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A Case Study of Edge Computing Implementations: Multi-Access Edge Computing, Fog Computing and Cloudlet

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With the explosive growth of intelligent and mobile devices, the current centralized cloud computing paradigm is encountering difficult challenges. Since the primary requirements have shifted towards implementing real-time response and supporting context awareness and mobility, there is an urgent need to bring resources and functions of centralized clouds to the edge of networks, which has led to the emergence of the edge computing paradigm. Edge computing increases the responsibilities of network edges by hosting computation and services, therefore enhancing performances and improving quality of experience (QoE). Fog computing, multi-access edge computing (MEC), and cloudlet are three typical and promising implementations of edge computing. Fog computing aims to build a system that enables cloud-to-thing service connectivity and works in concert with clouds, MEC is seen as a key technology of the fifth generation (5G) system, and cloudlet is a micro-data center deployed in close proximity. In terms of deployment scenarios, Fog computing focuses on the Internet of Things (IoT), MEC mainly provides mobile RAN application solutions for 5G systems, and cloudlet offloads computing power at the network edge. In this paper, we present a comprehensive case study on these three edge computing implementations, including their architectures, differences, and their respective application scenario in IoT, 5G wireless systems, and smart edge. We discuss the requirements, benefits, and mechanisms of typical co-deployment cases for each paradigm and identify challenges and future directions in edge computing.

ACM CCS (2012) Classification: Networks → Network services → Cloud computing

General and reference → Document types → Surveys and overviews

Keywords: multi-access edge computing, cloudlet, 5G, fog computing, cloud computing

1. Introduction

Cloud computing has seen extensive application and developed in the last decades. Cloud provides convenient, on-demand services for clients by renting out shared resource pools. These resources (*e.g.*, computation, storage, networks, servers, and services) can be quickly obtained and released with very few operations or vendor interactions. Current implementations of cloud computing mainly work in a centralized form in which processes are sent to the data centers (DCs) where the resources are allocated.

In parallel, the emerging wave of 5G systems and IoT is both astounding and unsustainable using the existing cloud-only architectural approaches. IoT applications impose stringent demands encompassing mobility, response time, and scalability. Most of them require nearly real-time responsiveness and location awareness, as well as security, privacy, and quality of service (QoS). Cisco expects that the amount of IoT-connected devices will grow 2.4-fold, from 6.1 billion in 2018 to 14.7 billion by 2023 [1]. With the explosive growth of heterogeneous devices and data, it will be very difficult for the independent IoT to allocate resources for tasks efficiently [2].

The traditional IoT-cloud paradigm encounters the following challenges: security, storage, and computational performance, reliability, and big data storage. Therefore, there is an urgent need for a computing paradigm that can function as the bridge between IoT and cloud, helping them to communicate with high performance.

Edge computing can be defined as a mesh network that consists of multiple microdata centers (MDCs). These MDCs can store and process vital data locally. Edge computing deploys most of the key equipment responsible for processing resources closer to where the data is produced. The edge means the first hop from the devices, not the devices themselves, for example, gateways or Wi-Fi access points. In comparison with traditional cloud, edge computing aims to reduce latency and improve quality by opening up the edge of the network for applications and migrating cloud resources closer to the end-users (devices). In this context, edge computing has merit in latency, network traffic congestion, energy consumption, reliability, and security. An overview of the existing papers on three edge computing paradigms is presented in Table 1.

This paper presents a comprehensive case study on three typical edge computing paradigms: multi-access edge computing (MEC), fog computing, and cloudlet. Within the context of edge computing implementations, this paper presents three representative and promising co-deployment scenarios, including 5G MEC, co-deployment of fog and IoT, cloudlet used in smart edge, as well as the main requirements, generic architectures, key enablers, application features, and benefits. Finally, the challenges and limitations in the edge computing research field are introduced and future directions are provided.

2. Implementations of Edge Computing

2.1. Multi-access Edge Computing

MEC is an implementation of edge computing. MEC brings resources to the periphery of the network within the radio access network (RAN). MEC nodes are normally co-deployed with macro base stations or radio network controllers and can run various MEC host instances that enable storage and computation on virtualized interfaces such as virtual machines or containers. These hosts are supervised by a hypervisor that processes the information offered by each MEC host as well as the network topology to allocate available resources and manage MEC applications.

2.2. Fog Computing

The fog implementation relies on fog computing nodes (FCNs). Fog can be defined as a decentralized computing infrastructure that can be deployed between edge devices and clouds. The FCNs can be various types of devices including but not limited to switchers, routers, IoT gateways, access points, and set-up boxes due to their heterogeneity. In addition, the FCNs support devices at different protocol layers, and is compatible with non-IP-based access technologies. The isomerism of FCNs is transparent to edge equipment because of a common fog abstraction layer that provides rich functionality such as resource assignment, security, monitoring, and equipment management. The service orchestration layer utilizes the above functions, receives requests from end users, and assigns resources according to these requests.

2.3. Cloudlet

A cloudlet is a cluster of multicore processors that offers resources in real-time to nearby end users and mobile devices based on WLAN networks. Services are offered with high bandwidth within the range of one-hop access, therefore implementing low delay. The implementation architecture of a cloudlet is made up of three layers: the cloudlet layer, the node layer, and the component layer. The component layer provides interfaces to the upper layers. The cloudlet layer consists of a cluster of co-deployed nodes which are operating systems with one or more execution environment(s). A node agent manages the nodes and a cloudlet agent oversees the cloudlet layer.

Table 1. Existing papers on edge computing and their features.

	Papers	Architecture and definition	EC based applications	Performance features	Case study	Contributions
Multi-access edge computing	[40]	✓	✓		✓	A survey on MEC concept, architecture, challenges, and simulation tools
	[41]	✓		✓	✓	Security, dependability, and performance features of 5G MEC
	[42]	✓		✓		A survey on the task offloading strategy for MEC
Fog computing	[13]	✓	✓	✓		A survey on fog design, resource management and assessment of fog systems
	[35]	✓	✓	✓	✓	A taxonomy for architectural, algorithmic and technologies of fog aspects of fog computing
	[36]		✓	✓		Summarized optimization methods and deployments in fog computing
	[37]		✓	✓	✓	An overview of fog applications in smart cities
Cloudlet	[24]	✓	✓	✓	✓	A taxonomy of cloudlet applications
	[44]		✓	✓		A study of cloudlet location algorithm
	[45]		✓	✓		Application and research proposals for cloudlets
	[46]	✓		✓		A survey on existing cloudlet scheduling algorithms
Comprehensive surveys	[16]	✓	✓	✓		An investigation of different fog and edge computing scenarios, and simulation challenges
	[25]	✓	✓		✓	An outline of benefits of MEC, fog, and cloudlets, and future directions for adopting these in industry
	[29]	✓	✓		✓	A study of definition, fundamental properties, use cases and future directions of MEC, fog, and cloudlets
	[38]	✓	✓	✓		A discussion on the computing paradigms and the latest innovations in edge computing
	[39]	✓		✓	✓	A study of architecture, limitations, and solutions of edge computing for IoT
	[43]	✓		✓		A tutorial on three edge computing paradigms

3. Multi-access Edge Computing & 5G System

In the 5G era, people utilize different types of devices to connect to the Internet, such as smartphones, tablet PCs, mobile vehicles, and wireless sensors. Diversification of application scenarios such as MBB (mobile broadband), internet of vehicles, and mission-critical communication networks as well as the widespread use of technologies like augmented reality (AR), and virtual reality (VR) [3] have prompted mobile networks to reach a higher standard with regard to flexibility, ultra-low delay, reliability, versatility, and high-bandwidth, in order to prevent mobile data traffic overload.

The conception of MEC, as defined by the European Telecommunications Standards Institute (ETSI), is a promising technology derived from mobile edge computing that distributes cloud capabilities and IT application environments to the periphery of mobile networks. In MEC, computation and storage resources are in close vicinity to both the end-users and application-generated data, within the radio access network (RAN) in 4G and 5G. ETSI has also established an Industry Specification Group (ISG) to publish industry specifications for MEC [4]. MEC enables RAN operators to expand edge computing functionality to existing cellular base stations and permit cloud-based gaming or low-delay video streaming. Since the RAN edge can provide context-related service environments with ultra-low latency, high capacity, and direct access to local resources and devices [5], MEC, as a 5G application functions, is recognized as one of the key technologies and architectural concepts to meet the demanding key performance indicators (KPIs) during the transition from pre-smartphone era to 5G wireless system era.

3.1. The Architecture of the MEC System

MEC offers a highly distributed standards-based environment closely integrated with mobile subscribers. The MEC system encompasses management and orchestration (MEC-MANO) entities together with functional entities. Applications can run in virtual machines or in virtual containers through a virtualization layer, following the infrastructure-as-a-service (IaaS) model. MEC is acknowledged by the European 5G PPP (5G Infrastructure Public Private Partnership) as one of the key emerging technologies for 5G networks, together with software-defined networking (SDN) and network function virtualization (NFV). NFV can decouple the network functions from the actual hardware and let the services run in a virtualized computing environment. Since NFV and MEC share a similar design philosophy of running applications on a virtualization platform, there is a chance for MEC and NFV to use the same MANO and NFV Infrastructure (NFVI). SDN allows rapid deployment of innovative services, enables network programmability, and supports multi-tenant applications. SDN and NFV are proposed as solutions for implementing MEC architectures.

According to ESTI GS MEC, the MEC servers allow deployments in different scenarios. For instance, at a 3G radio network controller (RNC) site, a multi-technology (3G/LTE) cell aggregation site, or an LTE macro base-station (eNB) site.

As shown in Figure 1, the MEC IT application server is the critical component of the MEC system and is integrated with the RAN elements. These servers can provide on-premises computation, storage resources, connectivity as well as traffic offload function (TOF), radio network information services (RNIS), and real-time communication services. The server platform comprises two main parts: an application platform and a hosting infrastructure. The hosting infrastructure includes physical hardware resources and a MEC virtualization layer on top of it. It is responsible for connecting with the radio network elements (eNB or RNC), based on different deployment scenarios. Above the MEC hosting infrastructure is the MEC application platform where applications run as virtual machines or containers. The MEC application platform is responsible for managing application virtualization and other services which are described as follows.

Middleware services:

- RNIS
- Infrastructure services
  - Service registry
  - Communication services
- TOF.

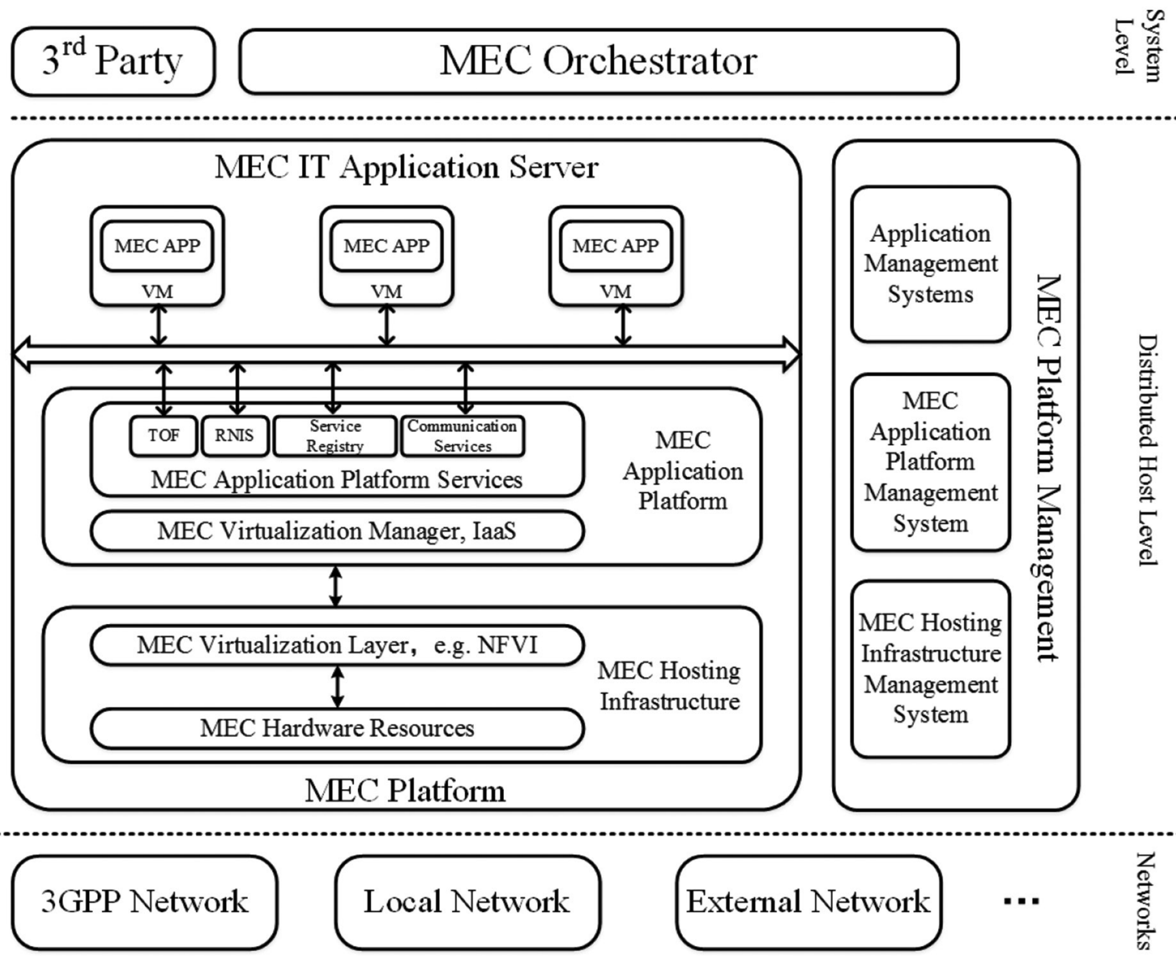

Figure 1. Illustrates the implementation architecture of MEC.

Management services:

- Application platform configuration
- Life cycle management
- VM operation and management (O&M).

3.2. 5G System Architecture

The 3rd Generation Partnership Project (3GPP) has established the 5G system architecture. A notable departure from the current point-to-point communication mode is that 5G systems allow vital network functions to communicate in service-based architecture (SBA), while the traditional reference points and interface approaches remain as available options.

As shown in Figure 2, the network resource function (NRF) is responsible for registering network functions/services and managing the list of available services, such as the service registry functions in the MEC system. If a service is registered, other network functions are able to interact directly with the network function running that service. The Network Exposure Function (NEF) is responsible for service exposure and access request authorization from external systems. The Authentication Server Function (AUSF) provides services for authentication-related programs. The Network Slice Selection Function (NSSF) provides assistance in selecting suitable resources and features for users, while the Access Management Function (AMF) allocates these required slice instances to users and devices. The Policy Control Function (PCF) manages the policies and rules in the 5G system. Tenants can access PCF either directly or via the NEF, up to the authentication of the Application Function (AF). The Unified Data Management (UDM) handles services related to subscriptions and users, for instance, managing user identification information, handling access authorization, and serving Session Management Function (SMF). The User Plane Function (UPF) plays a critical role in the case of deploying MEC in 5G networks. For MEC systems, UPF is similar to a distributed data plane that is configurable and can be controlled in the NEF-PCF-SMF route. N1, N2, N3, N4, N6, and N9 are signaling reference points between different network functions, the specific descriptions are as follows.

- N1: Reference point between User Equipment (UE) and AMF.
- N2: Reference point between (R)AN and AMF.
- N3: Reference point between (R)AN and UPF.
- N4: Reference point between SMF and UPF.
- N6: Reference point between UPF and a Data Network(DN).
- N9: Reference point between UPFs.

3.3. Deployment of MEC in 5G System

Figure 3 shows the co-deployment of MEC system and 5G system.

On the MEC system level, the MEC orchestrator interacts with the NEF, and occasionally interfaces directly with the target 5G functions. The MEC platform interacts with 5G functions on the MEC host level, acting as an AF. MEC hosts are always deployed in 5G networks. Besides, NEF is a core system-level entity. Instances of NEF are also allowed to be deployed at the edge, thus securing rapid, low-latency, and high-throughput service access from MEC hosts. User mobility management is another core function of the 5G system. AMF manages mobility-related processes, extending its responsibility to encompass the control plane of the Radio Access Network, along with and Non-Access Stratum (NAS) procedures. In SBA, the Mobility Management Function offers interaction and reachability services for other network functions as well as enables subscriptions to receive mobility event notifications. SMF can select and control UPFs as well as set traffic steering rules, while MEC services can be provided at both the center and edge of clouds. SMF enables MEC to manage the PDU sessions, configure policies and traffic rules, and accept session management event notifications by exposing service operations.

3.4. MEC as Enablers in 3GPP

The 5G system specifications proposed a series of new functions on duty for edge computing enablers. These edge computing enablers can be summarized as follows:

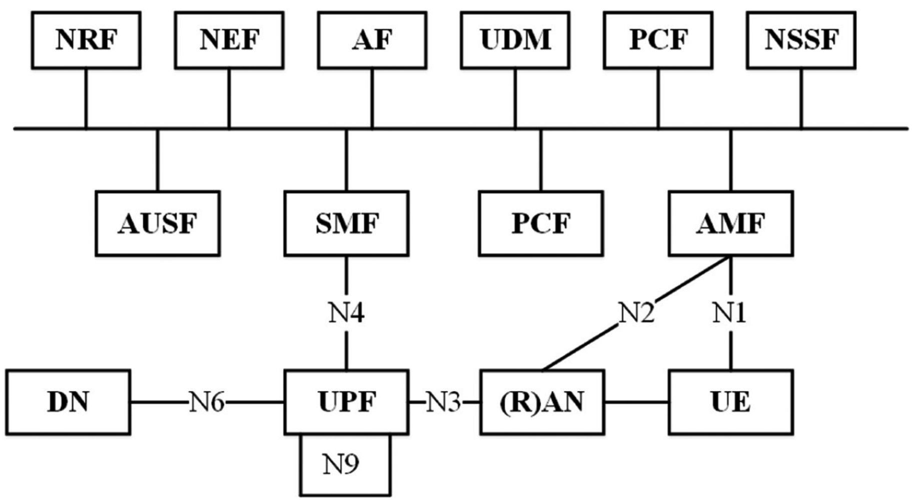

Figure 2. 5G Service Based Architecture.

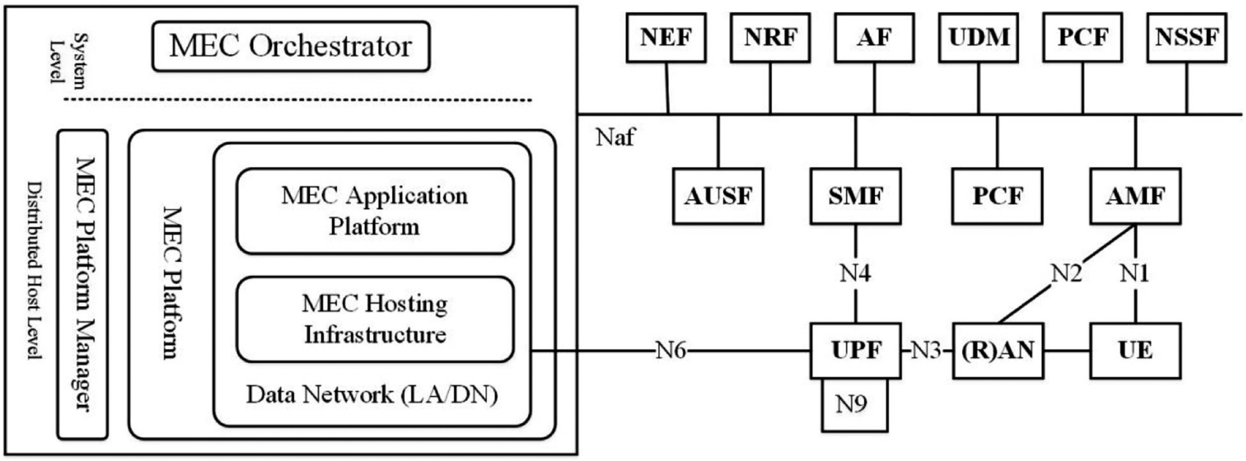

Figure 3. Deployment of MEC in 5G network.

- Routing and traffic steering for local devices: 5G networks can select the routing of edge applications' traffic. The UPFs determine the N6 reference points of a PDU session and support PDU session anchor functionality. Uplink classifiers support the implementation of the traffic steering functionality of UPFs.
- Application function of the User Plane Function selection and data routing selection: Two distinct approaches exist for realizing this function: one involves the direct influence over traffic routing by the PCFs, and the other involves an indirect influence facilitated by the NEFs.
- The Session and Service Continuity (SSC) in various UEs and application mobility scenarios.
- Local Area Data Network (LADN): a series of tracking areas, defined by the public land mobile network of the UEs.

4. Fog Computing & IoT

Fog computing is characterized by its distinct features, including its proximity to end-users, ability to ensure location awareness and ultra-low response time, extensive geographical distribution, mobility support, a significant number of nodes, heterogeneous composition, and the support for numerous protocols.

The architecture of fog implementation comprises both a data plane and a control plane, spanning across the physical, protocol, and application layers. To illustrate, here are several instances of each plane:

- Instances of fog data plane:
  - Client resources pool
  - User-to-user direct communications (*e.g.*, AirDrop, WiFi Direct, LTE Direct)
  - Cloudlets and micro DCs
  - Edge content caching services
  - Home bandwidth management.
- Instances of fog control plane:
  - Over the top (OTT) content management
  - Edge analytics and real-time stream mining
  - User-based HetNets control
  - Fog-RAN
  - User-controlled cloud storage.

4.1. IoT, from Cloud Computing to Fog Computing

The original cloud computing model is not designed for the volume, variety, veracity, and velocity (*i.e.*, big data dimensions) of data generated by IoT. The characteristics of fog computing and cloud computing is shown in Table 3 and Table 4.

Table 2. Existing papers on co-deployment of MEC and 5G.

Papers	Architectures	Challenges	Solutions	Enablers for 5G	Contributions
[6]	✓	Security, isolation	✓	MEC, Networking Slicing	A scheme for integration of MEC and Networking Slicing for 5G
[7]	✓	Multimedia Broadcast Multicast Services (eMBMS)	✓	MEC, Network Function Virtualization	A service-less multicast video delivery network architecture
[8]		Security, privacy, and trust	✓	Network Functions Virtualization (NFV), Cloud Computing, Software Defined Networking(SDN), Information Centric Network (ICN), MEC, Network Slicing	A survey on novel scientific contributions, demonstration results, and standardization efforts in 5G network security, privacy, and trust.
[9]	✓	Ultra-low-latency (ULL) services	✓	MEC, time-sensitive networking (TSN)	A 5G system model based on 3GPP to support MEC to provide ULL services
[10]	✓	QoE degradations	✓	MEC, Content Delivery Network (CDN)	A MEC system proposal for 5G network to enforce the QoE
[11]	✓	Mobility management	✓	Network Function Virtualization (NFV), MEC, Software defined Networking (SDN)	A survey on mobility management evolutionary steps in signaling
[12]	✓			Millimeter wave (mmWave), MEC, beamforming, massive multiple-input and multiple-output (Massive-MIMO), small cell	A survey on enhancements made towards 5G system
[47]	✓	Security	✓	MEC, blockchain	A survey on 5G and MEC approaches that benefits the drone-enabled environments
[48]		Minimum end-to-end latency, advanced context-awareness	✓	MEC, Network Function Virtualization (NFV)	A proposal of a hybrid architecture and a V2X service algorithm for 5G systems

Table 3. Comparison of cloud computing and fog computing characteristics.

	Cloud Computing	**Fog Computing**
Distribution	Centralized	Distributed
Size	Large	Relatively small
Latency	High	Low
Bandwidth	High	Relatively low after filter
Delay-Jitter	High	Very low
Service location	On the Internet	Local network edge
Power consumption	High	Low
Distance between client and server	Multiple hops	One hop
Security	Undefined	Can be defined
Enroute data attack	High possibility	Very low possibility
Location awareness	No	Yes
Physical distribution	Centralized	Distributed
Number of nodes	Few	Huge
Mobility	Limited	Supported
Real-time communications	Supported	Supported
Last-mile connectivity type	Leased line	Wireless
Internet connectivity	Must be connected	Can operate with no Internet
Hardware connectivity	WAN	WAN, LAN, Wi-Fi, cellular
Service access	Through core	Through edge devices
Main standardization	CSA, DMFT, NIST,OCC	OpenFog Consortium, IEEE

Table 4. Comparison of operating mechanism of cloud computing and fog computing.

Cloud Computing	**Fog Computing**
Data and applications are hosted in clouds: Due to the large scale of data, the tasks are time-consuming	Runs on local network edge: Quicker processing
Send data through cloud channels: Leads to bandwidth issues	Aggregates data at particular access points: Alleviates bandwidth requirements
Servers are deployed at a remote place: Causes latency and scalability issues	Sets servers close to client sides: Avoids latency and scalability issues

According to a recent Gartner study, by 2023, up to 75% of enterprise data will be gathered and managed by systems outside the corporate IT infrastructure and data centers. In the case of IoT deployments, IoT accelerates awareness and response to events, and the use of fog can guarantee some major features, including implementing ultra-low latency, optimizing network bandwidth usage, addressing security concerns, ensuring robust operational performance, accommodating a range of diverse and complex scenarios, making appropriate data routing decisions, and facilitating artificial intelligence (AI) computations [50].

4.2. Cloud Computing, Fog Computing, and IoT: Benefits of Co-deployment

Fog applications can monitor and analyze real-time data produced by devices connected to the networks, and then initiate a corresponding action in a machine-to-machine (M2M) manner or a human-machine (HMI) manner. Any devices with processing, storage, or network connectivity, such as industrial controllers, routers, and embedded servers, can work as fog nodes. Data generated by IoT devices is ingested by the fog nodes closest to network edges, and then the fog applications select an optimal route for these different types of data. A comparison of features of fog nodes with cloud are shown in Table 5.

The co-deployment architecture involving cloud computing, fog computing, and IoT is shown in Figure 4. The roles and responsibilities of component is described as follows:

Fog nodes:

- Collect data from IoT devices via multiple protocols including IP, BLE and Zigbee for ultra-low latency.
- Provide real-time management and analytics.
- Offer short-term storage, usually 1-2 hours.
- Periodically post data statistics to clouds.

Clouds:

- Collect data statistics from numerous fog nodes.
- Analyze IoT data to provide business insights.
- Send corresponding application policies back to fog nodes based on the above insights.

IoT edge-level sensors and devices:

- Offer direct connection to the cloud.
- Form clusters or aggregations near routers or gateways to offer staging areas and fog processing abilities [56].
- Manage security and authentication between sensors and the WAN.

Table 5. Comparison of features of fog nodes with cloud.

	Fog nodes closest to IoT devices	**Fog aggregation nodes**	**Cloud**
Types of data	Time-sensitive	Seconds or minutes	Less time-sensitive
Latency	Milliseconds to sub-seconds	Seconds to minutes	Minutes, days, or weeks
Application examples	M2M communication Haptics	Visualization, simple analytics	Big data analytics
How long IoT data is stored	Transient	Short duration	Months or years
Physical distribution	Very local	Wider	Global

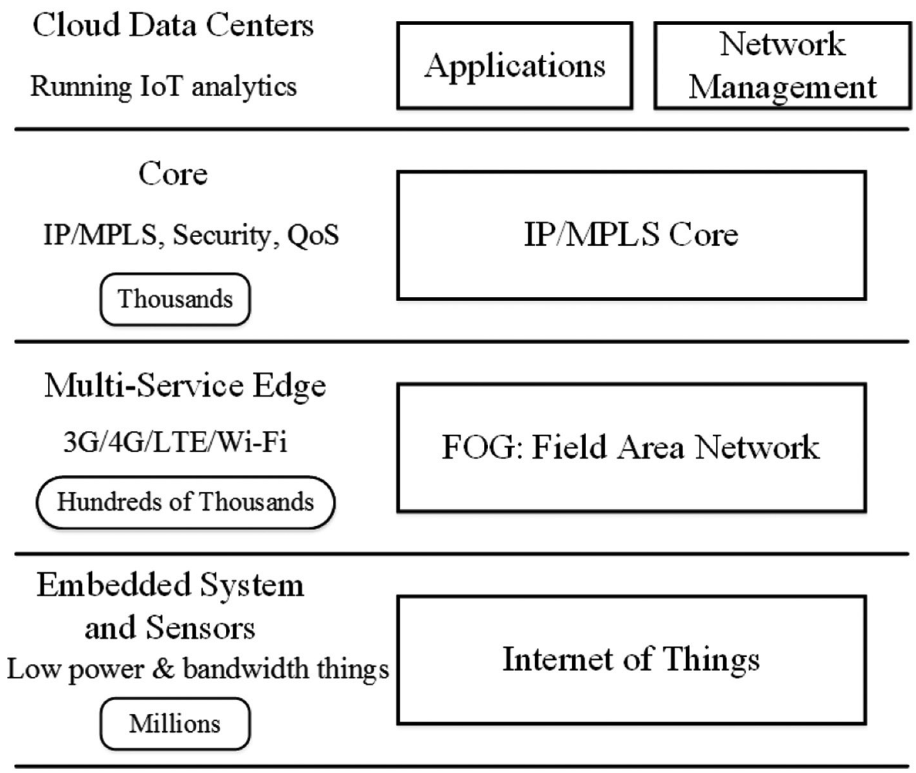

Figure 4. Fog architecture and IoT.

Fog nodes offer localization capabilities, enabling the realization of low latency and contextual awareness. The benefits stemming from the co-deployment of fog and IoT can be encapsulated as follows:

- Cognition: Fog can select the optimal routes for IoT data to required resources and functionalities along the cloud-to-thing path.
- Efficiency: Resources and functions are deployed anywhere between the cloud and the IoT endpoints. Tight integration of applications, IoT devices, and network edge capacities enhances overall system efficiency, which is crucial for cyber-physical systems [49].
- Flexibility: The co-deployment allows the same application to run anywhere and allows services from different providers to be processed on the identical physical platform. Also, it provides rapid innovation and affordable scaling, as well as a mutual lifecycle management infrastructure.
- Latency: The co-deployment implements real-time processing and big data analytics.

4.3. The Role of Fog Computing in IoT

Fog supports more functionalities and exposes more powerful capacities than mobile ad-hoc networks (MANET) and peer-to-peer (P2P) networks. The role that fog plays in co-deployment and the core attributes of fog computing in different scenarios of IoT are presented in this section.

4.3.1. Internet of Vehicles

The Internet of Vehicles (IoV) deployment involves a large number of interactions and connectivity setups among vehicles via vehicle-to-vehicle communications (V2V) or among vehicles and roadside infrastructures via vehicle-to-infrastructure communications (V2I). Fog plays a crucial part in different types of scenarios such as vehicles-to-vehicles, vehicles-to-access points (Wi-Fi, 3G, smart traffic lights), and access points-to-access points.

Table 6. The role of each layer of fog architecture.

	Function	The role of distributed control	Instances
Cloud DCs	In-depth data mining	Cloud-based control (slowest)	Healthcare, security, surveillance, environmental studies
Core	Analyze/act on the fly	Core-based control	Contact center, user experience, intrusion detection, network performance, sensor monitoring, fraud detection, environmental monitoring
Fog	Store	Fog-base control	Network management logs, traffic information, environmental data, smart cities, security logs
IoT	Ingest	Edge-point control (fastest)	Smart grid, network data, sensor networks, SCV&Transportation, smart cities

In smart traffic light systems, fog nodes interact locally with a series of sensors that monitor and capture road information. Meanwhile, they connect with adjacent nodes to adjust the green wave. Accordingly, smart lights can give warnings to vehicles and sometimes even be self-modified to prevent accidents [55].

A variety of fog attributes support the implementation of IoV deployments, such as geo-distribution (covering cities and roads), low delay, real-time interactions, location awareness, heterogeneity, and mobility.

4.3.2. Wireless Sensor and Actuator Networks (WSAN)

The wireless sensor nodes (WSNs) exhibit characteristics such as low bandwidth, limited computational capacity, and modest memory capacity, all while operating on minimal power consumption to preserve battery life. Actuator nodes can interact with each other via wireless links to enable real-time independent decision-making. WSANs consist of network sensors and actuator nodes. Due to the lack of uniform standardization for communication protocols, it is difficult to interconnect the WSANs and the Internet. Besides, data from WSANs cannot be transferred over long distances due to limitations in WSAN transmission protocols and sensing technologies. The attributes of fog computing that facilitate the implementation of WSAN deployments encompass geo-distribution, location awareness, proximity, and heterogeneity [54].

4.3.3. Smart Grid

Smart grids influence the entire value chain from electricity generation to transmission and distribution. In smart grid deployment scenarios, fog nodes host third-party security, and safety applications and collect vast amounts of IoT data. Fog is also capable uncovering meaningful insights within data prior to transferring it to the centralized servers. Precisely, the lowest layer is responsible for machine-to-machine (M2M) interaction, ingesting and processing data from grid sensors and devices, filtering parts of the data for local processing, and sending the rest to the higher layers. The second and the third layer oversee tasks related to visualization, HMI, and M2M interactions. Fog facilitates diverse storage options, ranging from transient storage for the lowest layer to semi-permanent storage for the highest layer, aligning with the varying duration of different kinds of interactions. The higher the layer, the longer the duration.

Fog has no software-defined, information-centric, or virtualization limitations. It contains both wireline and mobile networks, providing resources and services to applications anywhere along the cloud-to-thing continuum.

Table 7. Existing surveys on fog and IoT co-deployment.

Papers	Focus	Contributions
[14]	Soft simulator	Fog and IoT models and software quality of simulator
[15]	Fog employment in IoT	Fog characteristics for IoT
[17]	IoT security	How fog can be leveraged to improve the IoT security
[18]	Challenges, contributions, and technologies in fog/IoT paradigm	Integration of fog onto IoT
[19]	Real-time analytics	How fog platforms analyze data generated by IoT devices
[20]	Trust solutions	Fog-based trust solutions for IoT
[21]	Load balance	Fog architectures with load balancing technologies
[22]	Computation migration, service deployment	Optimization algorithms in fog-based IoT
[23]	Computation offloading, application deployment, resource allocation, load balancing	Resource management solutions in fog environment

5. Cloudlet & Smart Edge

5.1. Major Features of Cloudlet

The term "cloudlets" originated in the mobile edge computing industry, initially introduced by ETSI. A cloudlet is an entity designed to support resources-intensive scenarios within Client/Server (C/S) type services. By offloading computation from mobile devices to VM-based cloudlets situated at the edge of networks, this concept embodies the notion of a "data center in a box", aiming to bring cloud capabilities closer. This approach benefits from both MEC and mobile cloud computing (MCC), yet is not necessarily tied to radio communication or carrier infrastructure. There are four key characteristics of cloudlets:

- Soft state emphasis: Unlike clouds, cloudlets do not have any hard state which means there is no need for post-installation management. Cloudlets are inherently self-managing.
- Abundant resources, strong connectivity, and security: Compared to fog, cloudlets possess more powerful computing and storage capacities and have great connectivity to clouds (usually a wireless network connection).
- Proximity: Cloudlets are located in close logical proximity to mobile devices, usually within a single-hop range.
- Standard cloud technology foundation: Cloudlets resemble conventional cloud infrastructure, mirroring well-known cloud infrastructures such as Amazon EC2 and OpenStack.

5.2. Enabling Smart Edge through Cloudlets

The term "smart edge" was initially proposed to capture an emerging trend in IoT. Smart edge implies that sensors and devices should be deployed in environments that are capable of making smart, self-aware, and adaptive decisions. Collecting data from local sensors and devices is the key element of smart edge operation, and real-time network information can be used to offer context-awareness services for mobile customers. Smart edge tends to be compatible with different integrations and processing platforms [51]. Hub-and-spoke models enable devices to interact with a strategically deployed center node, while mesh networks are built on a decentralized architecture where all devices are peers. The challenges of smart edge and cloudlet co-deployments are presented in Table 8.

There are two major types of cloudlets. One is the transient cloudlet based on a standard hub-and-spoke model, which is built on a resource-rich computer infrastructure that offers resources and services to mobile devices over wireless networks, principally cellular and WLAN. The other type is the mobile cloudlet, where clusters of resourceful mobile devices (cloudlet nodes) can interact with each other over mesh networks. The mobile cloudlets count on peer-to-peer mesh communication. Mobile devices can connect over secured Wi-Fi or Bluetooth and share computation as mesh network nodes. Deploying small-scale cloudlets close to radio base stations is useful for service-specific use scenarios and can implement scalable and low-power computing support for smart edge [52].

Table 8. Challenges of smart edge and cloudlets co-deployment.

Papers	Use cases	Challenges	Cloudlet relevant factors	Methods and technologies
[26]	Smart transportation	Privacy, security	Authenticity	Security credential management system (SCMS) Cloudlets support attributes-based smart transportation model
[34]		Resource limitations	Control	Deployment Security Mediation Actuation
[27]	Smart city	Data management	Distribution	Distributed-to-centralized smart technology management
[33]		High bandwidth	Computation	VM IaaS, PaaS, SaaS Processing on demand Context as a service
[28]	Smart health	Data store	Real-time data access	NoSQL based model
[29]		DIL connectivity	Storage	Caching
[31]	Smart oil refineries	Low latency	Acceleration	NFV SDN GPU
[32]	Smart energy	Reliability	Networking	Bluetooth IP, TCP, UDP WAN

5.3. The Customization of Cloudlet

Cloudlets provide resources through virtual machines (VMs) on top of physical machines (PMs). Pre-use customization and post-use clearance are two major procedures that guarantee the cloudlets are restored to their original state after each use, free from manual operations. VMs can work in a middle layer between the transient user software and the cloudlet infrastructure's permanent host software. There are two possible solutions to transfer the VM state of mobile devices to cloudlet infrastructures which are less brittle than software virtualization and process migration.

5.3.1. VM Migration

To migrate a running VM, it has to be temporarily suspended. During this suspension, its processor, disk, and memory state are encapsulated for transfer. Once the migration is completed, the VM continues to execute from the point of suspension.

5.3.2. Dynamic VM Synthesis

Generally, the base VM customization varies little across various applications. A VM overlay represents a minor modification differentiating the base VM from a specific custom VM configuration. The process of transitioning VM overlays to cloudlets is referred to as VM synthesis.

As illustrated in Figure 5 and Figure 6, cloudlets serve as miniature data centers distributed geographically. To effectively utilize these resources, mobile devices must discover, request, and link to a suitable cloudlet. Instead of migrating an entire operational VM, mobile devices only need to transfer a small VM overlay to the cloudlet which already has the overlay's base VM. The cloudlet then applies the overlay to its corresponding base VM to create the so-called "launch VM." This launch VM can begin execution from a suspended state. As a result, mobile devices can run offload operations within cloudlets, adopting a streamlined thin-client approach.

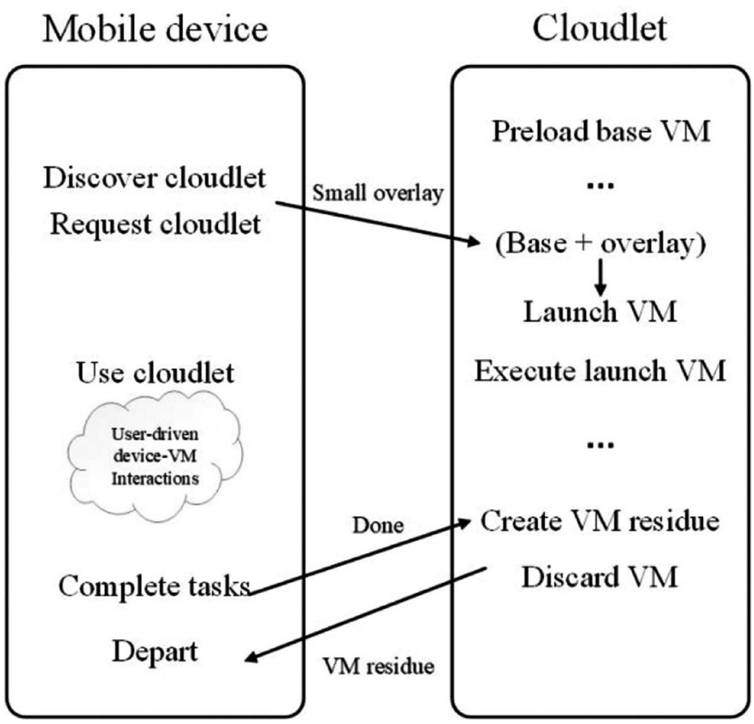

Figure 5. Timeline of VM-based cloudlets.

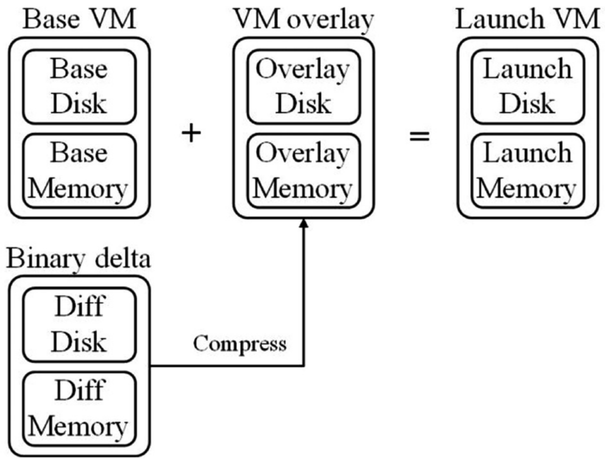

Figure 6. Process of creating a VM overlay.

Upon completing the offload operations, the VM instance is discarded; however, a residual VM state is retained for future offload operations. This VM residue is eventually relayed back to the mobile device, where it is merged into the existing overlay configuration. This dynamic VM synthesis and VM handoff enable seamless migration of offloaded services for users from the current cloudlet to the next cloudlet with low end-to-end delay and data placement.

6. Challenges and Future Directions

Table 9 shows a comparison of edge computing implementations. The requirements and benefits of each co-deployment case are presented in Table 10. The major challenges of the research in the area of edge computing together with future directions and possible related categories are presented as follows:

- Edge computing system service-level agreement (SLA): Current SLAs are designed for cloud and network infrastructures. Designing new SLA and SLA management techniques is one of the considered research directions in edge computing, concerning objectives such as QoS and cost.
- Bandwidth-saving edge computing system: One of the key characteristics of edge computing is offloading data traffic from the core. So far, only a few studies have focused on bandwidth-aware edge computing system design and how to measure the actual bandwidth usage. Scheduling, load balancing, and resource analysis may be key solutions for this challenge.
- Green edge computing: A limited number of works consider the overall energy efficiency of edge computing systems. Promising future directions of exploration could be the ways to reduce energy consumption during computation offloading, mobility management, and even co-deployment of IoT and fog.
- Edge computing node site selection: Few works focus on how to choose suitable locations for node deployments. To solve this problem, communication, storage, computation, and cost should be taken into consideration.
- Security: Site attacks are more likely to take place in edge computing nodes than cloud DCs. Future works can consider how to guarantee the security of nodes against physical damage, disturbance, *etc.*, or how to design powerful access control protocols for edge computing nodes to implement isolation/sandboxing [53].
- Network slicing: Network slicing entails partitioning the network into customized instances, each optimized for a specific demand or application. While the prevalent network-slicing designs are mostly business-driven, end-to-end network slicing creation in the context of edge computing requires also an understanding of the impact of radio transmission and the characteristics of edge computing. An integration of NFV, SDN, and edge computing is crucial in this future direction.
- End-to-end tradeoffs of architectures: Designing better end-to-end systems to implement greater tradeoffs among global centralized and local distributed architectures can also be a future direction. Establishing logical edge computing system topologies statically or dynamically based on the common physical network can provide solutions for a spectrum of architectures ranging from fully centralized to fully distributed.

Table 9. Comparison of edge computing implementations.

	MEC	**Fog**	**Cloudlet**
Node devices	Servers running in the base station	Routers, access points, gateways, switches	Datacenter in a box
Node location	Radio network controller/micro base station	Between end devices and cloud	Local/outdoor installation
Software architecture	Mobile orchestrator based	Fog abstraction layer based	Cloudlet agent based
Computing platform distribution	Distributed	Distributed	Distributed
Proximity	One hop	One or multiple hops	One hop
Context-awareness	High	Medium	Low
Lifecycle management providing	Via mobile orchestrator	Via fog service orchestration layer	Partly specified
Access	Mobile networks	Bluetooth, Wi-Fi, mobile networks	Wireless networks
IaaS platform	Virtualized	Virtualized	Virtualized
Multi-vendor environment	Allowed	Allowed	Allowed
Internode interaction	Partial	Supported	Partial
Efficient communication needs between edge nodes	Not stressed	Stressed	Not stressed
Support for N-tier hierarchy	N=2 (devices + one edge location) or 3 (devices + one edge location + main cloud)	N=3 or more (distributed fog infrastructure)	N=3 typically
Platform services	ETSI	OpenFog Consortium	OpenStack
Business driver	5G system, telecom use cases	Internet of Things, Wireless Sensor, and Actuator Networks (WSAN)	Some local business, Cognitive Assistance applications requirements. *E.g.*: Gabriel architecture

Table 10. Requirements and benefits of co-deployment cases.

	MEC&5G	**Fog&IoT**	**Cloudlet&Smart Edge**
Requirements	Mobility support Deployment independence Simple and controllable APIs Smart application location Application mobility	Latency minimization Bandwidth conservation Addressing data security concerns Reliable operation Site selection	Real-time situation awareness Heterogeneity support Cloudlet-VM synthesis Dynamic cloudlet provision
Benefits	Reduced latency Greater reliability and security Scalability and savings	Greater business agility Better security Deeper insights Lower operating expense	Data traffic filtering Rapid response Protection of backbone networks

7. Conclusion

Fog computing aims to build a system that enables cloud-to-thing service connectivity and works in concert with the cloud. Concurrently, Mobile Edge Computing (MEC) is seen as a key technology of the 5G system, while a cloudlet is a micro-data center deployed in close proximity.

In terms of deployment scenarios, fog computing focuses on IoT, whereas MEC mainly provides innovative mobile RAN application solutions for 5G systems. Cloudlets, on the other hand, offload computing power at the network edge. While each concept serves distinct purposes, the underlying goal of fog computing, MEC, and cloudlet is to provide application-centric environments that streamline automated application deployment, management, and business provisioning.

In the current landscape, most of the foundational hardware infrastructure and software technologies for edge computing have matured considerably. However, most of the co-deployment solutions rely heavily on accurate modeling and prediction of service response times, network fluctuations, request arrival patterns, *etc.*, making it difficult to achieve efficient scheduling decisions in real-world scenarios. Consequently, there is an urgent need for adapting or optimizing hardware and software according to the needs of edge computing. This encompasses a spectrum of areas, including the computing capacity of edge nodes, performance optimization, reliability, and disaster recovery of edge nodes. Furthermore, there is a need for intelligent scheduling of edge computing tasks, the unified management of heterogeneous edge nodes, the data distribution mechanism, and consistency. Finally, the edge computing network architecture, large-scale edge applications and services, and edge functions and technologies (*e.g.*, data granularity, video compression, and analytics), *etc.*, are areas yet to be further researched.

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