies

Various key technologies in fog computing involve [55,59].

7.1 Communication technologies

Various communication technologies have emerged with fog computing like Software-Defined Network (SDN) [60,61], Network Function Virtualization (NFV) [62],

Table 3 Fog and edge computing characteristics [55,56]

Characteristics	Fog computing	Edge computing
Hosting application	Yes	Less scope
Provides data service at edge	Yes	Yes
Management of device and application	Yes	Yes
Security	E2F, data protection, session and hardware level	Point to point partial solution VPN, FW
Resource pooling/elastics compute	Yes	No
Interchangeable hardware	Yes	No
Windows support virtualization	Yes	TBD
Real-time high availability control	Yes	No

Table 4 Difference between fog computing and edge computing [57,58]

S. no.	Fog computing	Edge computing
1	Device independent, intelligent, and knowledge of whole fog network	Device and services aware, no knowledge of entire network
2	Controls all devices in the network	Limited control in the edge network
3	Fog computing extends cloud to fog level in a continuum	Edge computing is cloud unaware
4	Complete network scope	Limited network scope
5	Enables multiple IoT verticals and provides support for them	No IoT vertical awareness
6	Supports integration of multiple verticals	No IoT vertical integration
7	Versatile fog nodes that perform variety of tasks like website hosting and management	Edge device is controlled and communicated with edge controllers
8	End-to-end security	Security scope is limited to devices

concept of 5G technology [63,64], Content Distribution Network(CDN) [65–67], Long-Reach Passive Optical Network (LRPON) [68–72].

I. **Software-defined network (SDN)** Scalability, flexibility, ability to program and global knowledge are provided by SDN architecture [73]. SDN separates data and control layers [74]. From the technical point of view, SDN is a new network architecture which comprises of three different layers as shown in Fig. 8. The third layer, i.e., application layer, is for covered applications, management applications and business applications, and places the demands for the network onto the control layer.

(a) **Components of SDN** SDN works on manageable networking devices. These devices consist in two parts: data plane and control plane. Earlier networking

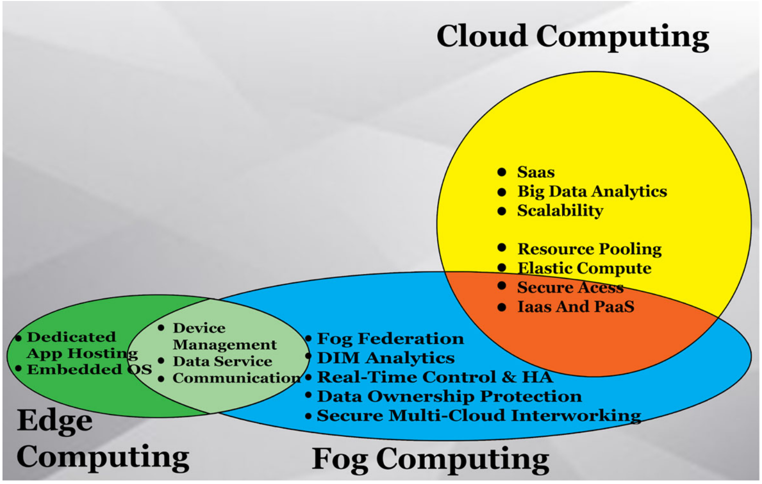


Fig. 7 Edge computing, fog computing and cloud computing

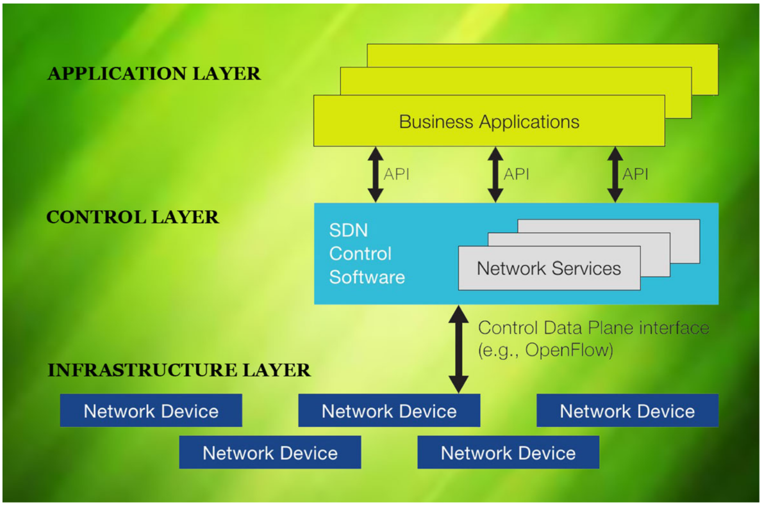


Fig. 8 SDN network architecture

devices were tightly coupled that means the data plane and control plane cannot be available separately. In tightly coupled devices, modifications are not possible as both the data plane and control plane are coupled with each other. To overcome above limitation, SDN technology gives ability to purchase data plane and control plane separately. Network intelligence is centralized in one network component by the SDN. This leads to the disassociation of forwarding process of network packets (i.e., data plane) from the routing process (i.e., control plane). It decouples data plane & control plane, by which we can design our own application/code as per our requirement, and we make that code compatible with control plane and data plane. Now only code decides, and device will work like a switch, like a router or a firewall (security device) [60].

i. *Data plane* Data plane in networking device works like forwarding plane, which actually forwards the data; for example, physical ports on switch work as data plane. Data plane is also known as forwarding device, open flow switch and SDN switch. There is no intelligence in data plane. It is like dummy device.

ii. *Control plane* Control plane in networking device works like controller that actually controls the flow of data. It is like IOS (Internetwork Operating System) of device which runs from CLI (Command Line Interface) mode. Control plane is also known as SDN controller.

Figure 9 shows the components of SDN. This comprises of data plane at the bottom, followed by the control plane and then the application plane. All the application logics reside on the application plane. Control plane consists of the SDN controller that controls all the flows of the network that is coming in and moving out of the SDN. The bottom part, i.e., the data plane, contains the network elements that perform the processing functions.

II. **Network function virtualization (NFV)** NFV is an emerging technology that can be used in 5G technology. It is the subset of Software-Defined Networking (SDN). NFV decouples hardware from software. The network operators are populated with the large hardware appliances. They require large hardware equipment for the number of users so that they can meet their growing demands and new services. In order to launch the new services, we require another variety of hardware, space and power. It is very difficult to achieve because we need increase cost of energy, a

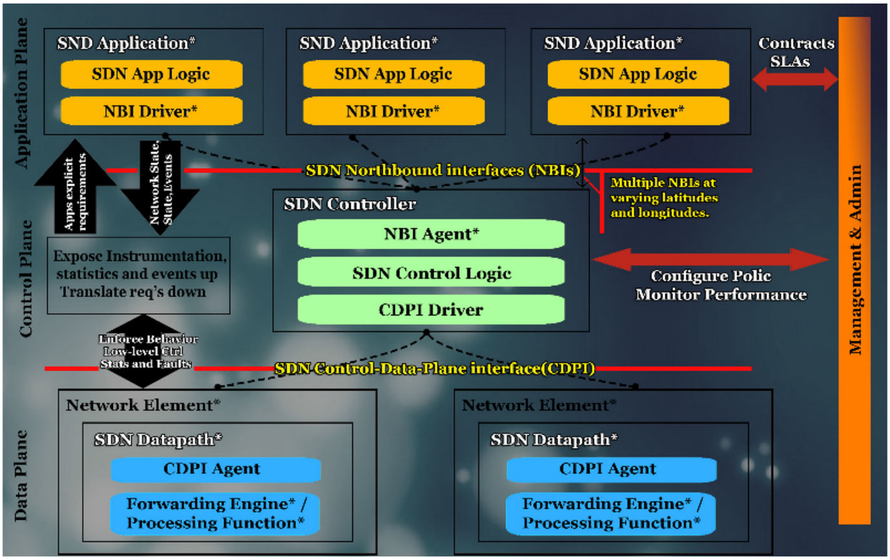


Fig. 9 SDN components

lot of investments and complex hardware designs. NFV is aimed to remove these problems while using IT virtualization technology to consolidate many hardware equipment types like server, switches and storage that are located in data center. Thus, the aim of NFV is to make network architecture simpler and faster.
NFV consists of various components. NFV Infrastructure (NFVI) provides the infrastructure to the NFV. This contains virtualization layer on which various modules will be deployed. These modules consist of virtual computation, virtual storage services and virtual network resources. This virtualization layer is hosted above the physical hardware resources. The administrators can access and manage this all using the NFV management console. On the top of the NFV Infrastructure (NFVI), there lies the Virtualized Network Functions (VNFs). This comprises of multiple VNFs deployed over the NFV Infrastructure (NFVI). Figures 10 and 11 show the components of NFV.

(a) **Benefits of NFV** The benefits of NFV are as follows.
   i. It provides more flexibility as it separates the hardware and software.
   ii. It is much more scalable and elastic.
   iii. The network function can be localized.
   iv. It will reduce equipment cost and consumption.
   v. It will increase the speed of time to market by minimizing operator cycle of innovation.
   vi. Operators can share resources that mean resources can be utilized more effectively.
   vii. Lower risks.

III. **Concepts of 5G technology** 5G wireless technology is the 5th generation of wireless technology. It provides wireless communication with almost no limitations. Every generation has some limitations like in first generation; it was a

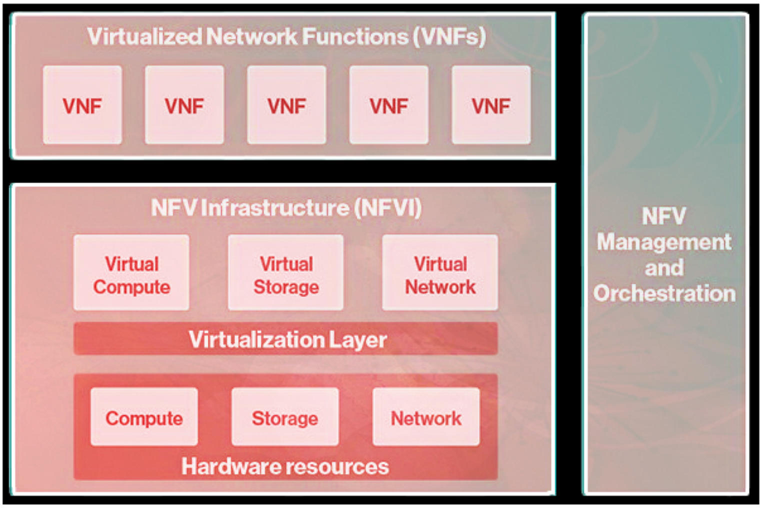


Fig. 10 NFV architecture

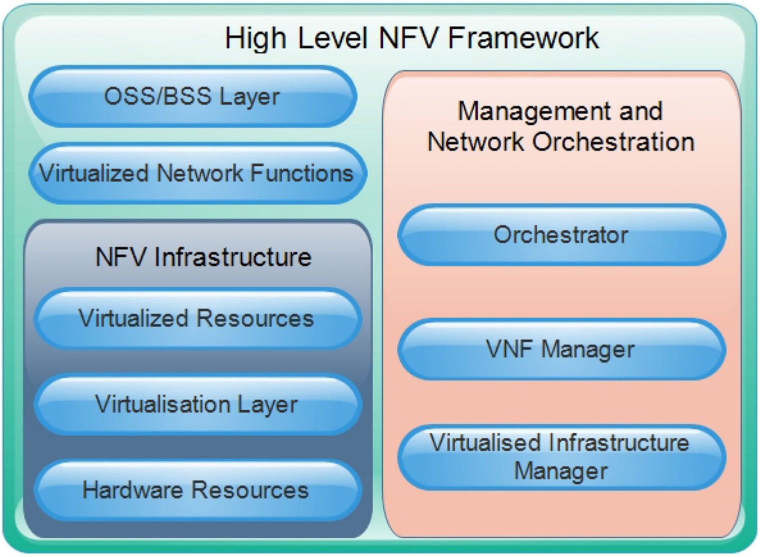


Fig. 11 Detailed components of NFV

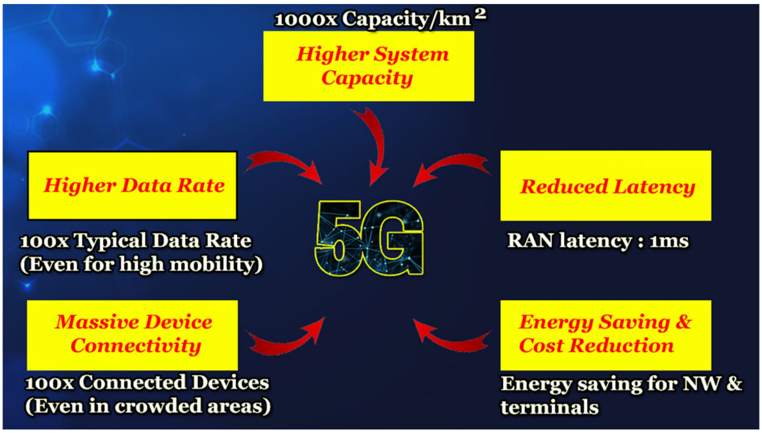


Fig. 12 Fifth-generation (5G) technology

speed limitation, call limitation and audio/video limitations. As the years pass on, with the progress in the technology, 5th generation has up to no limitations. This generation can be called a real wireless world. While sitting at the one end of the world, we can communicate with the person sitting at the other end of the world without any interruption, without any speed limitation or communication limitation and with incredible transmission speed [75]. Now we can transfer huge files up to GBs per second. This concept is only theory and has not launched in real world so far. The concepts involved in 5G technology are represented in Fig. 12.

(a) *5G technology opportunities* in context with fog computing are described below.
   i. It will offer worldwide cellular phones.
   ii. It will provide extraordinary data capability.
   iii. It will provide high connectivity. For example, if we are in some other continent and want to communicate with your friend residing in another continent, we can easily contact with high connectivity even in crowded areas.
   iv. It allows transfer of data at a very high rate. (100 times more than the typical data rate even for high mobility.)
   v. It will provide more power and features in handheld phones. We can roam and do your work while communicating.
   vi. It will offer large phone memory. Previously phone memory was up to 1 GB or 2 GB, but now it can be up to 120 GB.
   vii. It will provide more dialing speed. We can connect a person within seconds.
   viii. It will provide more clarity in audio and video.

   Figure 12 shows about the advantages that fifth generation offers.

(b) Basic architecture of 5G technology

   Figure 13 shows the layered architecture of both the normal ISO/OSI model and 5G technology, and Fig. 14 describes the basic architecture of 5G technology. The Open Wireless Architecture of 5G layer is the combination of both the physical layer and data link layer of OSI Model. The upper network layer and the lower network layer of 5G technology architecture are a combination of network layer of OSI Model. Similarly, the Open Transfer Protocol of 5G architecture is a combination of session layer and transport layer and application (service) is the combination of application layer and presentation layer of OSI Model.

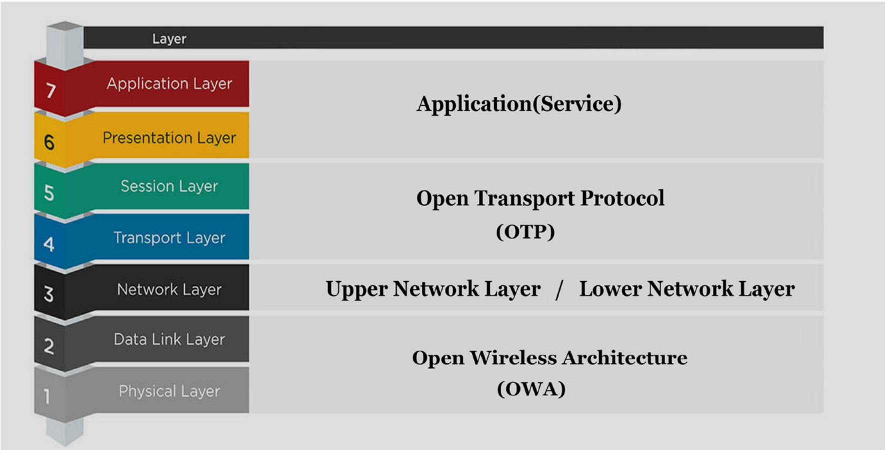


Fig. 13 Layered architecture of ISO/OSI model and 5G technology

Fig. 14 Basic architecture of 5G technology [76]

IV. **Content distribution network (CDN)** Content Delivery Network or Content Distribution Network, simply put, is a collection of thousands of thousands computes (fog devices). This is simply the network of attached computers (fog network). All of these computers are ready to serve any request sent to them. They deliver requested Web pages and other Web content to the user. The goal of CDN is to provide high availability and high performance to users. CDNs provide faster request–response cycle in case of Web pages and thus give better performance during high traffic. The speed of delivery of contents is based on users geographical location. The closer the CDN server is to the user geographically, the faster the user will get the requested contents. Figure 15 shows the Content Delivery Network.

(a) Why we need CDN
To understand the need of CDN, we must be knowing how we can construct a typical Web page [65]. A client that could be a Web browser, mobile device or any other computer connected to the Internet sends a request to the server. For example, when one type in his browser, www.google.com, that browser (client) sends request to google.com (server) and asks for the Web pages. Then, the Google server does some computations and sends raw html page back to the client. This html page has multiple links like CSS, JavaScript and images. Figure 16 shows this scenario. This same process of request and response cycles works in case of fog computing also while communicating with the fog devices.
After client downloads the initial html page, it makes another html requests to get CSS, JavaScript and images. Thus, client sends so many requests for just one page www.google.com. The CSS, JavaScript and images are static

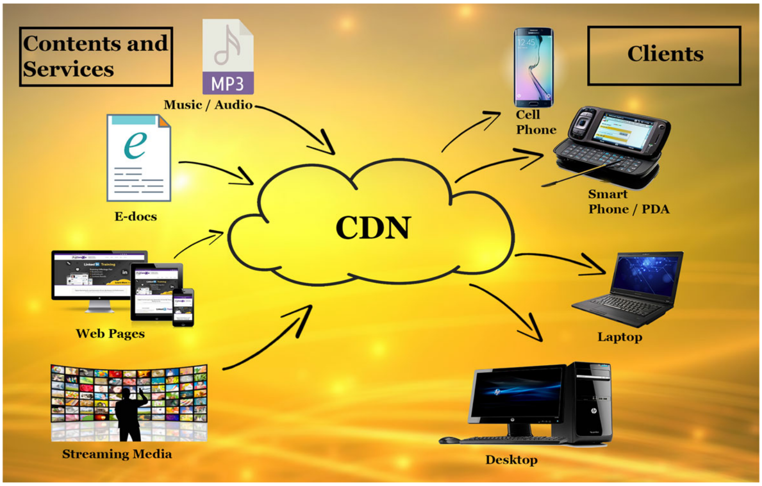


Fig. 15 Content delivery network (CDN)

Fig. 16 Layered architecture of OSI/ISO model and 5G technology

contents, i.e., contents that do not change. They remain static with time rather than dynamic contents [67].

In a small company, a center server serves all the requests from its clients. The same server manages many connections from a single client. This leads to shortage of bandwidth or capability to serve large number of requests from millions of clients even you may have thousands of servers.
Content Distributed Network (CDN) provides the better solution for such problems. CDN helps to remove all of that traffic, and it also takes over the load

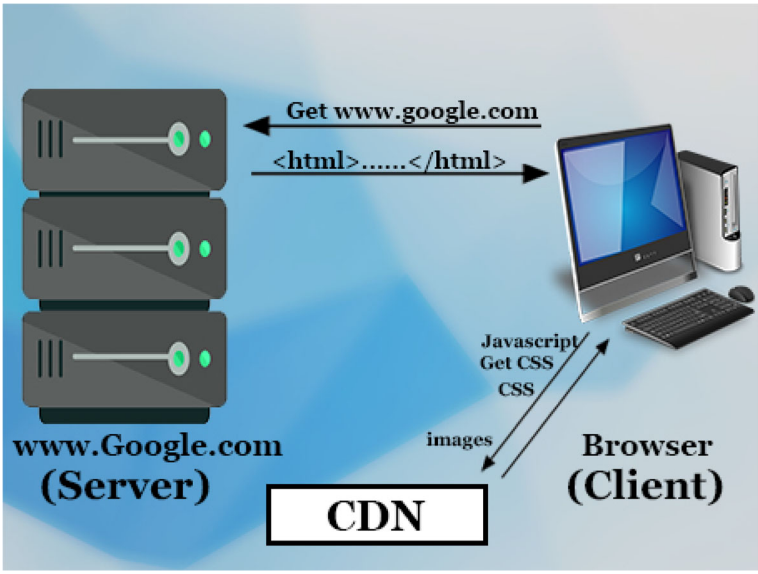


Fig. 17 Layered architecture of ISO/OSI model and 5G technology

of all the CSS, images and JavaScript (js) that the original server was not able to serve and also frees up a lot of bandwidth to serve in future and for more dynamic stuff [66]. This scenario is shown in Fig. 17.

Thus, the www.google.com or any Internet skilled companies like Facebook, Linkedin serve dynamic contents and links to CSS, images and JavaScript are redirected to CDN provider. Thus, they uses a CDN to serve their needs of the static contents and their servers are free to serve all the extra requests.

(b) Advantages of using CDN

i. As CDN is a collection of computer spread across the earth, it stores a cached version of its content in multiple geographical locations. So the client from Brazil, for example, would get the closest network of computers and would get all the static contents from the closest location of that CDN machine rather than traveling the full width of US server and back. Thus, it provides faster content delivery to end-users.

ii. It provides a lot of free bandwidth to the server.

iii. One of the major advantages is warm cache. If there is a new feature coming out and all the browsers do not have those new static contents, CDN helps to warm the cache earlier when we are testing the feature, and all the static contents will be cached. So all of those resources are available for the client for the new features.

iv. It provides security of data in case of Denial-of-Service (DoS) attacks.

V. **Long-reach passive optical network (LRPON)** Emergence of technology leads to the increase in span of Passive Optical Network (PON) broadband access to a larger extent. This extended reach Passive Optical Network (PON) is called as Long-Reach Passive Optical Network (LRPON). Generally, this extension is

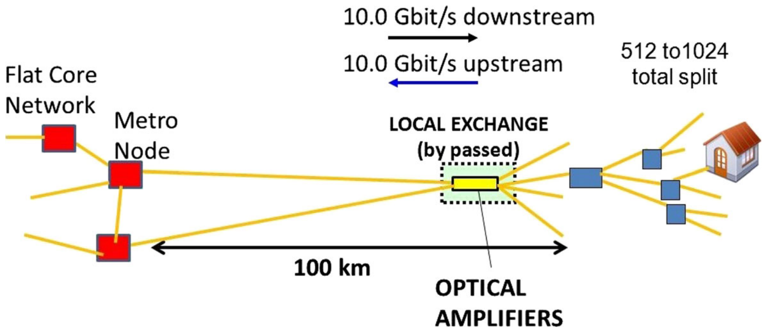


Fig. 18 Long-reach passive optical network (LRPON) [80,81]

from 20 km (in case of PON) to 100 km or higher (in case of LRPON). This technology enables broadband access among large number of users with reduced cost [77–79]. LRPON network is shown in Fig. 18.
LRPON is designed for long-range coverage of broadband access. This helps to serve large number of users. Revenue and data loss occur for network operator and customers if any network failure occurs. The architecture comprises of fiber cable that connects customer directly with the local exchange and has an optical splitter which connects users to the shared fiber [82]. This technology is very useful for voice over IP (VoIP) and IP video delivery. Allocation of resources, management, service aggregation and control are the various research challenges in this technology [83,84].
Advantages of Long-Reach Passive Optical Network (LRPON) are as follows [68,69,71].

(a) It provides large split 512–1024 instead of 32–64 as shown in Fig. 18.
(b) It provides 10 Gb/s peak to customers ($\sim$ 10,000 times DSL rate) and 10–20 Mb/s sustained bandwidth ($\sim$200 times DSL rates).
(c) Future bandwidth can be $\sim$ 100 times greater via WDM.
(d) 5600 local exchanges in UK can be reduced to $\sim$ 100.
(e) Optical networks are more reliable than copper.

7.2 Storage technologies

Storage is the key technology in fog computing. Bringing storage closer to the user enhances security and privacy and enhances the low latency. Fog network comprises of heterogeneous nodes that have small computing capabilities, but vary in physical components. Thus, how to deploy the applications on the fog devices and in a proper manner is the major concern [58,85,86].

8 Advantages of fog computing

Various advantages of fog computing [30,87–89] include:

I. **Efficiency and cost** It reduces the need for bandwidth using distributed strategy which results in lower costs and improves efficiencies. Fog computing is placed at the edge of the network, which is one hop from the user. This is the place where all the computations are carried out [90,91]. This reduces bandwidth and hence enhances efficiency.
II. **Location awareness** Using fog computing, latitude and longitude values of the fog devices can be captured. This provides location awareness and minimum latency and improves the Quality of Service (QoS) in real-time interactions as this is placed very close to the user [79,92].
III. **Geographical distribution** It provides widespread geographical distribution which consists of a network of fog nodes that are geographically distributed and are connected to the centralized cloud server [93,94].
IV. **Mobility:** It provides mobility and closeness as it is operating at the edge of the network. This is simply like we are having a moving VM that keeps on moving as we are navigating from here and there and in that VM, and all the data of the user are stored [95,96].
V. **Enhanced security** Fog computing provides enhanced security. Policies and procedures can be made to protect the fog nodes in the network [97,98].
VI. **Deeper privacy control** Fog computing provides greater privacy over cloud computing. The sensitive information is analyzed locally near to the user, rather than sending the sensitive information on the network to the cloud. Fog devices can easily track and managed by the IT team within the organization, hence enhancing the privacy [99,100].
VII. **Better interconnectivity** As the fog network is nearer to the user, connectivity capacity is good between the user and the fog node. This helps to get faster response and better analytics using the fog nodes [101].
VIII. **Reduced latency** The analysis time gets reduced with the emergence of fog computing. This is because of bringing computation closer to the user. Since, response time of computation is quick as compared to cloud computing, hence reducing the latency in computation [102,103].
IX. **Better quality of service (QoS)** Quality of Service (QoS) depends upon many factors like reliability, link health, bandwidth of the link. All these factors performed well in fog computing as compared to cloud computing [104–106]. Thus, Quality of Service (QoS) is enhanced using fog computing technology.

9 Applications

Fog computing, being placed closer to the user, is used in many applications, especially those that are latency-sensitive. Few applications are as follows:

I. **Smart grid** Fog computing plays a vital role in energy management in smart grid application. Comparing the energy demand, these devices have the capability of switching to the alternative energies like wind and solar energy system [107–109]. In this application, grid devices like sensors, which are present at the edges, are attached to the fog devices. These grid devices generate the data and

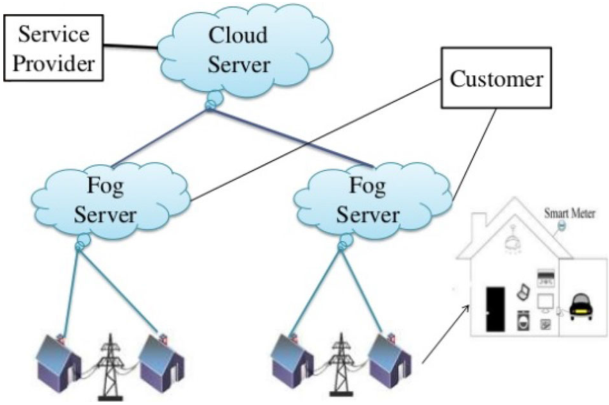


Fig. 19 Smart grid

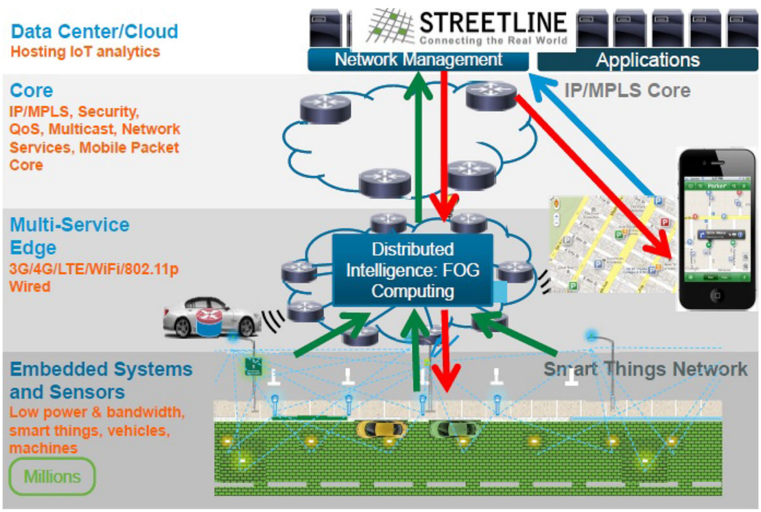


Fig. 20 Streetline parking automation system [22]

fog devices issues commands to the actuators for managing the generated data [6,24,110]. Figure 19 represents smart grid application.

II. **Streetline parking automation system** The streetline parking automation system [11,22] is represented in Fig. 20. The vehicles like cars have the sensors attached to them. This is represented as embedded systems and sensor layer in Fig. 20. These sensors remain continuous in connection with the fog network. The sensors emit continuous signals/data that are received by the nearest fog node inside the fog network. The fog network forms the multi-service edge layer that consists of the fog nodes connected together. All the intelligence is performed here. This layer is in link with the cloud layer using the Multi-Protocol Label Switching (MPLS) and other protocols.

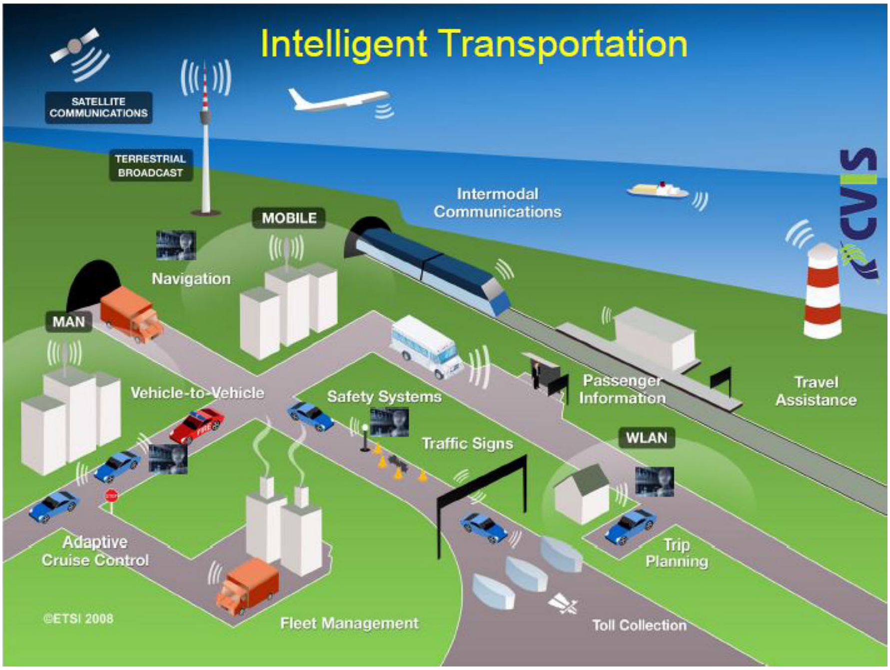


Fig. 21 Application: intelligent transportation system [22]

III. **Intelligent transportation system** Another application of fog computing is the Intelligent Transportation System. In this, all the vehicles are having sensors that are connected with the fog devices. This also provides an ease for vehicle-to-vehicle communication. Figure 21 describes the Intelligent Transportation System. This system involves many communications including satellite communications, vehicle-to-vehicle communications, safety systems, traffic signs, fleet management [98,111].

IV. **Smart health-care monitoring system** Health monitoring or observations, which have significant variations, are the focus of applications during analytics of data in biomedical area for correctly identifying smart health-care decisions in the future [12]. In real time, this is possible by three-level hierarchal structure comprising of fog nodes rather than using cloud computing technology independently.

U-Fall, a real-time monitoring application proposed by Cao et al. [112], has three main sections: front end, back end and communication module. In this application, front end and back end both take independent decisions, and then, their collaborative results form the actual solution. This independently detection technique reduces the wrong alarm rate of the application and improves the accuracy of the collaborative result. Gia et al. [113] utilized fog computing as a smart gateway for computing various complicated methods. Aazam and Huh [114] proposed Emergency Help Alert Mobile Cloud, a smart phone application that uses fog nodes for preprocessing the data and offloading the response to

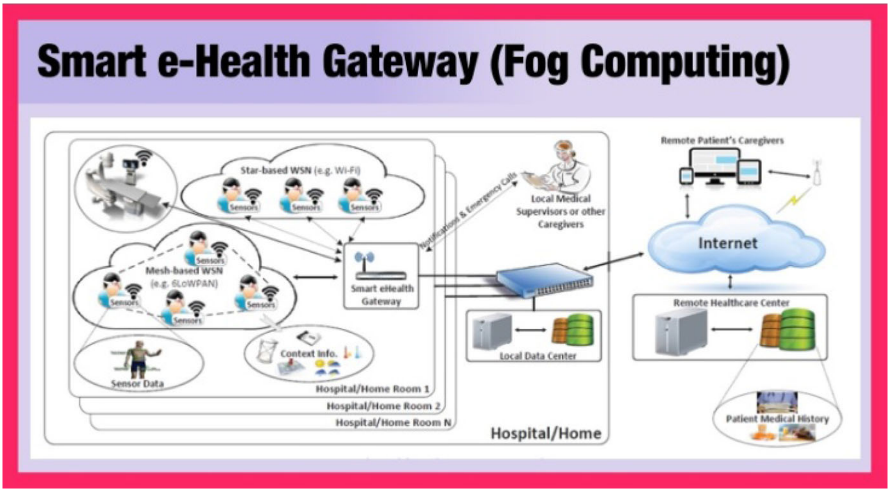


Fig. 22 Smart health-care monitoring system

appropriate department (like ambulance) having contact details already stored within the application. They proposed the application for real-time use. Figure 22 describes smart health-care monitoring system.

V. **Real-time video analytics** Fog computing provides well-organized platform for the applications that contains video content. This technology overcomes latency issues in the packets transmitted over the network, thus making the video quality rich to the user [12,115]. This technology plays a vital role in real-time data analysis. Hong et al. [116] performed face recognition process by identifying data collection process at various cloud instances. They used three-level hierarchal structure comprising of fog nodes to act upon smart cameras using motion detectors. Fog computing is also used in on-demand video streaming. Zhu et al. [117] performed real-time analytics on video data for surveillance cameras and enhanced the communication in a virtual desktop structured system. Figure 23 represents video analytics.

VI. **Smart traffic lights system** Smart traffic lights system is used for monitoring instances like accidents, flow of the traffic and collects the related data for future analysis [118,119]. In smart traffic lights system, many sensors interact with this system for obtaining the information [12]. Information collected using this system further helps in prevention of accidents by generating warning signals in connected vehicles. Stojmenovic and Wen [120] proposed a system with video surveillance cameras for sensing and monitoring the accidents and sending alert alarm to an ambulance. Further, this system has emergency traffic light support to pass the ambulance in emergency situations. Many researchers [92,121–129] also presented their work on smart traffic lights system using fog computing technology. Figure 24 represents smart traffic lights system.

VII. **Gaming** The emergence of cloud computing allowed gaming users to play with more than one players. With the emergence of fog computing technology, well-

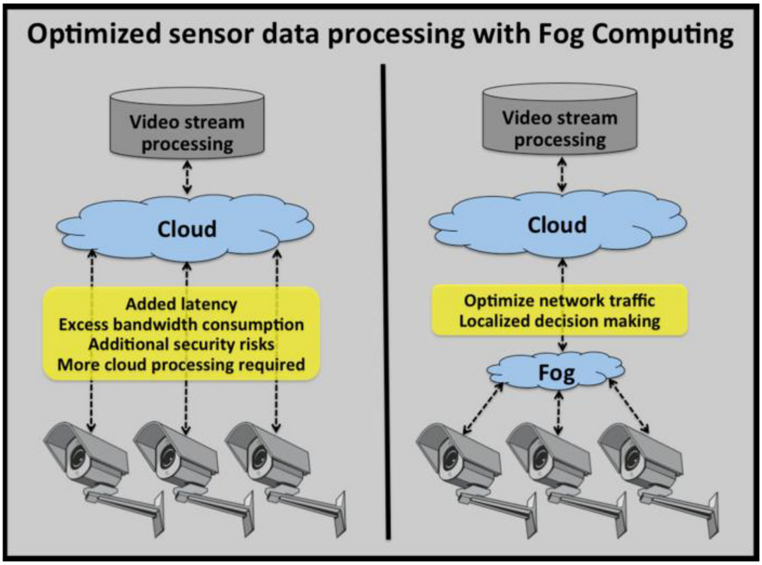


Fig. 23 Video analytics

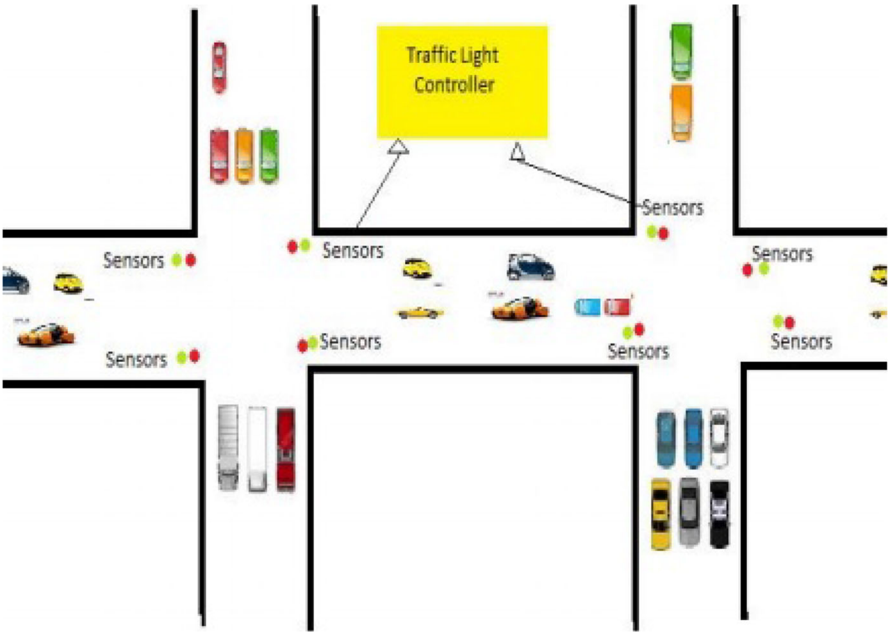


Fig. 24 Smart traffic lights system

organized platform is introduced for online gaming users. With this, essential gaming hardware along with multiple players for playing is made available [12]. This results in rapid growth of online gaming players. Wang and Dey [130] discussed mobile gaming application framework that works with cloud

Table 5 Application of fog computing in various fields [30,89,120,136]

Field	Description
Health maintenance	Real-time monitoring system for patients in critical care units [137–139]
Gas and oil	Parallel monitoring system for leakage, theft, fire etc.
Agriculture	Smart farms with crop monitoring and irrigation control systems
Management of energy	Control of smart grid having privilege to switch between various sources of energy
Travel management	Vehicle health monitoring systems for buses, trucks
Retail management	Shopping cart tracking and automated billing systems
Smart home	Ease and security systems like weather control, fire alarms, intruder detection
Smart traffic lights	Presence of pedestrians and vehicles can be detected using smart street lights

computing. They discussed quality issues with high latency in the application. Zhao et al. [131] targeted Quality of Service (QoS) in fog computing to obtain high gaming Quality of Experience (QoE).

VIII. **Mobile big data analytics** Emerging area in research for big data architecture in mobile and in cloud computing nowadays is the big data processing [132–134]. Fog computing overcomes cloud computing issues by providing various resources for large-scale data processing. Thus, big data processing is handled by integration of fog and cloud technologies. This reduces total computation power in processing big data. This forms the key technique to perform analytics on large generated data in context of IoT [135].

There are various applications of fog computing in different fields as described in Table 5.

10 Challenges in fog computing

In spite of fog computing that brings computing capabilities closer to the user and provides many additional benefits over cloud computing, still fog computing, in its initial face, is facing many challenges. The various challenges in fog computing are [140–142]:

I. *Load balancing* is a concept in fog computing which is very useful to achieve an energy efficient system. The research work proposed by Varghese et al. [143] contains heterogeneous nodes that range from sensors to user devices and to routers, switches and mobile base stations. To perform general purpose computing on these different types of resources, both horizontal scaling and vertical scaling are required. The authors have not considered the vertical scaling. Both the horizontal scaling and vertical scaling can be considered as the resources which might not be under the ownership of same server and might not be so tightly coupled, as the servers in a data center [79,107,144,145].

II. *Deployment strategy* The biggest challenge is the deployment strategy. How the work load is deployed on the fog nodes placed in the fog network? [90,146,147].
III. *Connection policy* Another challenge is how the fog nodes are connected with each other and how to use the available fog nodes for handling the work load [148].
IV. *Resource provisioning* may need to be carefully designed by using the priority model for better scheduling of resources [31,32]. Resource discovery and sharing are critical for performance of applications in fog computing. The resource sharing optimization techniques can be formulated for maximizing the availability of resources and minimizing the energy consumption [8,31,32,149]. VM scheduling needs a new design to provide an optimal solution for scheduling VMs [32,106,150,151].
V. *Heterogeneous environment* Since fog nodes comprise of different devices like mobile phones, sensor, desktop, laptops, thus heterogeneity is the challenge in fog computing, i.e., how different devices communicate each other for handing the tasks? [152–155].
VI. *Energy minimization* Dastjerdi et al. [8] considered fog computing as a network consisting of a large number of fog nodes within which the computation is distributed. This can be less energy efficient as compared to cloud computation model. The improved model can be proposed by taking energy minimization into consideration. Many researchers [145,152,156] have focused on energy minimization in fog computing.
VII. *Tasks offloading* Task offloading is the process of executing the tasks on the fog nodes and on the cloud. This selection of execution depends upon various parameters like tasks that require high computing capabilities which are offloaded to the cloud for execution and tasks that require less computing capabilities which are handled on the fog nodes. Task offloading can also be carried out considering the latency like tasks that are latency-sensitive are executed on fog nodes and non-latency-sensitive tasks that are offloaded to the cloud [157–160].
VIII. *Quality of service (QoS)* Fog computing challenge is to increase the QoS. This includes the link quality, energy aspects, bandwidth issues, traffic constraints on the network parameters that affect the quality of the link. The stronger the quality of the link, the best will be the quality of service [31,32,54].
IX. *Fog node security and privacy* Security is an important challenge. Data follow from the user to the fog network and to the cloud. All computations are carried out at fog nodes and in the fog network; thus, securing the fog network is important. Security and privacy need to be examined at every stage of fog computing paradigm. Malicious user might pose as a device and may access information without authorization leading to security violation [8,15,161]. To mitigate the risk, encrypted data exchanged between the devices and the fog controller can be proposed using Public Key Infrastructure. In addition, monitoring of the data patterns received by the fog controller may be performed to detect the fake devices signatures for taking necessary action to block it off the network access control. Security also comprises secure data computation, secure data storage, access control, network security etc. [122,162–167]. Pri-

vacy comprises of data privacy at end devices, intrusion detection, rogue node detection, etc. [162,166–176].

X. *Software-Defined Network* handles issues due to the reliability of wireless links and mobility of devices in the network and maintains connectivity. Issues like fog controller placement, communication between different controllers like constantly connected controller (at edge infrastructures) or intermittently connected controller (at end devices) and the designing of the distributed SDN system to meet the fog computing requirements can be considered [15,31,62].

XI. The authors of [31,32] proposed Network Function Virtualization technique that can create virtual machine instances on the fog controller to handle functions like gateway, intrusion detection, firewall, etc as per requirement and help in configuration of the network under dynamic conditions. The performance of virtualized network appliances needs to be addressed, which has two aspects: latency or throughput of virtualized network appliances and other is how to achieve efficient placement, instantiation and migration of virtual appliances in a dynamic network [62].

11 Conclusion and future scope

Fog computing brings computing nearer to the user. Fog computing is not a different technology. It works in coordination with the cloud computing. This helps in overcome drawbacks of cloud computing. Fog computing is useful in applications that are latency-sensitive and require computations to be performed near to the user. This technology reduces congestion on the network, hence improving the overall network performance.

This work discusses the fog computing covering the taxonomy of this technology's architecture, which involves with cloud computing, to reduce the computation time. The analysis and comparison of different technologies (like edge computing, fog computing and the cloud computing) are discussed. This work covers the drawbacks of cloud computing that overcomes with fog computing technology.

With the emergence of IoT and widely increasing trend of IoT devices, fog computing technology has become the need of the hour. Fog computing performs computation at the edge of the network, closer to the user. This work covers the key technologies that have originated with fog computing.

This paper discusses various research challenges in fog computing. Being an emerging technology, this technology has challenges in resources distribution, tasks offloading, performance and capacity of the network links, etc.

In future work, these challenges may be worked on and many new advancements in the area of fog computing may be originated. In spite of many opportunities of fog computing for cost reduction, proficiency and business continuity, there are many challenges also that are being faced by industrial data management. SDN and NVF both when used together lead to cost reduction and increased network scalability.

With the emergence of IoT devices, huge load is moving on the network. This leads to arising big data problems. Fog computing technology is the need to refine this load on the network. This technology efficiently regains network performance in terms of bandwidth consumption, data storage, processing of data and data movement.

Fog computing is necessary for the emerging technologies like IoT, 5G, virtual reality. Remote operations and data incentive are also supported by fog computing technology. Fog computing manages the bandwidth, energy, and computing needs. This is also resilient to network disruption and adapts to bandwidth changes. Fog computing enables trusted, rapid and secure transmissions over the network.

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