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Introduction to Fog and Cloud Computing

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All one needs to know about fog computing and related edge computing paradigms: A complete survey.
Ashkan Yousefpour, Caleb Fung, Tam Nguyen, Krishna Kadiyala, Fatemeh Jalali, Amirreza Niakanlahiji, Jian Kong, Jason P. Jue.
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Contents

- Introduction
- A comparison of fog computing and related computing paradigms
- Taxonomy of fog computing
- Challenges and future directions

Section III: A Comparison of Fog Computing and Related Computing Paradigms

- Cloud Computing
- Fog Computing
- Mobile Computing
- Mobile Cloud Computing
- Mobile ad hoc Cloud Computing
- Edge Computing
- Multi-access Edge Computing
- Cloudlet Computing
- Mist Computing
- Other Similar Computing Paradigms
- Concluding Remarks

Section IV: Taxonomy of Fog Computing Through a Complete Survey

- Foundations
- Frameworks and Programming Models
- Design and Planning
- Resource Management and Provisioning
- Operation
- Software and Tools
- Testbeds and Experiments
- Hardware and Protocol Stack
- Security and Privacy

Section V: Challenges and Future Research Directions

Video on Fog Computing

https://www.youtube.com/watch?v=tuo5Pxc4w3c

Introduction (1/3)

- In today's information technology age, **data** is the main commodity
- Possessing **more data** typically generates **more value** in data-driven businesses
- According to the International Data Corporation (IDC):
  - the amount of digital data generated surpassed **1 zettabyte in 2010**
- **2.5 exabytes of new data** is generated each day since 2012
- Cisco estimates that there were around 50 billion connected devices by 2020
- All these connected devices constitute the **Internet of Things (IoT)** and possibly generate a **massive amount of data**
- With this astronomical amount of data, current mobile network architectures will have trouble **managing the momentum and magnitude of data**

Byte-størrelser				
SI-prefikser			binærprefikser (IEC 60027-2)	
Navn (Symbol)	Vanlig bruk	Standard SI	Navn (Symbol)	Verdi
kilobyte (kB)	2^{10}	10^{3}	kibibyte (KiB)	2^{10}
megabyte (MB)	2^{20}	10^{6}	mebibyte (MiB)	2^{20}
gigabyte (GB)	2^{30}	10^{9}	gibibyte (GiB)	2^{30}
terabyte (TB)	2^{40}	10^{12}	tebibyte (TiB)	2^{40}
petabyte (PB)	2^{50}	10^{15}	pebibyte (PiB)	2^{50}
exabyte (EB)	2^{60}	10^{18}	exbibyte (EiB)	2^{60}
zettabyte (ZB)	2^{70}	10^{21}	zebibyte (ZiB)	2^{70}
yottabyte (YB)	2^{80}	10^{24}	yobibyte (YiB)	2^{80}

Introduction (2/3)

- In current implementations of cloud-based applications:
  - most data needs **storage**, **analysis**, and **decision making**
  - such data is sent to the data centers in the **cloud**
- As the data velocity and volume increases:
  - **moving** the big data from IoT devices to the cloud **might not be efficient**, or might be even infeasible in some cases due to **bandwidth** constraints
- On the other hand, as time-sensitive and location-aware applications emerge (such as patient monitoring, real-time manufacturing, self-driving cars, etc.):
  - the distant cloud will not be able to satisfy the ultra-low **latency** requirements of these applications, provide location-aware services, or scale to the magnitude of the data that these applications produce
- Moreover, in some applications:
  - sending the data to the cloud may not be a feasible solution due to **privacy** concerns

Introduction (3/3)

- To address the issues of **high-bandwidth**, **geographically dispersed**, **ultra-low latency**, and **privacy-sensitive** applications, there is a quintessential need for a computing paradigm that takes place closer to connected devices
- **Fog computing** has been proposed by both industry and academia to address the above issues and to quench the need for computing paradigm closer to connected devices:
  - it bridges the **gap between the cloud and IoT devices** by enabling computing, storage, networking, and data management on the network nodes within the close vicinity of IoT devices
  - computation, storage, networking, decision making, and data management occur along the **path between IoT devices and the cloud**, as data moves to the cloud from the IoT devices

Comparing fog computing and related computing paradigms

- Cloud computing
  - cloud services
  - cloud resource provisioning
  - types of cloud
- Fog computing
  - fog vs. cloud
  - fog-cloud federation
  - fog RAN (Radio Access Network)
- Mobile computing
- Mobile cloud computing

- Other similar computing paradigms:
  - Micro data center
  - Cloud of things
  - Edge cloud

- Mobile ad hoc cloud computing
  - MACC (Mobile ad hoc Cloud Computing) vs. cloud computing
  - MACC vs. MCC (Mobile Cloud Computing)
  - MACC vs. fog
  - MACC vs. MANET (Mobile Ad hoc Network)
- Edge computing
  - edge computing vs. fog computing
  - where is edge?
- Multi-access edge computing
- Cloudlet computing
- Mist computing

What is cloud computing ?

Cloud Computing

- **Cloud computing** has been instrumental in expanding the reach and capabilities of computing, storage, and networking infrastructure to the applications
- The National Institute of Standards and Technology (NIST) defines cloud computing as:
  - **a model that promotes ubiquitous, on-demand network access to shared computing resources**
- Cloud data centers are:
  - large pools of highly accessible virtualized resources that can be **dynamically reconfigured** for a scalable workload
  - this reconfigurability is beneficial for clouds services that are offered with a **pay-as-you-go** cost model
- The pay-as-you-go cost model:
  - allows users to conveniently **access remote computing resources and data management services**,
  - while **only being charged for the amount of resources they use**
- Cloud providers, such as Google, IBM, Microsoft, and Amazon provide and provision large data centers to host these cloud-based resources

Cloud Computing - cloud services

- Cloud offers **infrastructure, platform, and software** as services (IaaS, PaaS, SaaS)
- Application developers can use a variety of these services depending on the **needs of the applications** they develop

Cloud Computing - cloud services / IaaS

- **Infrastructure as a service** (IaaS) allows:
  - cloud consumers to **directly access IT infrastructures for processing, storage, and networking resources**

- Example of IaaS:
  - suppose Sam wants to set up a high-tech agricultural system that utilizes IoT devices to monitor the condition of crops
  - Sam contacts a cloud provider and acquires an IaaS for development of his system
  - Sam now can configure the IaaS (**often offered as a standalone VM**) in terms of hardware and corresponding software for his need
  - control over infrastructure (IaaS) allows Sam to **customize hardware configuration**, such as the **number of CPU cores and RAM capacity, in addition to systems-level software**
  - Sam can obtain an IaaS from Amazon Web Services (AWS), Microsoft Azure, or Google Compute Engine (GCE)

Cloud Computing - cloud services / PaaS

- **Platform as a service** (PaaS) allows:
  - cloud consumers to **develop software and fully supports software lifecycle** –often with the help of a middleware –for software management and configuration.

- Example of PaaS:
  - if Sam **does not need to configure the infrastructure of the cloud**, managing and configuration of hardware and software may detract from the productivity of Sam's business
  - now, Sam could consider using PaaS offered by Apache Stratos, Azure App Services, or Google App Engine for his business
  - PaaS **manages the underlying low-level processes** and allows Sam to focus on managing software for his IoT-specific interactions
  - moreover, PaaS providers often include tools for convenient management of **databases and scaling applications**

Cloud Computing - cloud services / SaaS

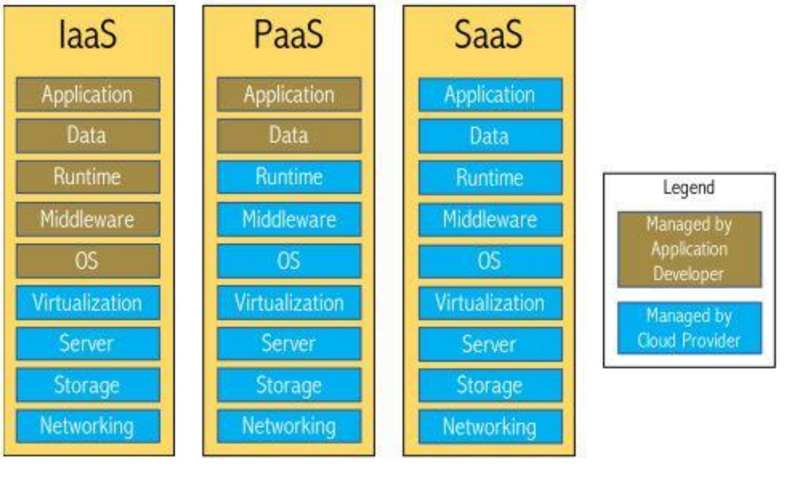
- **Software as a service** (SaaS) provides:
  - an environment to **centrally host applications and removes the need for to install software manually**

- Example of SaaS:
  - Sam is willing to spend more money and likes to **get full software packages**, and
  - he **does not want to take care of software issues, such as database scalability, socket management**, etc.
  - Sam's client software now can be hosted on Google Apps or as a Web application

Cloud Computing - cloud services / IaaS, PaaS, SaaS

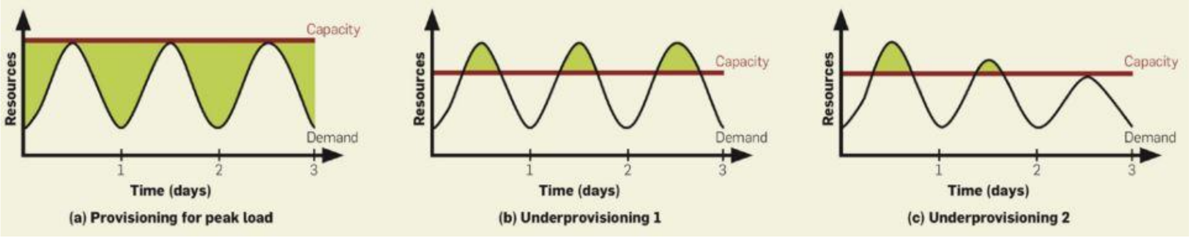
- In short, **cloud services can be utilized for distinct use cases for a variety of end users**

This figure illustrates the relationship among IaaS, PaaS, and SaaS with the underlying cloud infrastructure, and illustrates what portion of the application stack is managed by cloud providers.



Cloud Computing - cloud resource provisioning

- Since the **demand for cloud resources is not fixed** and **can change over time**:
  - setting a fixed amount of resources results in either **overprovisioning** or **under-provisioning**



Cloud Computing - cloud resource provisioning (cont)

- A foundation of cloud computing is based on **provisioning only the required resources for the demand**:
  - this includes the **use of virtualization for on-demand application deployment**, and
  - the use of **resource provisioning to manage hardware and software** in cloud data centers
- Provisioning resources is an important topic in cloud computing that is widely explored
- Since it is difficult to estimate service usage from tenants, **most cloud providers have a pay-as-you-go payment scheme**:
  - as a result, **providers can be more flexible on how to provision resources**, and
  - **clients only pay for the amount of resources they actually use**

Cloud Computing - types of cloud / private cloud

- There are **four types of cloud deployments**:
  - **private** cloud,
  - **community** cloud,
  - **public** cloud, and
  - **hybrid** cloud

- **Private clouds:**
  - designed for use by a singular entity and ensure high privacy and configurability
  - good choice for organizations that require an infrastructure for their applications
  - similar to traditional company-owned server farms and often do not benefit from a pay-as-you-go cost model

Cloud Computing - types of cloud / community cloud

- **Community clouds:**
  - used by a community of users, and the infrastructure is shared between several organizations
  - it results in decentralized ownership of the cloud by multiple organizations within the community,
  - without relying on a large cloud vendor for the IT infrastructure

Cloud Computing - types of cloud / public cloud

- **Public clouds** are the typical model of cloud computing:
  - where the cloud services are offered by cloud service providers, such as Amazon, IBM, Google, Microsoft, etc.

- **Public clouds** are generally:
  - more popular,
  - easy-to-maintain, and
  - cost-effective compared to private clouds

- In **contrast to private clouds**:
  - public clouds may **benefit from the pay-as-you-go** pricing model
  - however, **public clouds do not always offer users complete customization of hardware, middleware, network, and security settings**

Cloud Computing - types of cloud / hybrid cloud

- **Hybrid clouds:**
  - are simply a combination of the cloud types previously mentioned

- It allows users:
  - to have **finer control over virtualized infrastructure**, and
  - **combining the capabilities from different types of cloud deployments** is accomplished through standardized or proprietary technology

Cloud Computing

- The cloud computing paradigm was initially established to **allow users to access a pool of computing resources for ubiquitous computing**
- Even though cloud computing has helped bring forth accessible computing:
  - the **time required to access cloud-based applications may be too high**, and
  - **may not be practical for some mission-critical applications**, or **applications with ultra-low latency requirements**
  - also, the **rapid growth in the amount of data generated at the network edge** by an increasing number of connected devices **requires cloud resources to be closer to where the data is generated**
- Greater **demand for high-bandwidth, geographically-dispersed, low-latency, and privacy-sensitive data** processing has emerged:
  - need for **computing paradigms that take place closer to connected devices**
  - supporting **low-latency, high-bandwidth, decentralized applications**
- To address these needs, **fog computing** has been proposed

What is fog computing ?

Fog Computing

- Fog computing bridges the **gap between the cloud and end devices** (e.g., IoT nodes)
- It enables computing, storage, networking, and data management on network nodes within the **close vicinity of IoT devices**
- Consequentially:
  - computation, storage, networking, decision making and data management **not only occur in the cloud**, but also
  - **occur along the IoT-to-Cloud path** as data traverses to the cloud (preferably close to the IoT devices)
- Example:
  - compressing the GPS data can happen at the edge before transmission to the cloud in Intelligent Transportation Systems (ITS)

Fog Computing (cont.)

- **Fog computing** is defined by the OpenFog Consortium as:
  - a **horizontal system-level architecture** that distributes computing, storage, control and networking functions closer to the users along a cloud-to-thing continuum
- The “horizontal” platform in fog computing allows computing functions to be:
  - distributed between different platforms and industries, whereas
  - a **vertical platform promotes “siloed”** applications
- A vertical platform:
  - may provide **strong support for a single type of application** (silo),
  - but it **does not account for platform-to-platform interaction** in other vertically focused platforms
- In addition to facilitating a horizontal architecture:
  - fog computing provides a **flexible platform to meet the data-driven needs of operators and users**

Fog computing - fog vs. cloud (1/4)

- Fog computing is intended to provide **strong support for the Internet of Things**
- A common example that is often used to **distinguish fog and cloud computing** is:
  - whether **latency-sensitive applications** can be supported while maintaining satisfactory **quality of service (QoS)**
  - fog nodes can be placed close to IoT source nodes, allowing **latency to be noticeably reduced** compared to traditional cloud computing
- While this example gives an intuitive motivation for fog:
  - **latency-sensitive applications are only one of the many applications** that warrant the need for fog computing
- Nodes in fog computing are **generally deployed in less centralized locations** compared to centralized cloud data centers

25

Fog computing - fog vs. cloud (2/4)

- Fog nodes are **wide-spread and geographically available in large numbers**
- In fog computing:
  - security must be **provided at the edge** or in the dedicated locations of fog nodes,
  - as opposed to the **centrally-developed security mechanisms** in dedicated buildings for cloud data centers
- The **decentralized nature of fog computing** allows devices to:
  - **either serve as fog computing nodes themselves** (e.g., a car acts as a fog node for onboard sensors) or
  - **use fog resources as the clients of the fog**
- The majority of **differences between cloud and fog computing** are attributed to:
  - the **scale of hardware components** associated with these computing paradigms

26

Fog computing - fog vs. cloud (3/4)

- Cloud computing :
  - provides **high availability** of computing resources at relatively **high power consumption**
  - typically utilizes **large data centers**
  - must be accessed through the **network core**
  - requires **devices to be connected when the cloud service is in progress**

- Fog computing:
  - provides **moderate availability** of computing resources at **lower power consumption**
  - utilizes **small servers, routers, switches, gateways, set-top boxes, or access points**
  - hardware occupies **much less space than that of cloud computing**; thus, it can be located **closer to users**
  - can be **accessed through connected devices from the edge of the network to the network core**
  - **continuous Internet connectivity is not essential** for the fog-based services to work (send necessary updates to the cloud whenever the connection is available)

Fog computing - fog vs. cloud (4/4)

- **Fog helps devices to**:
  - measure, monitor, process, analyze and react, and distributes computation, communication, storage, control, and decision making **closer to IoT devices**

- Many industries could **use fog to their benefit**:
  - energy,
  - manufacturing,
  - transportation,
  - healthcare,
  - smart cities,
  - etc.

Real-World Deployments

- It seems **that it is not the short latency that matters the most**
- It is **availability of safety critical applications and bandwidth**

Industry		Company	Use case	Edge location
Business	Restaurants	Chick-fil-A	– forecast food preparation (e.g., more food needs to be fried)	In store
Business	Retail	Wal-Mart, Coca Cola (vending machines)	– monitoring (e.g., fridge temperature ensuring produce quality) – tracking customers & improving sales (e.g., customized coupons)	In store
Business	Gas station	Shell	– detect safety hazards (e.g., a person smoking a cigarette) across their 44,000 gas stations	In gas stations
Smart Cities	Cities	City of Bellevue	– traffic administration (e.g., intelligent control of traffic light) – safety at intersections (e.g., alerting drivers to prevent accidents)	Intersections & City clusters
Smart Cities	Construction	PCL, ATF Services	– increase safety, efficiency, and productivity (e.g., detecting a temperature spike or gas leak in a unit) – increase security of construction cites (e.g., protecting equipment overnight)	Construction site
Transportation	Aviation	Airbus, Bombardier	– analyze in-flight experience of customers – monitor aircraft operations and maintenance	On Plane
Transportation	Railway	CAF	– monitor train tracks, freight cars, and wheels for problems that lead to derailment	On the train
Transportation	Road Control	Alaska DOT	– monitor quality of roads and detect roads with need of maintenance (e.g., finding spots that need snow plowing to prevent icing)	On Trucks
Industrial Plants	Oil Refinary	Schneider Electric, ExxonMobil	– predictive maintenance (of the pumps and equipment) – workplace safety	Oil rig or pump
Industrial Plants	Manufacturing	GE, CPG, DAIHEN, Airbus	– improve manufacturing yields (e.g., automation or detecting defected products) – monitor equipment & predict need for maintenance	In factory
Industrial Plants	Manufacturing	BMW	– manage fleet of robots aiding in production pipeline	In factory
Industrial Plants	Agriculture	Buhler	– control quality of produce at harvest, storage, and processing using imagery (e.g., for grains, processing 20,000 kernels/s).	In field
Industrial Plants	Agriculture	DroneWorks, FarmBeats	– observe and monitor agricultural fields using sensors and drone imagery (e.g., detect areas that need water or pesticides)	In field

Fog computing related paradigms

Fog computing - fog–cloud federation (1/2)

- There are clear **differences and trade-offs between cloud and fog computing**
- **Fog and cloud complement each other**; one cannot replace the need of the other
- By **coupling cloud and fog computing**, the services that connected devices use can be **optimized even further**
- **Federation between fog and cloud allows enhanced capabilities** for data aggregation, processing, and storage
- For example:
  - in a stream processing application, the **fog could filter, preprocess, and aggregate** traffic streams from source devices,
  - while **queries with heavy analytical processing, or archival results** could be sent to the cloud

Fog computing - fog–cloud federation (2/2)

- An **orchestrator** could handle the **cooperation between cloud and fog**
- Specifically:
  - a fog orchestrator could **provide an interoperable resource pool, deploy and schedule resources to application workflows, and control QoS**
- Through the use of SDN:
  - **fog service providers will have greater control over how the network is configured** with a large number of fog nodes that transfer data between the cloud and IoT devices

Fog computing - fog RAN (1/2)

- Fog computing can be **integrated into mobile technologies in the form of radio access networks (RAN)**, to form what is referred to as fog RAN (F-RAN)

- Computing resources on F-RANs may be **used for caching at the edge of the network**:
  - which **enables faster retrieval of content** and a **lower burden on the front-haul**
  - F-RAN can be **implemented through 5G** related mobile technologies

- On the other hand, **cloud RAN (C-RAN) provides centralized control over F-RAN nodes**:
  - C-RAN takes **advantage of virtualization**, and **decouples the base stations within a cell of the mobile network from its baseband functions** by virtualizing those functions
  - in C-RAN a **large number of low-cost Remote Radio Heads (RRHs) are randomly deployed and connected to the Base Band Unit (BBU) pool** through the front-haul links

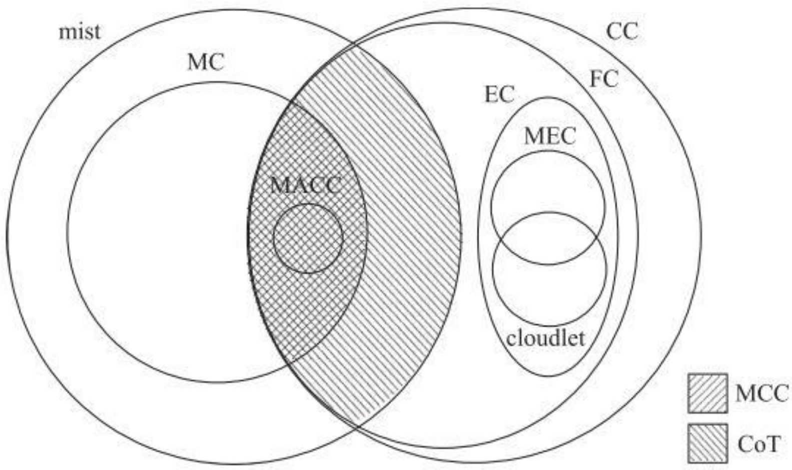
Fog computing - fog RAN (2/2)

- **Both F-RAN and C-RAN are suited for mobile networks with base stations** and are **candidates for 5G** deployments

- Also, the **use of F-RAN and C-RAN brings a more energy efficient form of network operation**

Classification of Computing Paradigms

MC	Mobile Computing
EC	Edge Computing
MCC	Mobile Cloud Computing
CoT	Cloud of Things
CC	Cloud Computing
FC	Fog Computing
MEC	Multi-access Edge Computing
MACC	Mobile ad hoc Cloud Computing
mist	Mist Computing



The figure illustrates our comparison of fog computing and its related computing paradigms

Mobile computing (1/3)

- The advancement in fog and cloud computing is influenced by the groundwork set forth by the development of **mobile computing**
- Mobile computing, or nomadic computing, is:
  - **when computing is performed via mobile, portable devices, such as laptops, tablets, or mobile phones**
- Mobile computing can be utilized to create **pervasive context-aware applications**
- At the heart of mobile computing is the vision for:
  - **adaptation in an environment of low processing power and intermittent, sparse network connectivity**
- The **peak of mobile computing technologies precedes cloud computing**

Mobile computing (2/3)

- A large number of **fundamental challenges** (such as user mobility, network heterogeneity, and low bandwidth) in mobile computing **have been addressed**
- Due to the evolving requirements of connected consumer devices:
  - **mobile computing alone is not suitable for many recent computing challenges**
- With fog and cloud computing:
  - **computation is no longer tied to a local network**
  - **fog and cloud computing expand the scale and scope of mobile computing**
- The only **type of hardware that mobile computing requires are mobile devices**:
  - which can be connected through Bluetooth, WiFi, ZigBee, and other cellular protocols
- In contrast, **cloud computing require more resource-rich hardware with virtualization** capabilities

Mobile computing (3/3)

- **Security** in mobile computing must be **provided on the mobile device itself**
- **Compared to cloud computing**:
  - **mobile computing is more resource-constrained**,
  - in recent years, **mobile hardware and wireless protocols have been improved**
- The **power of mobile computing** comes from its **distributed computing architecture:**
  - distributed applications benefit from this architecture because **mobile machines do not need a centralized location to operate**
- Mobile computing, however, comes with many drawbacks such as:
  - **poor-resource** constraints, the **balance between autonomy and interdependence** (prevalent in all distributed architectures), **communication latency**, and the **need for mobile clients to efficiently adapt to changing environments**
- These drawbacks often make mobile computing **unsuitable for current applications that require low-latency or robustness**, or that **need large amounts of data** to be generated, processed, and stored on devices

Mobile cloud computing (1/4)

- **Cloud computing** became a valuable **complement to mobile computing**
- This combination resulted in **mobile cloud computing (MCC)**:
  - an **infrastructure** where **both the data storage and data processing occur outside of the mobile device**, bringing mobile computing applications to not just smartphone users but a **much broader range of mobile subscribers**
- **NIST** extends this definition to **include mobile devices**:
  - the synergy between IoT devices, mobile devices, and cloud computing that **enables data intensive and CPU-intensive applications for IoT environments**
- Some of these applications in MCC include **crowdsourcing, healthcare, sensor data processing, and task offloading**
- Mobile applications can be **partitioned at runtime**:
  - computationally intensive components of the application can be handled through **adaptive offloading**

Mobile cloud computing (2/4)

- Mobile cloud computing (MCC):
  - resource constrained **mobile devices can leverage resource-rich cloud services**
  - it **shifts the majority of computation from mobile devices to the cloud**
  - it **helps to run computation intensive applications** and to **increase the battery life of mobile devices**
  - it **shares a blend of capabilities and characteristics in mobile computing and cloud computing**

- By adopting a combination of mobile computing and cloud computing objectives:
  - **high availability** of computing resources is present in MCC as opposed to resource-constrained mobile computing
  - this **allows for the emergence of high computation applications**, such as mobile augmented reality

Mobile cloud computing (3/4)

- The **availability of cloud-based services in MCC is considerably higher than that of mobile computing**
- Similar to cloud computing and fog computing:
  - **MCC relies on cloud services for operating high-computation services**
- **Computation in MCC can also be operated by mobile devices**
- Similar to cloud computing:
  - **security in MCC must be provisioned in both mobile devices and in the cloud**
  - e.g., an Android app that helps drivers find parking space availability using MCC

Mobile cloud computing (4/4)

- MCC also **suffers from the same limitations of mobile computing and cloud computing**:
  - since both cloud computing and MCC require cloud-based services, and as access to those services is through the network core by WAN connection, **applications running on these platforms require connection to the Internet all the time**
  - **offloading computation to the cloud causes the latency to be relatively high** for delay-sensitive applications
- For example:
  - a food recognition system based on MCC that distributes the data analytics between the mobile devices and the servers in the cloud
  - **mobile phones can perform light-weight computation on food images for food recognition**, which allows the system to **overcome some inherent limitations of traditional MCC paradigm, such as high latency and low battery life of mobile devices**

Mobile ad hoc cloud computing

- Despite the pervasive nature of **MCC**, this **computing paradigm is not always suitable for scenarios in which there is a lack of infrastructure or a centralized cloud**
- An **ad hoc mobile network** consists of nodes that:
  - form a **temporary, dynamic network** through routing and transport protocols
  - it is the **most decentralized form of a network**
- Mobile devices in an ad hoc mobile network form a highly dynamic network topology:
  - the network formed by the mobile devices is **highly dynamic** and must **accommodate for devices that continuously join or leave the network**
  - **ad hoc mobile devices can form clouds that can be used for networking, storage, and computing**
- MACC could include use cases such as **disaster relief, group live video streaming, and unmanned vehicular systems**

Mobile ad hoc cloud computing-MACC vs. cloud computing

- Mobile ad hoc cloud computing (**MACC**) **is fundamentally different from cloud computing**, mainly due to the ad hoc nature of the resources
- **MACC involves mobile devices** that function as data providers, storage, and processing devices
- **Mobile devices in a mobile ad hoc cloud network are also responsible for routing traffic among themselves**, because of the lack of network infrastructure
- By pooling local mobile resources to form an ad hoc cloud, **MACC offers reasonably high computation**
- These **attributes differ from the target users, architecture, and connectivity in cloud computing**

Mobile ad hoc cloud computing-MACC vs. MCC

- **MACC is also different from MCC** in the hardware, service access method, and the distance from users:
  - since computation is done on mobile devices in MACC,
  - whereas it is far from mobile devices in MCC
- **MACC only requires mobile devices to operate**, whereas MCC requires large-scale data centers used for cloud computing in addition to mobile devices:
  - this results in **high computation power**, but also **higher latency in MCC**
- **Security in MACC must be provided only in mobile devices**, but ensuring trust may be challenging in MACC without a secure collaboration framework
- Finally, in **MACC, services are only accessed through mobile devices that are connected via Bluetooth, WiFi, and other cellular protocols**

 45

45

Mobile ad hoc cloud computing-MACC vs. fog

- Although **fog computing can be performed across a variety of resource-rich and resource deficient devices**:
  - mobile ad hoc cloud computing is better suited for highly decentralized, dynamic network topologies in which Internet connection is not guaranteed
- **Connected devices in MACC are more decentralized compared to fog computing**:
  - this allows the devices to form a more dynamic network in places of sparely connected devices or a constantly changing network
- Example:
  - an ad hoc network for **peer-to-peer file sharing**

 46

46

Mobile ad hoc cloud computing-MACC vs. MANET

- A **similar concept to MACC is a mobile ad hoc network (MANET)**
- MANETs consist of:
  - **mobile host devices that are connected to each other with single hop without base stations**
- MANET devices form **dynamic networks but do not necessarily form a cloud**:
  - the computing or storage resource pools are not necessary for MANETs
  - however, many solutions to MANETS, such as redundancy and broadcasting, can be applied to MACC
- In a resource-constrained environment, **peers may want to pool resources together to achieve a computationally demanding task** that may not be feasible on a single device
- Use case:
  - an **unmanned vehicular system** that consists of multiple unmanned vehicles and traffic devices

Edge computing (1/3)

- **Similar to how MCC extends the capabilities of mobile devices**:
  - edge computing **also enhances the management, storage, and processing power of data generated by connected devices**
- Unlike MCC:
  - **edge computing is located at the edge of the network close to IoT devices**
  - note that the edge is not located on the IoT devices, but **as close as one hop to them**
- The edge can be **more than one hop away from IoT devices** in the local IoT network
- OpenEdge Computing defines edge computing as:
  - **computation done at the edge of the network through small data centers that are close to users**
- The original vision for **edge computing is to provide**:
  - compute and storage resources close to the user in open standards and ubiquitous manner

Edge computing (2/3)

- **Edge computing is a crucial computing paradigm** in the current landscape of IoT devices:
  - it integrates the IoT devices with the cloud by filtering, preprocessing, and aggregating IoT data intelligently via cloud services deployed **close to IoT devices**
- Some issues that edge computing is well equipped to handle are **privacy, latency, and connectivity**
- Due to its **proximity to the users**:
  - **latency in edge computing is typically lower than in MCC and cloud computing**, if enough local computation power is provided
  - **latency in edge computing can be slower than cloud or MCC if the local computation unit is not powerful enough**

Edge computing (3/3)

- **Service availability** is also **higher in edge computing** because:
  - connected devices do not have to wait for a highly centralized platform to provide a service
- Compared to MACC, **edge computing has small data centers**, whereas MACC fundamentally does not need data centers:
  - as a result, **edge computing has higher service availability**
- **Edge computing also can expand with broader computing capabilities than MACC** by forming hybrid architectures with peer-to-peer and cloud computing models

Edge computing-Edge computing vs. fog computing

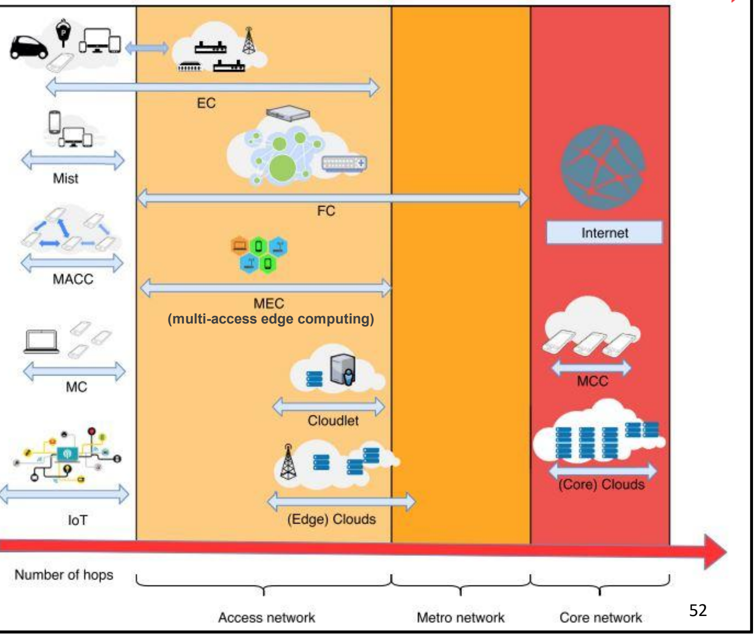
- Although fog computing and edge computing both **move the computation and storage to the edge of the network and closer to end-nodes**:
  - these paradigms **are not identical**
- In fact, the OpenFog Consortium states that **edge computing is often erroneously called fog computing**
- OpenFog Consortium makes the distinction that:
  - **fog computing is hierarchical** and it provides computing, networking, storage, control, and acceleration **anywhere from cloud to things**
  - while, **edge computing tends to be limited to computing at the edge**

Comparison of fog computing and its related computing paradigms

"fog is inclusive of cloud, core, metro, edge, clients, and things"

"fog seeks to realize a seamless continuum of computing services from the cloud to the things rather than treating the network edges as isolated computing platforms"

"fog envisions a horizontal platform that will support the common fog computing functions for multiple industries and application domains, including but not limited to traditional telco services"



Edge computing-Where is edge?

- It is worth mentioning that:
  - **edge computing, cloudlets, fog computing, and mist computing** (to be discussed later) are **used interchangeably in some papers**, as they all have "edge "as a common term
- The term **edge used by the telecommunications** industry usually:
  - **refers to 4G/5G base stations, RANs, and ISP (Internet Service Provider) access/edge networks**
- Yet, the **term edge** that is recently used in the IoT landscape:
  - **refers to the local network where sensors and IoT devices are located**
  - in other words, the **edge is the immediate first hop from the IoT devices** (not the IoT nodes themselves), such as the WiFi access points or gateways
- **If the computation is done on IoT devices themselves:**
  - **this computing paradigm is referred to as mist computing**
- General Electric notes that:
  - **fog computing focuses on interactions between edge devices** (e.g., RANs, base stations, or edge routers),
  - whereas **edge computing focuses on the technology attached to the connected things** (e.g., WiFi access points)

 53

53

Multi-access edge computing (1/4)

- **Mobile cloud computing (MCC) is an extension of mobile computing (MC) through cloud computing**
- Analogously, **multi-access edge (MEC) computing is an extension of mobile computing (MC) through edge computing**
- ETSI (European Telecommunications Standards Institute) defines **MEC as a platform** that:
  - provides IT and cloud-computing capabilities within the Radio Access Network (RAN) in 4G and 5G, in **close proximity to mobile subscribers**
- **Multi-access edge computing was previously referred to as "mobile edge computing"**:
  - but the paradigm has been expanded to include a broader range of applications beyond mobile device-specific tasks
- Examples of multi-access edge computing applications include **video analytics, connected vehicles, health monitoring, and augmented reality**

 54

54

Multi-access edge computing (2/4)

- MEC:
  - **extends edge computing by providing compute and storage resources near low energy, low resource mobile devices**
  - it **allows RAN operators to add edge computing functionality** to existing base stations
- **Similar to edge computing**:
  - small-scale data centers with virtualization capacity can also be used in MEC
- Due to underlying hardware used in MEC and edge computing:
  - **available computing resources is moderate**, in comparison to cloud computing
  - furthermore, **low-latency applications can be supported in MEC**
- **MEC applications** can benefit from real-time radio and network information hence:
  - **can offer a personalized and contextualized experience to the mobile subscriber**

Multi-access edge computing (3/4)

- Both **edge computing and MEC computing services**:
  - **operate from the edge of the Internet**, and
  - **can function with little to no Internet connectivity**
- **MEC**, however, **establishes connectivity through a WAN, WiFi, and cellular connections**:
  - whereas **edge computing generally can establish any form of connectivity**
- **MEC also primarily differs from MCC in its operations**:
  - research in **MCC focuses on the relationship between cloud service users (on mobile devices) and cloud service providers**,
  - whereas research in **MEC focuses on (RAN-based) network infrastructure providers**
- **MEC is expected to benefit significantly from the up-and-coming 5G** platform
- Likewise, **5G is seen as an enabler of MEC** as:
  - it **allows for lower latency and higher bandwidth among mobile devices**, and
  - it supports a wide range of mobile devices with finer granularity

Multi-access edge computing (4/4)

- **MEC allows edge computing to be accessible to a wide range of mobile devices with reduced latency and more efficient mobile core networks**
- **MEC also allows for mission-critical delay-sensitive applications** over the mobile network
- **It has also incorporated the use of SDN and network function virtualization (NFV)** capabilities, **in addition to 5G** technologies
  - SDN allows for virtual networking devices to be easily managed through software APIs
  - NFV allows for reduced deployment times for networking services through virtualized infrastructure
- Moreover, **through SDN and NFV**:
  - network engineers and possibly enterprise application developers can **develop their own orchestrator**, whose goal is to **coordinate the resource provisioning across multiple layers**

Cloudlet computing (1/4)

- Proposed by Carnegie Mellon University, **cloudlet computing is another direction in mobile computing**:
  - it **shares many traits with MCC and MEC** (Multi-access edge computing)
  - it **addresses some of the disadvantages of MCC**
- A **cloudlet is**:
  - a **trusted resource-rich computer or a cluster of computers with strong connection to the Internet** that is utilized by **nearby mobile devices**
- **Cloudlets are small data centers** (miniature clouds, as the name suggests) that are **typically one hop away from mobile devices**:
  - the idea is to **offload computation from mobile devices to VM-based cloudlets** located on the network edge
- Although academia mostly drives current studies in cloudlet computing, it has **high potential in domains such as wearable cognitive assistance and web applications companies**

Cloudlet computing (2/4)

- Cloudlet is the middle tier of a 3-tier continuum:
  - **mobile device – cloudlet - cloud**
- Given the nature of cloudlets as a **small cloud close to mobile devices**:
  - **operators for cloudlet computing could be cloud service providers** who want their services to be accessible closer to mobile devices
- **Network infrastructure owners** (e.g., AT&T, Nokia, etc.) **can enable cloudlets with virtualization capacity to be situated closer to mobile devices**:
  - in **smaller hardware footprints compared to the massive data centers used in cloud computing**
  - the small footprint of cloudlets result in more **moderate computing resources, but lower latency and energy consumption** compared to cloud computing
- Cloudlet computing is intended to **serve devices in the local area**

 59

59

Cloudlet computing (3/4)

- Just as **MACC greatly differs from cloud computing** it **also highly differs from cloudlet computing**
- **Cloudlet needs infrastructure with virtualization in the form of virtual machine** (VM) capability:
  - whereas **MACC does not require such infrastructure**
- **MACC and cloudlet computing both support mobility**:
  - but **MACC is resource constrained and lacks virtualization support** for real-time IoT applications
- **Cloudlets support local services for mobile clients** by dividing tasks among cloudlet nodes in the proximity of mobile devices

 60

60

Cloudlet computing (4/4)

- Although **cloudlet computing fits well with the mobile-cloudlet-cloud framework**:
  - **fog computing** offers a more generic alternative that natively supports large amounts of traffic, and allows resources to be anywhere along the thing-to-cloud continuum
- The concept of **mobile cloudlets is similar to cloudlets**, in which the cloudlets are a group of nearby mobile devices that are connected wirelessly, e.g., using WiFi or Bluetooth
- In **mobile cloudlets, mobile devices can be providers as well as clients of computing service**

Mist computing (1/2)

- Recently, **mist computing has been introduced to capture a more extreme edge** – the endpoints – of connected devices
- **This computing paradigm describes dispersed computing at the extreme edge (the IoT devices themselves)**:
  - it has been proposed with future self-aware and autonomic systems in mind
- **Mist computing could be seen as the first computing location in the IoT-fog-cloud continuum**:
  - it can be informally labeled as **"IoT computing "or "things computing"**
  - it **extends compute, storage, and networking across the fog through the things**
  - it is a **superset of MACC**
- **In mist, the networking may not be necessarily ad hoc, and the devices may be mobile devices**

Mist computing (2/2)

- It is **possible to use mobile devices in the vicinity as a cloud computing environment** for storage, caching, and computing purposes:
  - **mist computing is used to reduce the load** in traditional WiFi infrastructures for video dissemination applications
  - the **spectators of a sport event organize themselves into WiFi-Direct groups and exchange video replays** whenever possible, bypassing the central server and access points
  - it is an example of mist computing, in which **IoT devices act not only as "thin clients, "but also as "thin servers"**
- Some **other uses of mist computing** are to **preserve the privacy of users' data** via local processing, and to **efficiently deploy virtualized instances on single-board computers**

Other similar computing paradigms

- Micro data center
- Cloud of things
- Edge cloud

Micro data center

- **Cloudlet is sometimes referred to as micro data center (MDC) in some studies**

- The term **micro data center (MDC) was proposed by Microsoft Research in 2015:**
  - it is defined as "**an extension of traditional data centers used in cloud computing**"

- An **MDC can be an edge node or a cloudlet** that is deployed between IoT devices and the cloud

Cloud of things (1/4)

- Another **similar concept to mist computing is the Cloud of Things (CoT)**:
  - where **IoT devices form a virtualized cloud infrastructure**

- In **mist computing computation is done on IoT devices**, possibly via message exchange, and **not necessarily in a cloud of pooled resources**:
  - **however, in Cloud of Things, computation is done over the cloud that is formed by pooled resources of IoT devices**

- Cloud of Things **can also be used for sensing-as a service**:
  - which **uses edge nodes as cloud agents sitting close to IoT nodes**
  - it **follows the idea of dynamically scaling up existing cloud resources** (compute, storage, and network) by **using the sensing capability of IoT devices**
  - **edge nodes are used as cloud agents near the edge** to discover, virtualize, and form a cloud network of IoT devices (CoT)
  - this network is a **geographically distributed infrastructure**, in which cloud agents constantly discover resources of IoT devices and pool them as cloud resources

Cloud of things (2/4)

- **CoT enables remote sensing and in-network distributed processing of data**

- For example:
  - a cloud user can view pollution levels in cities from real-time temperature and CO2 concentration sensors in vehicles with defined accuracy
  - the CoT framework is scalable to IoT networks, supports heterogeneity of IoT devices and edge computing nodes, and provides a foundation of sensing-as a service using fog computing

Cloud of things (3/4)

- **Similar to CoT**, there is the concept of **Pclouds (personal clouds)**:
  - these are a **distributed networked resources** that are from both local/personal and remote/public devices and machines

- **PCloud can service end users even when remote cloud resources are not present** or difficult to access due to insufficient network connectivity

- Another novel idea **similar to Cloud of Things and MACC is the Cloudrone**:
  - an idea of **deploying ad hoc micro cloud infrastructures in the sky using low-cost drones**, **single-board computers, and lightweight OS virtualization technologies**
  - the drones in this scheme form a **cloud computing cluster in the sky**, which provisions the cloud services nearer to the user, even in the absence of a terrestrial infrastructure to access the remote cloud

Cloud of things (4/4)

- **Similar to the concept of Cloud of Things, Femtoclouds** have been proposed:
  - Femtoclouds take advantage of clusters of devices that tend to be co-located in places such as schools, public transit, or malls
  - tap into the computational capability and pervasiveness of underutilized mobile devices

- A hybrid edge-cloud workload management scheme can also be used for management of resources and tasks in Femtoclouds, to provide **low latency**

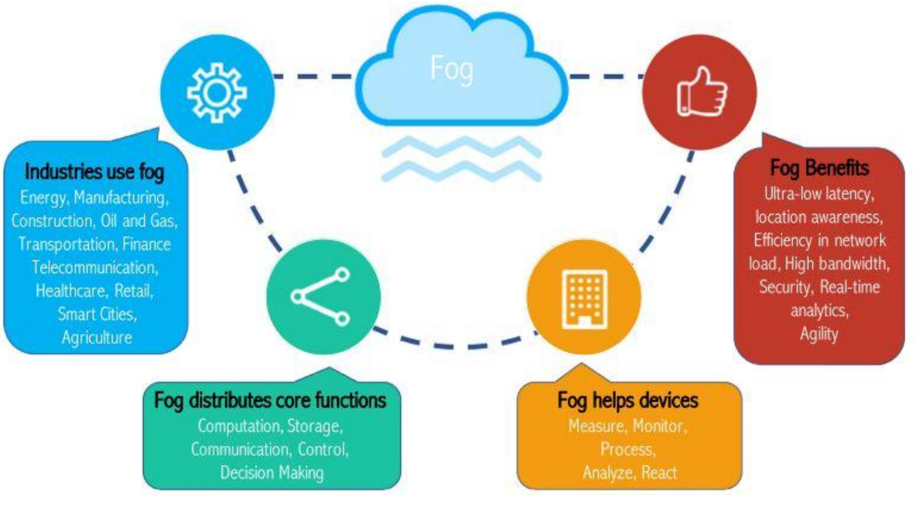
Edge cloud (1/2)

- The **concept of edge cloud is similar to edge computing**:
  - the **edge cloud extends cloud capabilities at the edge** by leveraging user or operator-contributed compute nodes at the edge of the network
- When we talk about cloud computing, we mainly talk about **"core " or "distant " clouds**, which are far from the user or devices
- **Core clouds** are **further from connected things** and are **responsible for heavy computation**
- In contrast, **edge clouds are smaller scale** compared to core clouds and are **closer to the devices**
- **Similar to fog, in edge clouds**:
  - the **ability to run an application in a coordinated manner in both edge and the distant cloud is envisaged**
- **Edge clouds are nodes at the edge**, e.g.micro data centers, cloudlets, and MEC

Edge cloud (2/2)

- Researchers have begun studying **federation of both edge clouds and core clouds**, and proposed the **"osmotic computing " paradigm**:
  - it implies "**the dynamic management of services and micro-services across cloud and edge data centers, addressing issues related to deployment, networking, and security**"
  - it utilizes **both edge and cloud resources**, each contained **in two separate layers**
- Application delivery follows an osmotic behavior where **virtualized micro-services are deployed opportunistically either in the cloud or edge layers**
- The **ability to control how micro-services can be balanced between edge and cloud** is a significant advantage of osmotic computing

Fog Benefits



Fog brings several benefits for the application developers, applications, and different industries by distributing the core functions

Discussion (1/5)

- The previous discussion about **fog computing and related paradigms** demonstrate the **importance of understanding the characteristics of these platforms** in the changing IT landscape
- As demonstrated by the **strength and weaknesses attributed to these computing paradigms**, some paradigms may be **better suited for a particular use case than others**
- Even so, **fog computing is suited for a large number of use cases** in the current landscape of **IoT and connected devices**
- The **versatility of fog computing makes it suitable for many cases of data-driven computing and low-latency applications**

Discussion (2/5)

- Even though **it may not be suitable for a few extreme applications**, such as disaster zones or sparse network topologies where ad hoc computing (e.g., MACC) or extreme edge clouds (e.g., mist, CoT) may be a better fit
- Nonetheless, **fog computing is considered a more general form of computing when compared to other similar paradigms** (e.g., EC, MEC, cloudlet):
  - because of its comprehensive definition scope, generality, and extensive presence along the thing-to cloud continuum
- Fog computing **offers a bright future** for an open-standards environment of connected devices, as it is evident by IEEE Standard’s adoption of OpenFog Reference Architecture
- See Table 2 and 3 in the accompanying paper for a summary of these characteristics (shown in the next 2 slides)

Discus

Attributes of fog-computing related paradigms.

Attribute	CC	MC	FC	EC	MCC	MACC	MEC	cC	mist
Users	General	Mobile	General	General	Mobile	Mobile	Mobile	Mobile	General
General Use Cases	Scalable data storage, virtualized apps, distributed computing for large data sets (Google MapReduce)	Mobile sales transactions, location dependent queries (travel recommendations), multimedia applications on mobile devices	IoT, Connected vehicles, smart grid/smart city, health care, smart delivery (high-scale package drone delivery), real-time subsurface imaging, video surveillance	Local video surveillance, video caching, traffic control	Social networking, sensor data processing, health care (tele-monitoring and tele-surgery)	Networking and computing for disaster relief, group live video streaming, unmanned vehicular system	Content Delivery, Video analytics, connected vehicles, health monitoring, augmented reality	Optical character recognition (OCR), wearable cognitive assistance (Google Glass)	Parallel computation on IoT devices, autonomous vehicles, privacy-preserving local processing
Operators	Cloud service providers	Self-organized	Users and cloud service providers	Network infrastructure providers or local businesses	Users and cloud service providers	Self-organized	Network infrastructure providers (RAN-based)	Cloud service providers and network infrastructure providers	Self-organized or local businesses
Service Type	Global	Local	Less global	Local	Local	Local	Less global	Local	Local
Hardware	Large-scale data centers with devices with virtualization capacity	Mobile devices	Devices with virtualization capacity (servers, routers, switches, access points)	Edge devices with computing capability	Mobile devices or large-scale data centers with devices with virtual capability	Mobile devices	Small-scale data centers with devices with virtualization capacity, RAN in 4G and 5G	Devices with virtualization capability (micro and nano data centers)	IoT devices (e.g. sensors, cell phones, home appliance devices)
Available Computing Resources	High	Limited	Moderate	Moderate	High	Relatively less limited	Moderate	Moderate	Limited
Main Driver	Academia/industry	Academia	Academia/industry	Academia/industry	Academia	Academia	Academia/industry	Academia	Academia
Distance from Users	Far	Very close	Relatively close	Close	Far	Very close	Close	Close	Very close
Main Standardization Entity	CSA, DMFT, NIST, OCC, GICTF	MobileInfo	OpenFog Consortium, IEEE	—	NIST	—	ETSI, 3GPP, ITU-T	OpenEdge	—
ApplicationType	Ample computation	Distributed and mobile processing	High computation with lower latency	Low latency computation	High computation	High computation with lower latency	Low latency computation	High computation with lower latency	Distributed processing on IoT devices
Architecture	Centralized/ hierarchical	Distributed	Decentralized/ hierarchical	Localized/ distributed	Central cloud with distributed mobile devices	Distributed	Localized/ hierarchical	Localized	Localized/ distributed
Availability	High	Low	High	Average	High	Low	Average	High	Low
Latency	Relatively high	Moderate	Low	Low	Relatively high	Moderate	Low	Low	Moderate
Security	Must be provided along cloud-to-things continuum	Must be provided on mobile devices	Must be provided on participant nodes	Must be provided on edge devices	Must be provided along cloud-to-things continuum and on mobile devices	Must be provided on mobile devices	Must be provided on edge network equipment (RAN, AP)	Must be provided on participant nodes	Must be provided on IoT devices
Server Location	Installed in large dedicated buildings	—	Can be installed at the edge or in dedicated locations	Near edge devices	Installed in large dedicated buildings	—	Can be installed at the edge	Near mobile devices	—
Power Consumption	Relatively high	—	Low	Low	Low on mobile devices	Low	High	Moderate	Low
Internet Connectivity	Must be connected to the Internet for the duration of services	Can operate with low or intermittent Internet connectivity	Can operate autonomously with no or intermittent Internet connectivity	Can operate autonomously with no or intermittent Internet connectivity	Requires Internet connection for offloading tasks or obtaining computation results from the cloud	Can operate autonomously with no or intermittent the Internet	May operate autonomously or connect to the Internet through RAN	Can operate with no or intermittent Internet connectivity; often requires connection to the Internet	Can operate with low or intermittent Internet connectivity
Hardware Connectivity	WAN	Bluetooth, WiFi, cellular, ZigBee	WAN, LAN, WLAN, WiFi, cellular	WAN, LAN, WLAN, WiFi, cellular, ZigBee	WAN	Bluetooth, WiFi, cellular, ZigBee	WAN, cellular	WAN, LAN, WLAN, WiFi, cellular	LAN, Bluetooth, WiFi, cellular, ZigBee
Service Access	Through core	Through mobile devices	Through connected devices from the edge to the core	At the edge of the Internet	Through core	Through mobile devices	At the edge of the Internet	Through resource-rich computers at the edge of the Internet	Through IoT devices

Discussion (4/5) - Table

Features of fog-computing related paradigms.

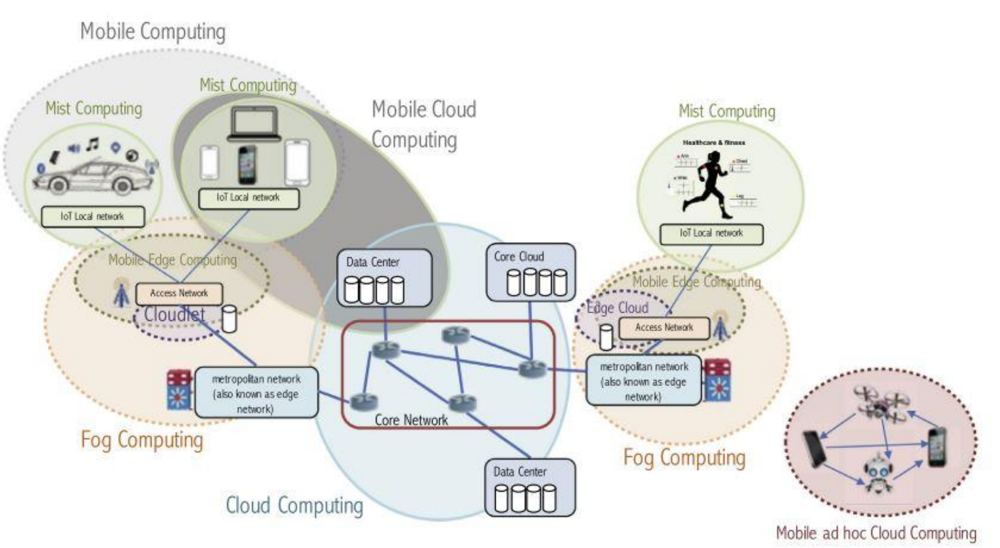
Feature	CC	MC	FC	EC	MCC	MACC	MEC	cC	mist
Heterogeneity support	√	✗	√	√	√	✗	✗	✗	√
Infrastructure need	√	✗	√	√	√	✗	√	√	√
Geographically distributed	✗	✗	√	√	✗	✗	√	√	√
Location awareness	✗	√	√	√	✗	√	√	√	√
Ultra-low latency	✗	✗	√	√	✗	✗	√	√	√
Mobility support	✗	√	√	√	√	√	√	√	√
Real-time application support	✗	✗	√	√	✗	✗	√	√	√
Large-scale application support	√	✗	√	√	✗	✗	√	✗	√
Standardized	√	√	√	√	✗	✗	√	✗	✗
Multiple IoT Applications	√	✗	√	✗	✗	✗	✗	√	√
Virtualization support	√	✗	√	✗	✗	✗	√	√	✗

Discussion (5/5)

- There **does not yet exist a globally unanimous distinction between fog computing and related computing paradigms**:
  - such as edge computing, mist computing, and cloudlets across researchers and industries
- We **attempt to clarify the distinctions between fog computing and the related computing paradigms**
- See next slide for a **comparison of the underlying infrastructure of fog computing and its related computing paradigms from the networking perspective**

Comparison of Fog with Related Paradigms

Comparison of the infrastructure of fog computing and its related computing paradigms from the networking perspective



Conclusion (1/2)

- The **Internet of Things** accelerates digital transformation and provides benefits to many industries, including manufacturing, energy, transportation, smart cities, education, retail, healthcare, and government
- Due to **IoT's fundamental benefits**, the number of connected devices and the IoT networks is on the rise, as individuals and companies deploy more and more IoT devices
- **IoT is expected to connect billions of devices and humans** to bring promising advantages for us
- **Fog computing is one of the promising solutions** for handling the big data that is being produced by the IoT, which is often security-critical and time sensitive

Conclusion (2/2)

- We provided a **tutorial on what fog computing is and how it relates to or differs from other computing paradigms**, such as cloudlets, MEC, and edge computing
- The paper provides a **taxonomy of research topics in fog computing** and summarizes the relevant papers on fog computing and its related computing paradigms
- Finally, the paper shows some **challenges and future directions for research in fog computing**