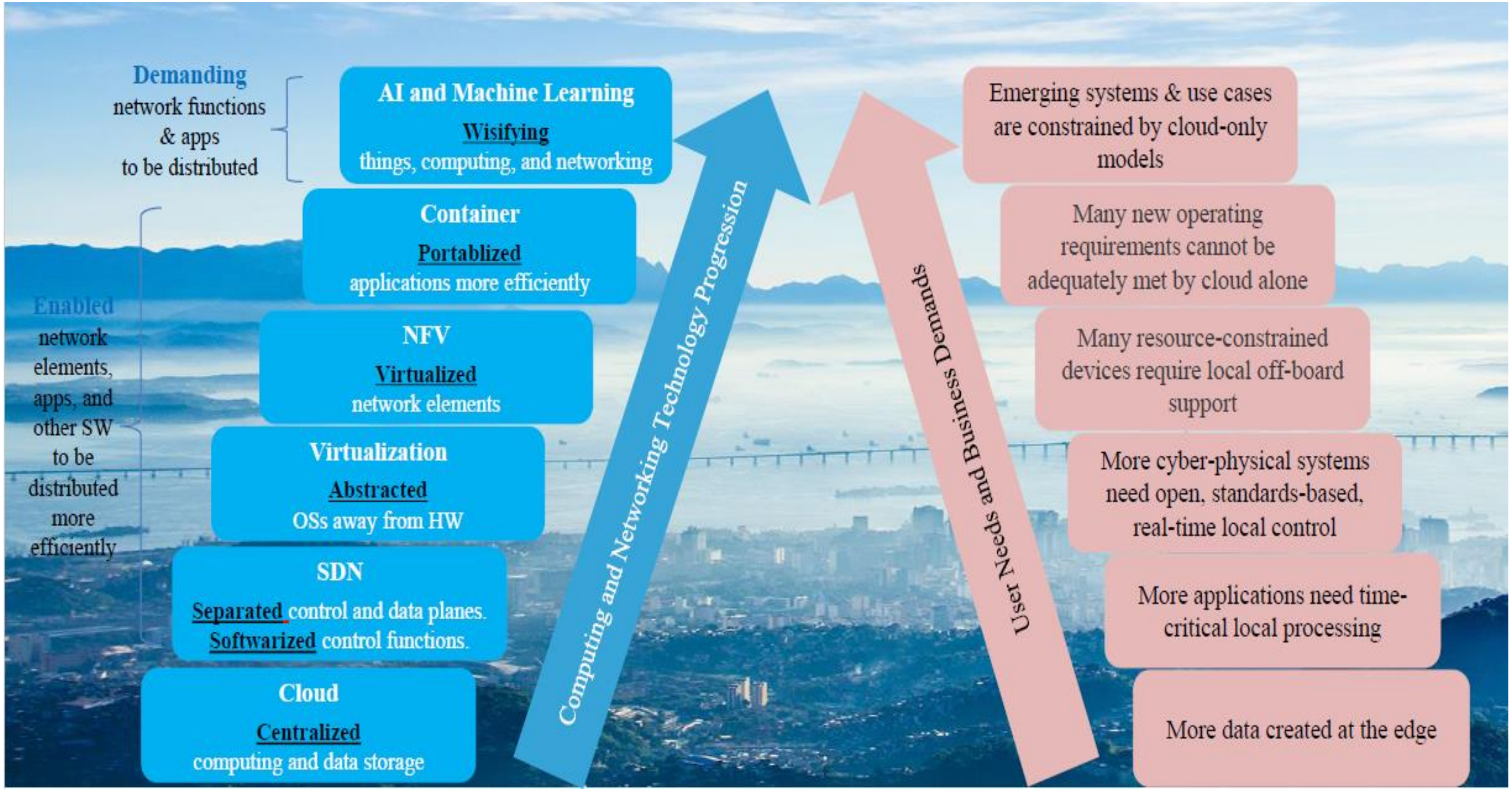
Fog Computing

Nelson L. S. da Fonseca
IEEE ComSoc Summer Scool
Albuquerque, July 17-21, 2017

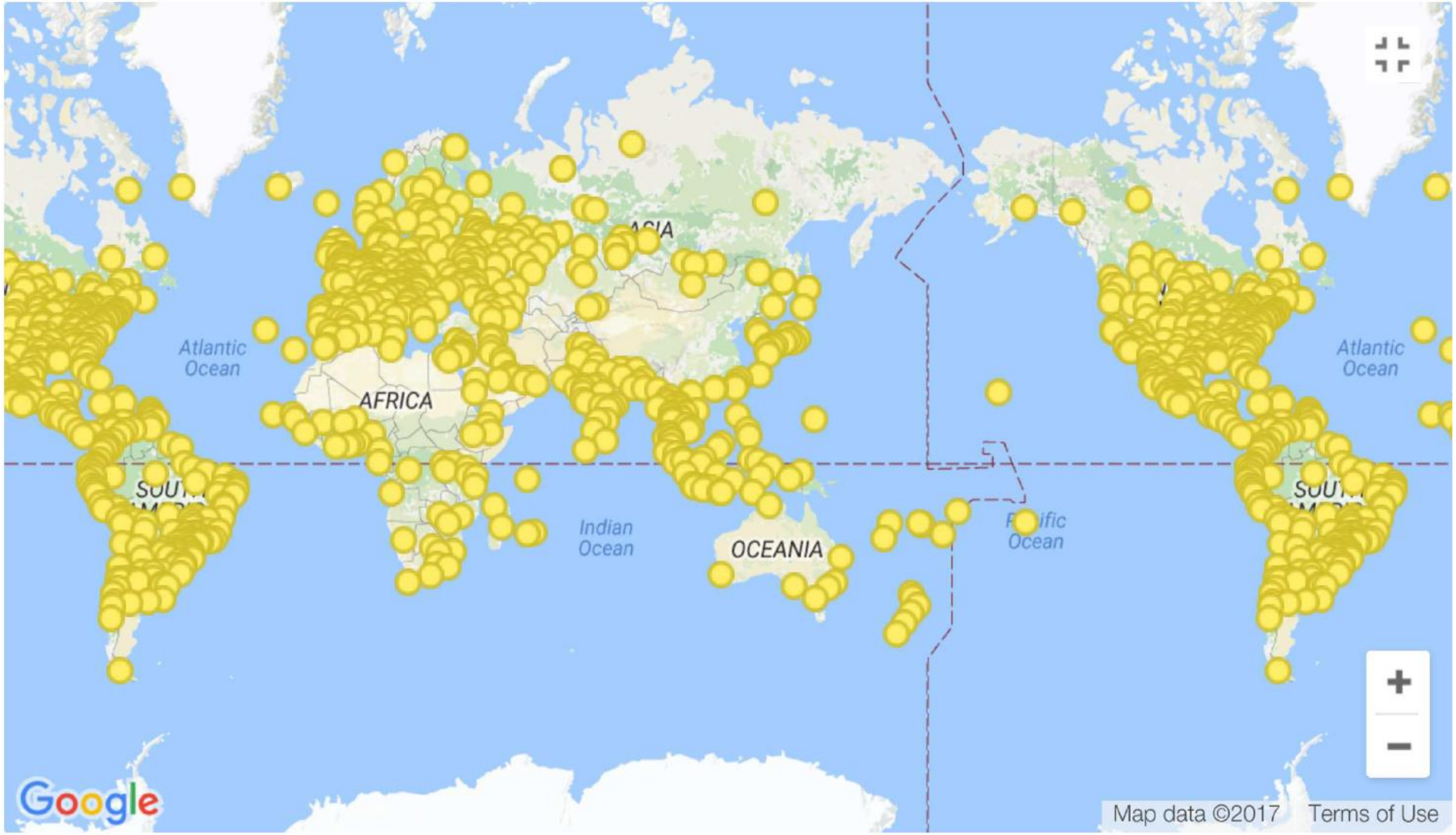
Current Tech Scenario



T. Zhang, T. Quek, J.Huang, Ai-Chun Pang, Y. Yang, "Fog Computing and Networking:A New Paradigm for 5G and IoT Applicationns, IEEE ICC 2017

Cloud Computing – Centralized Model

Edge Devices

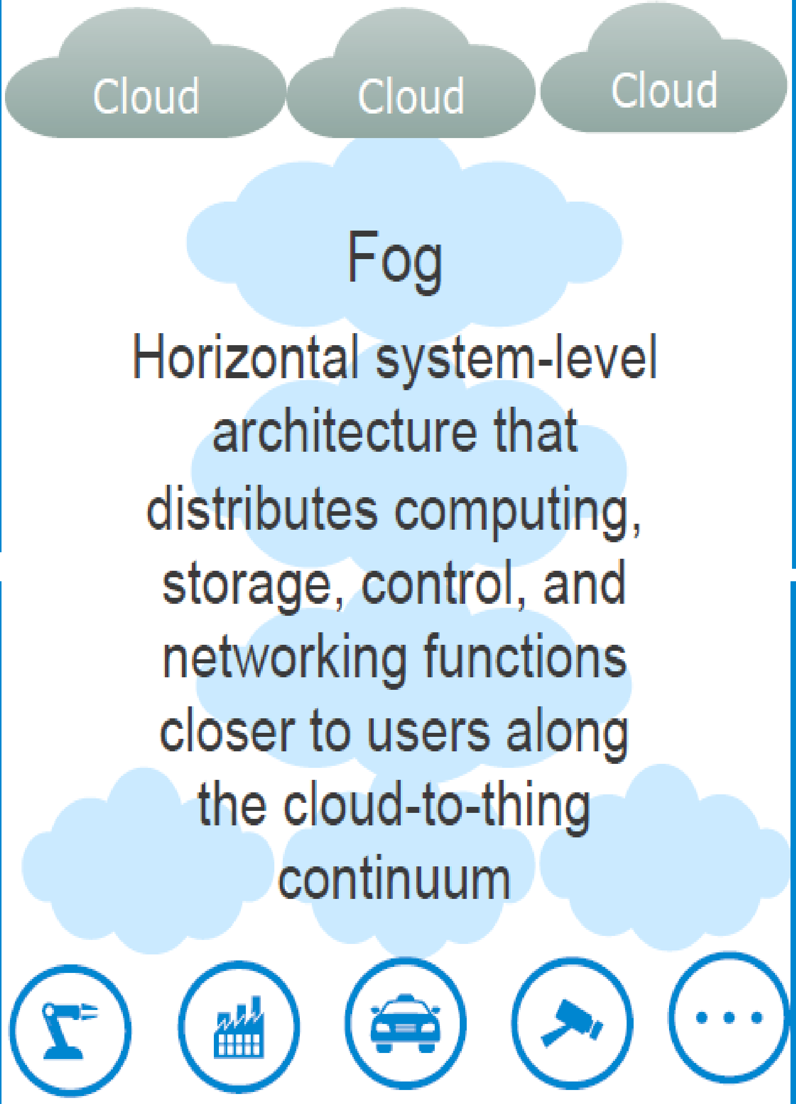


Horizontal

- Support multiple network types and industry verticals
  (not silo-ed systems for different networks, industries, or application domains)

Works Over and Inside Wired or Wireless Networks

(no need for silo-ed platforms just for moving computing inside any specific network such as 5G)



E2E Architecture

- Distribute, use, manage, and secure resources & services
- Enable horizontal and vertical interoperability, orcherstration, and automation
  (not just placing servers, apps, or small clouds at edges)

Cloud-to-Thing Continuum

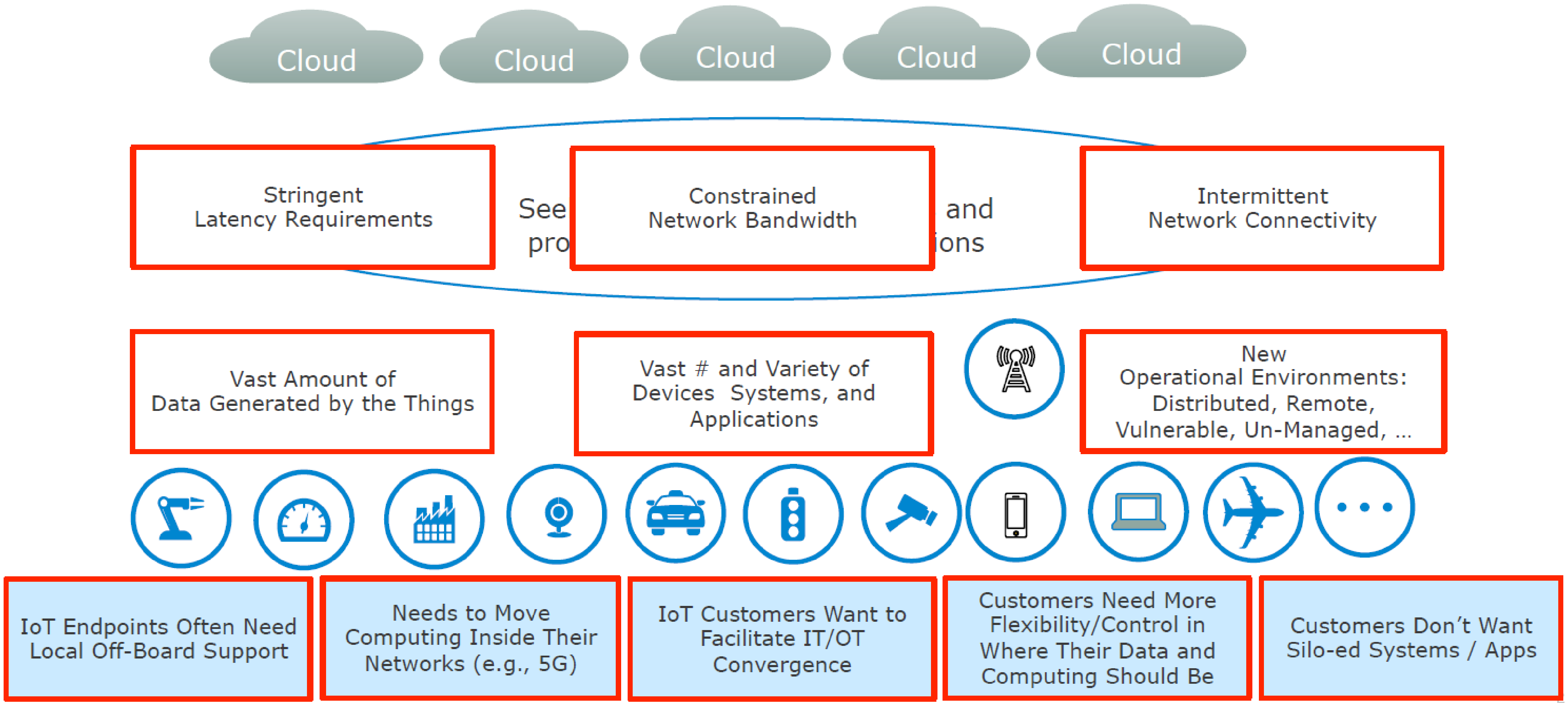
- Enable computing anywhere along the continuum
  (not just at any specific edge)
- Orchestrate resources in clouds, fogs, and things
  (not just isolated edge devices, systems, or apps)

T. Zhang, T. Quek, J.Huang, Ai-Chun Pang, Y. Yang, "Fog Computing and Networking:A New Paradigm for 5G and IoT Applicationns, IEEE ICC 2017

Distributed Computing Function

TCP/IP	WWW	Fog Computing and OpenFog Consortium
A horizontal framework for distributing data packets	A horizontal framework for accessing files anywhere	A horizontal framework for distributing computing functions and using, managing, & securing distributed resources and services
Wouldn't it be better if we also had a TCP-for-2.5G? for 3G?, for 4G, … **NO**	Wouldn't is be better if we also had a HTTP-for-2.5G? for 3G? for 4G? for wired telecom? … **NO**	Should we have a separate fog-like system for 5G? another for wired telecom? another for enterprises? another for smart city? another for manufacturing? … **NO**

T. Zhang, T. Quek, J.Huang, Ai-Chun Pang, Y. Yang, "Fog Computing and Networking:A New Paradigm for 5G and IoT Applicationns, IEEE ICC 2017



T. Zhang, T. Quek, J.Huang, Ai-Chun Pang, Y. Yang, "Fog Computing and Networking:A New Paradigm for 5G and IoT Applicationns, IEEE ICC 2017

Silo-ed
Systems

- For different networks: 5G, wired telecom, enterprises
- For different industry verticals: manufacturing, smart cities, ...
- For different applications inside same industry verticals
- For different types of edge devices: mobile edge, enterprise edge, users' edges, and more

Isolated
Systems and Applications

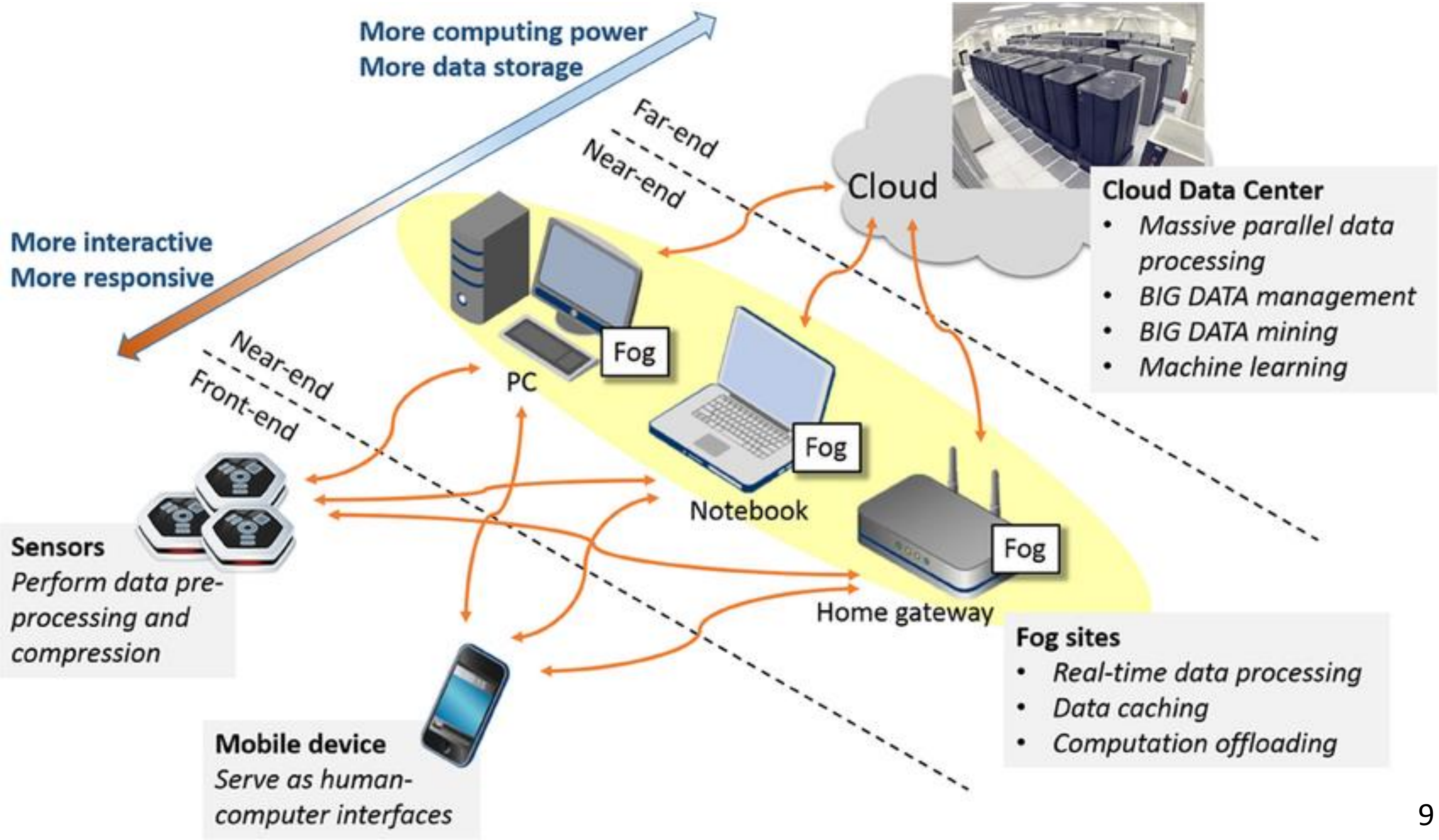
- Poor integration with the cloud
- Difficult to interoperate or collaborate with each other

Massively Confused
Market and Customers

- Edge Computing vs. Mobile Edge Computing vs. Multi-access Edge Computing vs. Mobile Edge Cloud vs. Cloud RAN vs. MiniCloud vs. Cloudlet vs. CORD vs. ...
- … and where does the Cloud fit in all these?

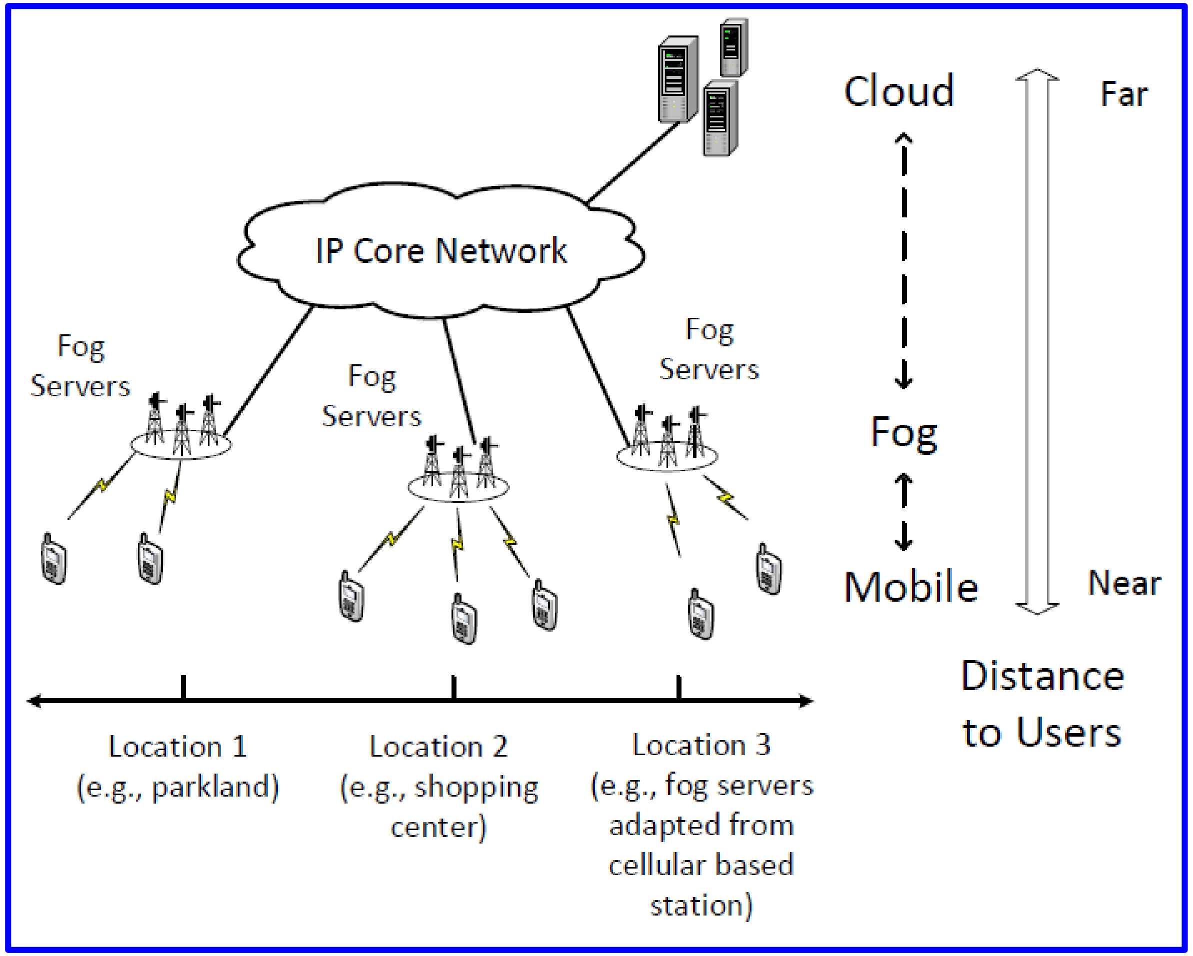
T. Zhang, T. Quek, J.Huang, Ai-Chun Pang, Y. Yang, "Fog Computing and Networking:A New Paradigm for 5G and IoT Applicationns, IEEE ICC 2017

Fog Computing

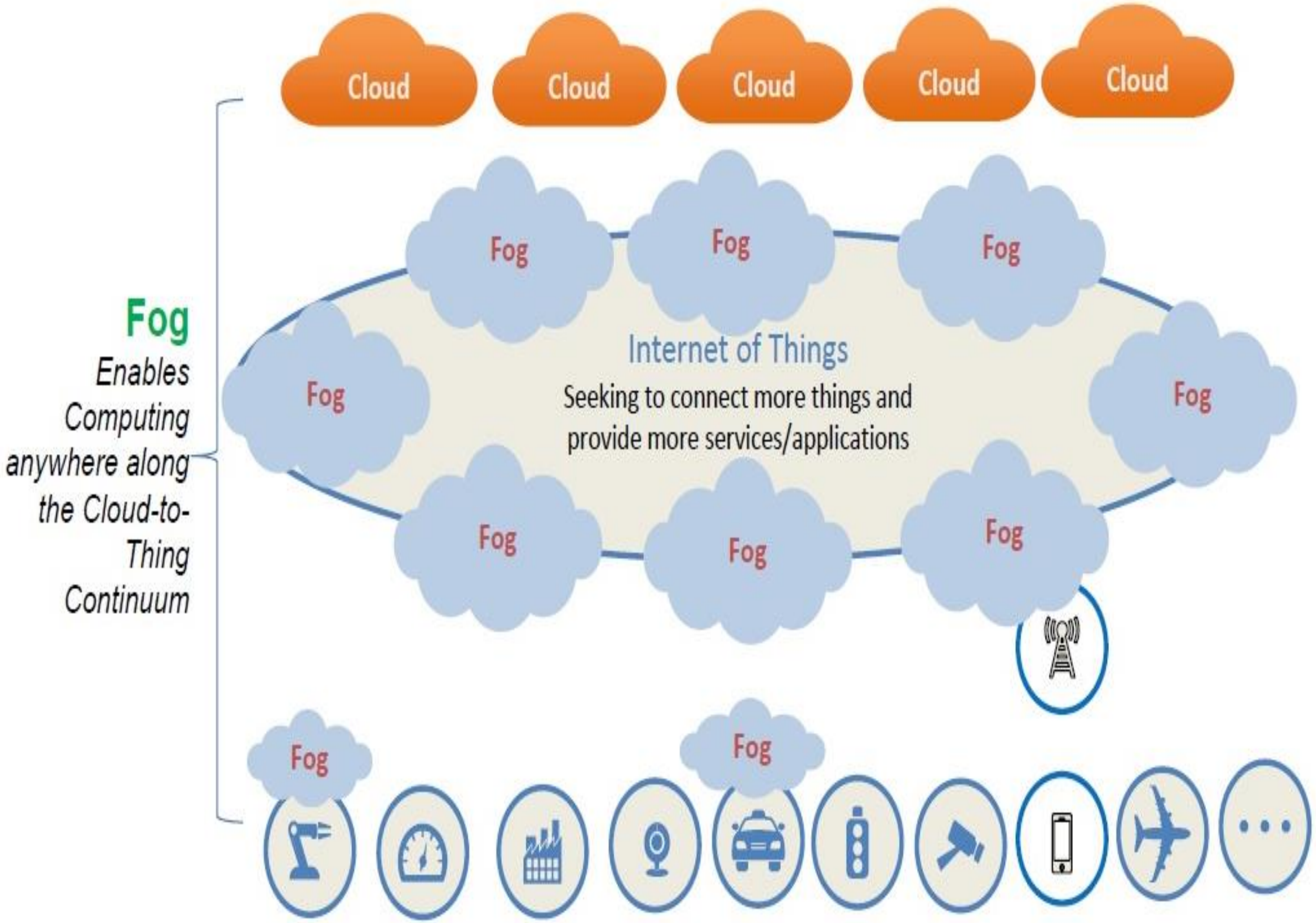


Characteristics of Fog Computing

- ✓ Proximity
- ✓ Location awareness
- ✓ Geo-distribution
- ✓ Hierarchical organization
- ✓ Pre-processing
- ✓ Mobility support
- ✓ Multimedia support
- ✓ Low latency (support realtime and interactive applications)
- ✓ Scalability
- ✓ Heterogeneity (Devices and applications)
- ✓ Interoperability and federation



Source: T. H. Luan, L. Gao, Z. Li, Y. Xiang, G. Wei, and L. Sun, "Fog Computing: Focusing on Mobile Users at the Edge," *arXiv:1502.01815 [cs]*, Feb. 2015.



T. Zhang, T. Quek, J.Huang, Ai-Chun Pang, Y. Yang, "Fog Computing and Networking:A New Paradigm for 5G and IoT Applicationns, IEEE ICC 2017

The OpenFog Consortium

Founding Members

Contributing Members

57 members and counting!

OpenFog member Companies. Retrieved from https://www.openfogconsortium.org/about-us/#member-companies

Advantages of Fog Computing

Security : Reducing the distance that information needs to traverse.

Cognition: Be better aware of and closely reflect customer requirements.

Agility: It is usually much faster and cheaper to experiment with client and edge devices

Latency: support time-sensitive control functions

Efficiency: Distribute computing, storage, and control functions anywhere between the cloud and the endpoint

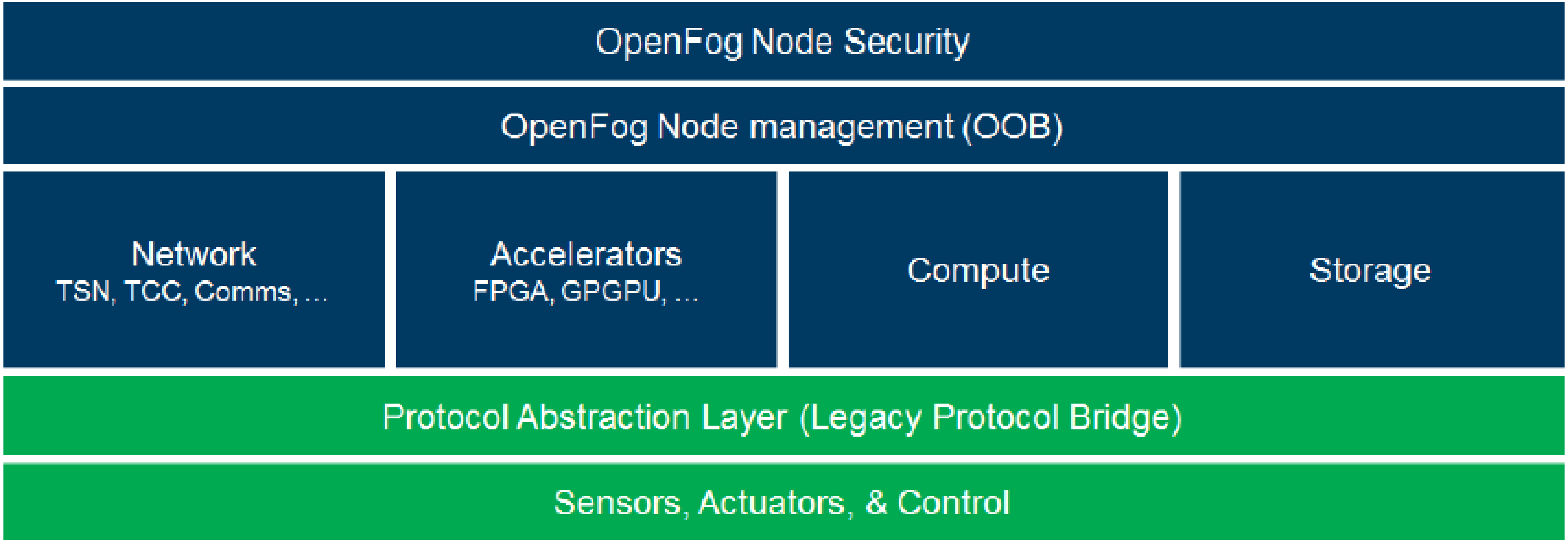
Source: "OpenFog Reference Architecture: OpenFog Consortium". Available: https://www.openfogconsortium.org/ra/ [Accessed: 24/05/2017].

Architecture Requirements

Requirement	Details
Unified computing platforms and seamless services along cloud-to-thing continuum	❑ Distribute resources/apps to large # of fogs – remote, diverse capabilities, user requirements, and operating environments ❑ Orchestrate resources in clouds, fogs, and things to enable seamless E2E services ❑ Support fog-based services: interfaces, protocols, procedures, management, …
Distributed systems and services	❑ Scalable and trustworthy monitoring ❑ Lifecycle management of resources/apps distributed over many fogs ❑ High degree of automation for managing large # of remote fog systems, apps, and resources
Hierarchical architecture	❑ Interactions and interfaces between different hierarchical levels, between fogs, between fog and cloud
Integration with Operational Technology (OT) systems	❑ Fog nodes/systems may often be closely integrated into the operations of end-user systems: machines, cars, trains, drones, actuators, controllers, sensors, ... ❑ These fogs therefore “inherit” requirements from these OT systems
Work over and inside wireless and wireline networks	❑ Moving computing into 5G Radio Access Networks (RANs), wired telecom central offices, …
Highly elastic architecture	❑ Fog systems can vary widely in size, # of users, # of applications, and requirements on performance, networks, processing capabilities, reliability, security, …
Security	❑ Protect distributed fog systems - remote, vulnerable environments, run by non-IT experts, … ❑ Handle new threats, unique operational constraints, resource constraints, … ❑ Enable fog-based security services

T. Zhang , T. Quek , J Huang, Ai-Chun Pang, Y. Yang, "Fog Computing and Networking:A New Paradigm for 5G and IoT Applicationns, IEEE ICC 2017

Fog computing - Node view

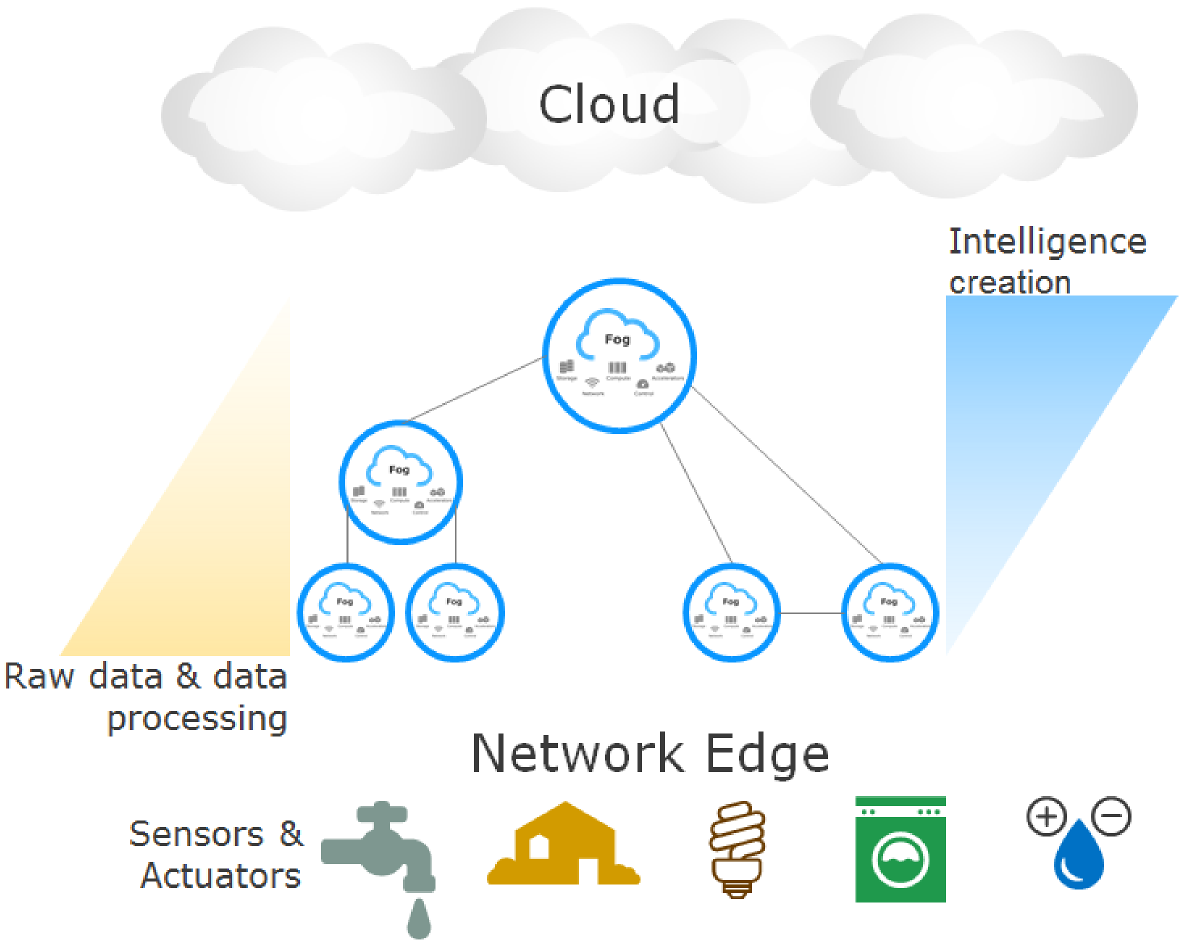


Source: "OpenFog Reference Architecture: OpenFog Consortium". Available: https://www.openfogconsortium.org/ra/ [Accessed: 24/05/2017].

Use Cases determine the number of Tiers

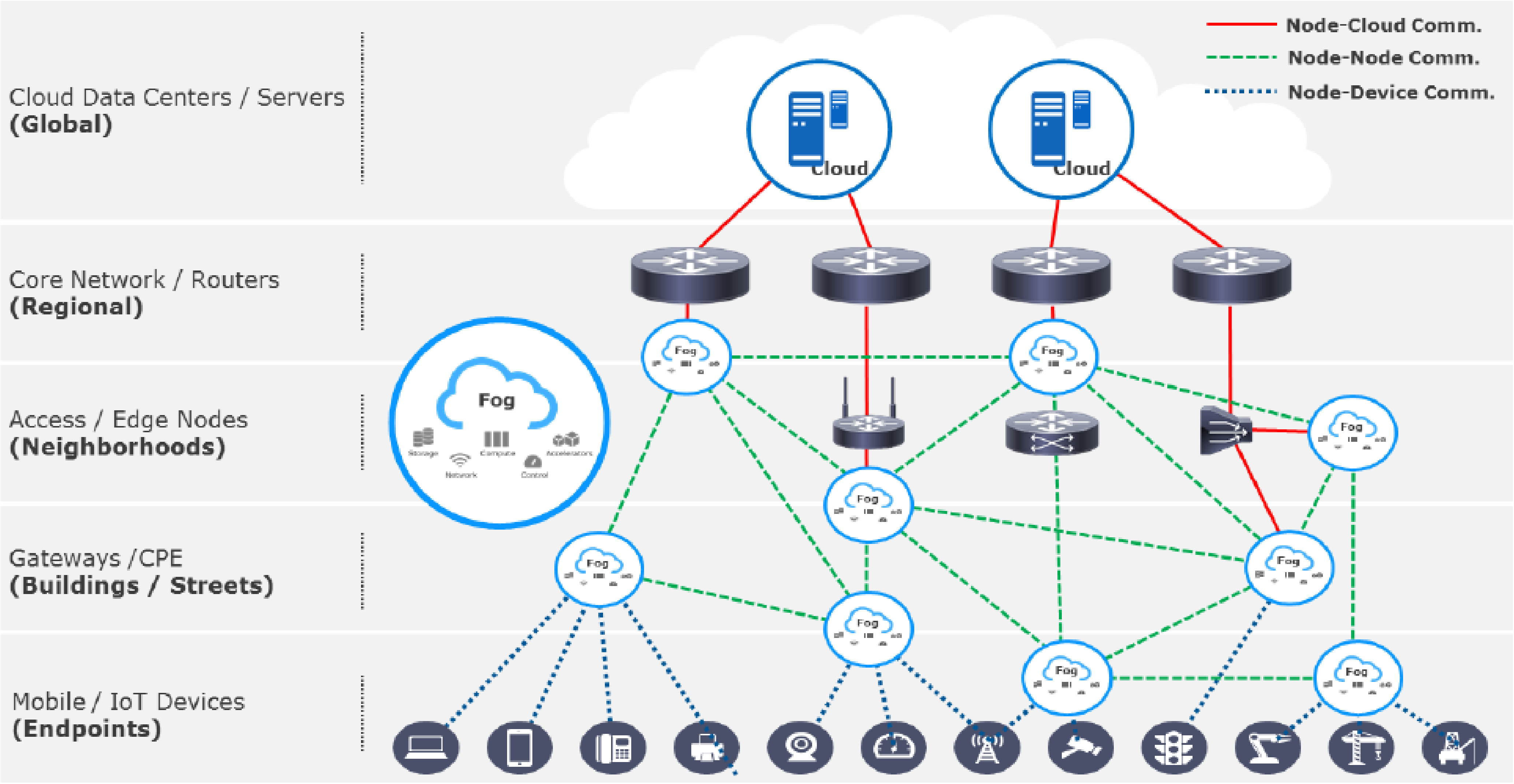
The number of tiers in a fog network depends on:

- Amount and type of work required by each tier
- Number of sensors
- Capabilities of the nodes at each tier
- Latency between nodes and latency between sensors and actuation
- Reliability/availability of nodes



Source: “OpenFog Reference Architecture: OpenFog Consortium”. Available: https://www.openfogconsortium.org/ra/ [Accessed: 24/05/2017].

OpenFog Secure Communication Pathways

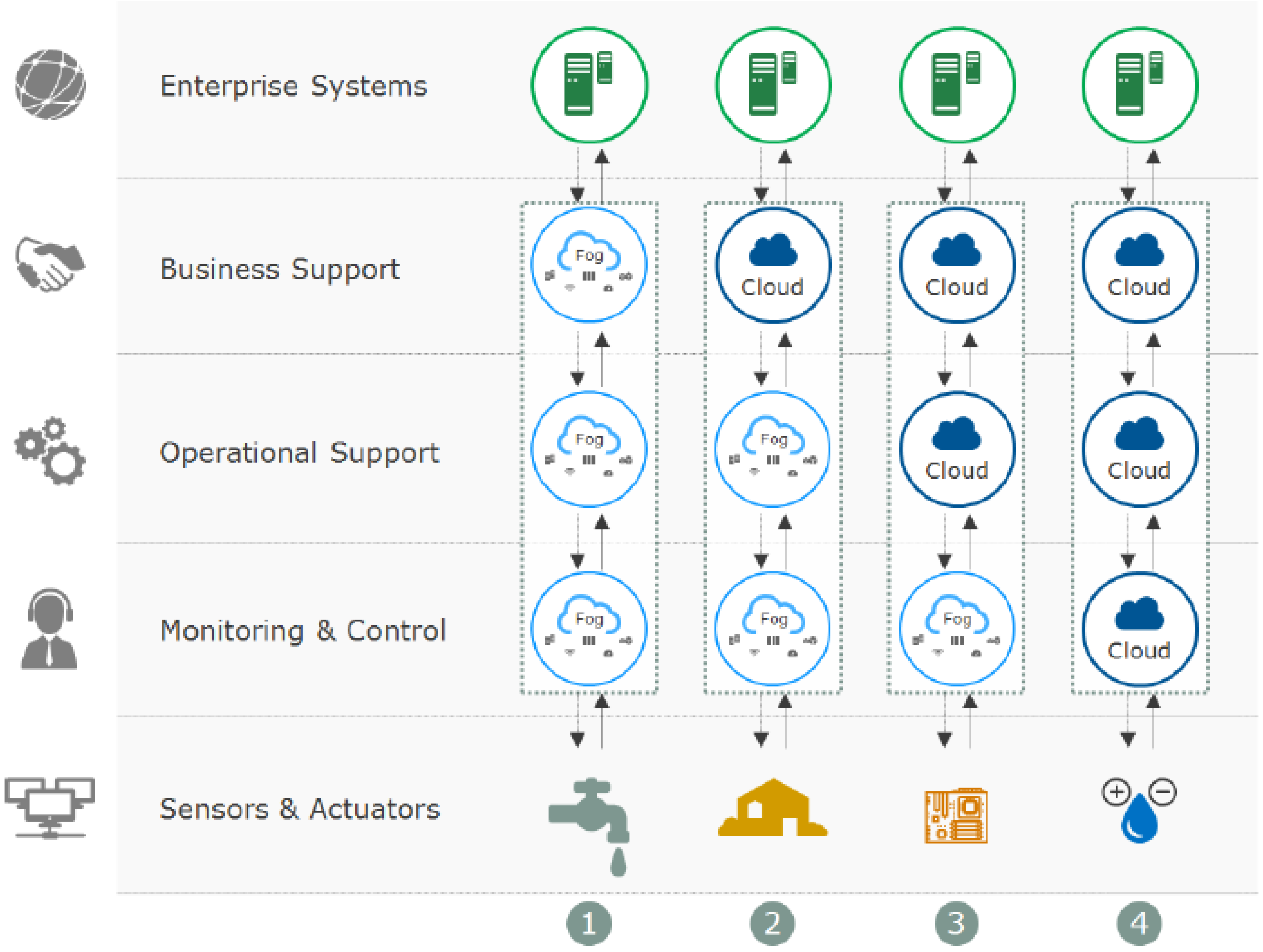


Source: "OpenFog Reference Architecture: OpenFog Consortium". Available: https://www.openfogconsortium.org/ra/ [Accessed: 24/05/2017].

Hierarchical Fog Deployment Models

- Depending on the scenario, multiple Fog and Cloud elements may collapse into a single physical deployment.

- Each fog element may also represent a mesh of peer fog nodes



Source: "OpenFog Reference Architecture: OpenFog Consortium". Available: https://www.openfogconsortium.org/ra/ [Accessed: 24/05/2017].

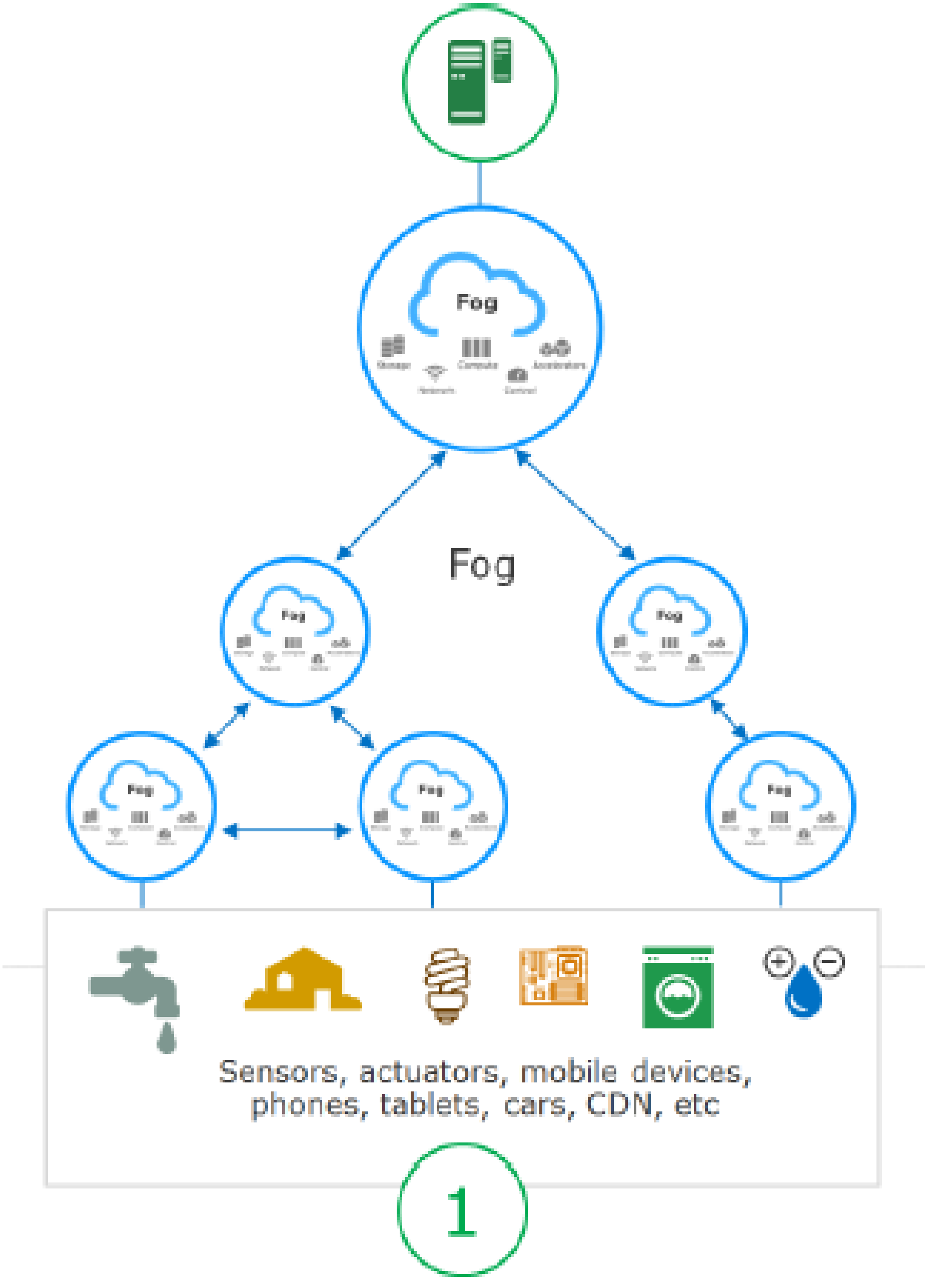
Independent of the Cloud

Context:

- Low event to action time window
- Regulatory compliance,
- Military grade security and privacy
- Unavailability of a central cloud in a particular geography.

Use cases:

- Armed forces combat systems
- Drone operations
- Healthcare systems
- Hospitals
- ATM banking systems.



Source: “OpenFog Reference Architecture: OpenFog Consortium”. Available: https://www.openfogconsortium.org/ra/ [Accessed: 24/05/2017].

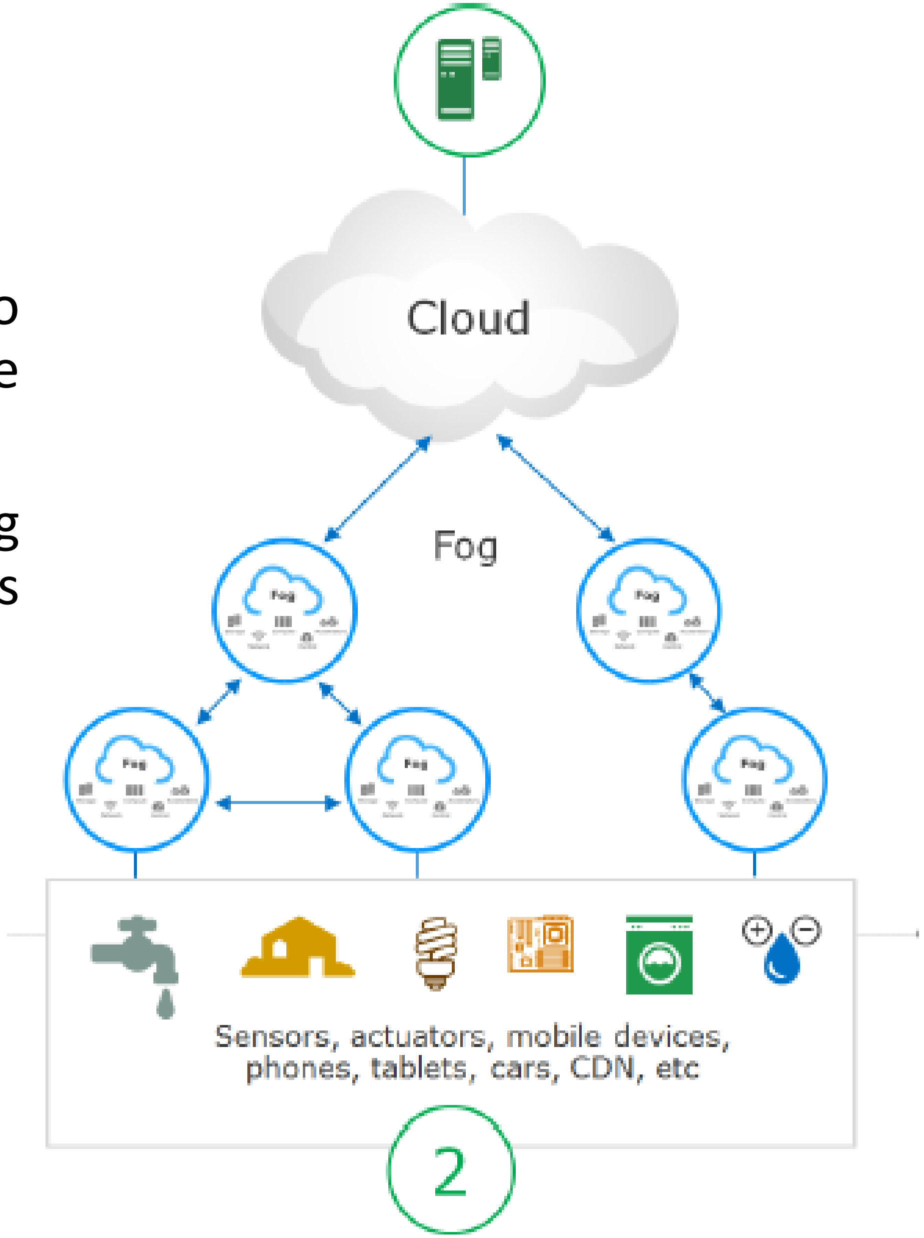
MultiFog + Cloud

Context:

- The cloud is used for information processing related to decision making that may have event-to-action time window ranging from hours to days to months.
- Operation-centric information processing is done by fog deployments located close to the infrastructure/process being managed.

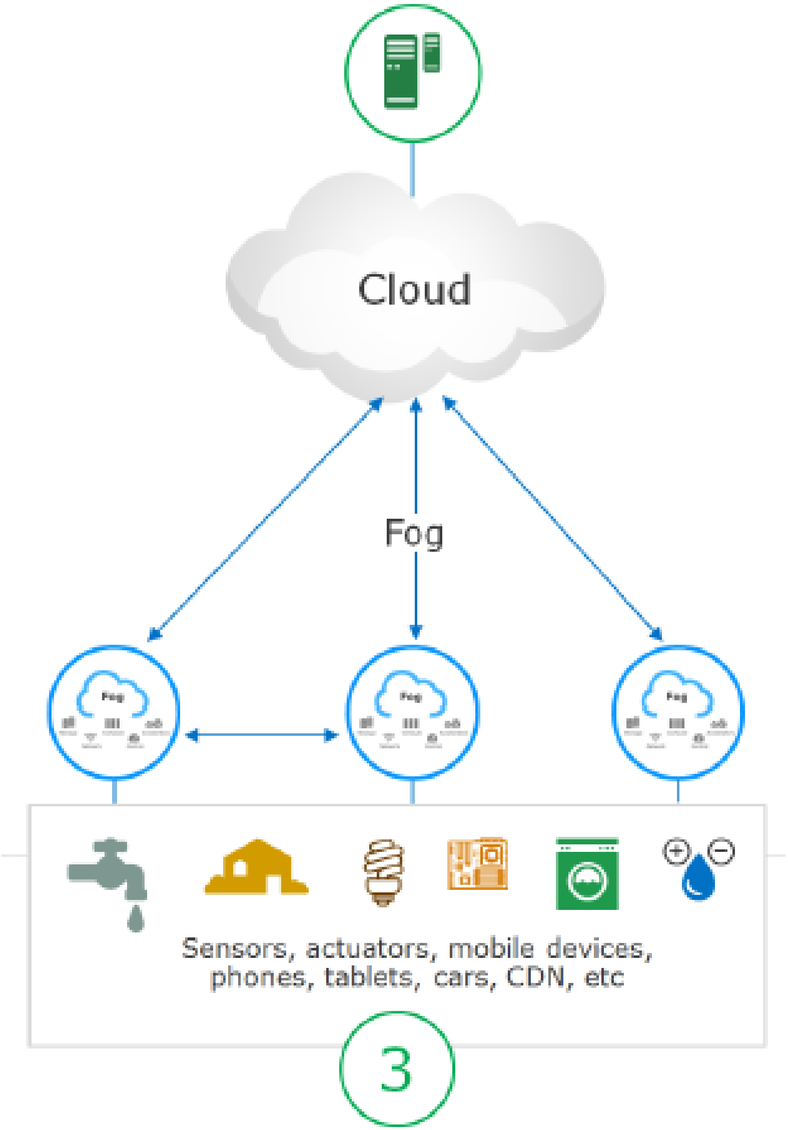
Use cases:

- Commercial building management,
- Commercial solar panel monitoring,
- Retail.



Source: "OpenFog Reference Architecture: OpenFog Consortium". Available: https://www.openfogconsortium.org/ra/ [Accessed: 24/05/2017].

Fog to Cloud



Context:

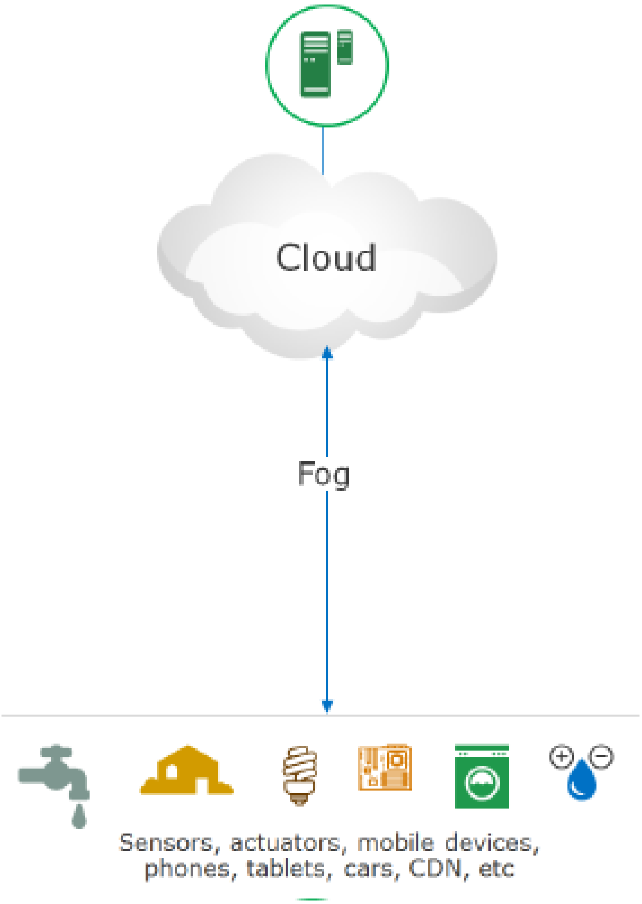
The local fog infrastructure used for time-sensitive computation, while the cloud is used for the balance of operational and business-related information processing.

Use cases:

- Commercial UPS device monitoring,
- Mobile network acceleration,
- Content delivery networks (CDNs) for Internet acceleration.

Source: "OpenFog Reference Architecture: OpenFog Consortium". Available: https://www.openfogconsortium.org/ra/ [Accessed: 24/05/2017].

Only Cloud



- **Context:**
- These use cases leverage the cloud for the entire stack due to the constrained environments in which the deployment of fog infrastructure may not be feasible or economical.

- **Use cases:**
- Agriculture
- Connected cars
- Remote weather stations.
- The enterprise systems integrate with cloud for business operations.

Source: "OpenFog Reference Architecture: OpenFog Consortium". Available: https://www.openfogconsortium.org/ra/ [Accessed: 24/05/2017].

Fog Predecessors

..

Mobile Cloud Computing (MCC)

Figure 1

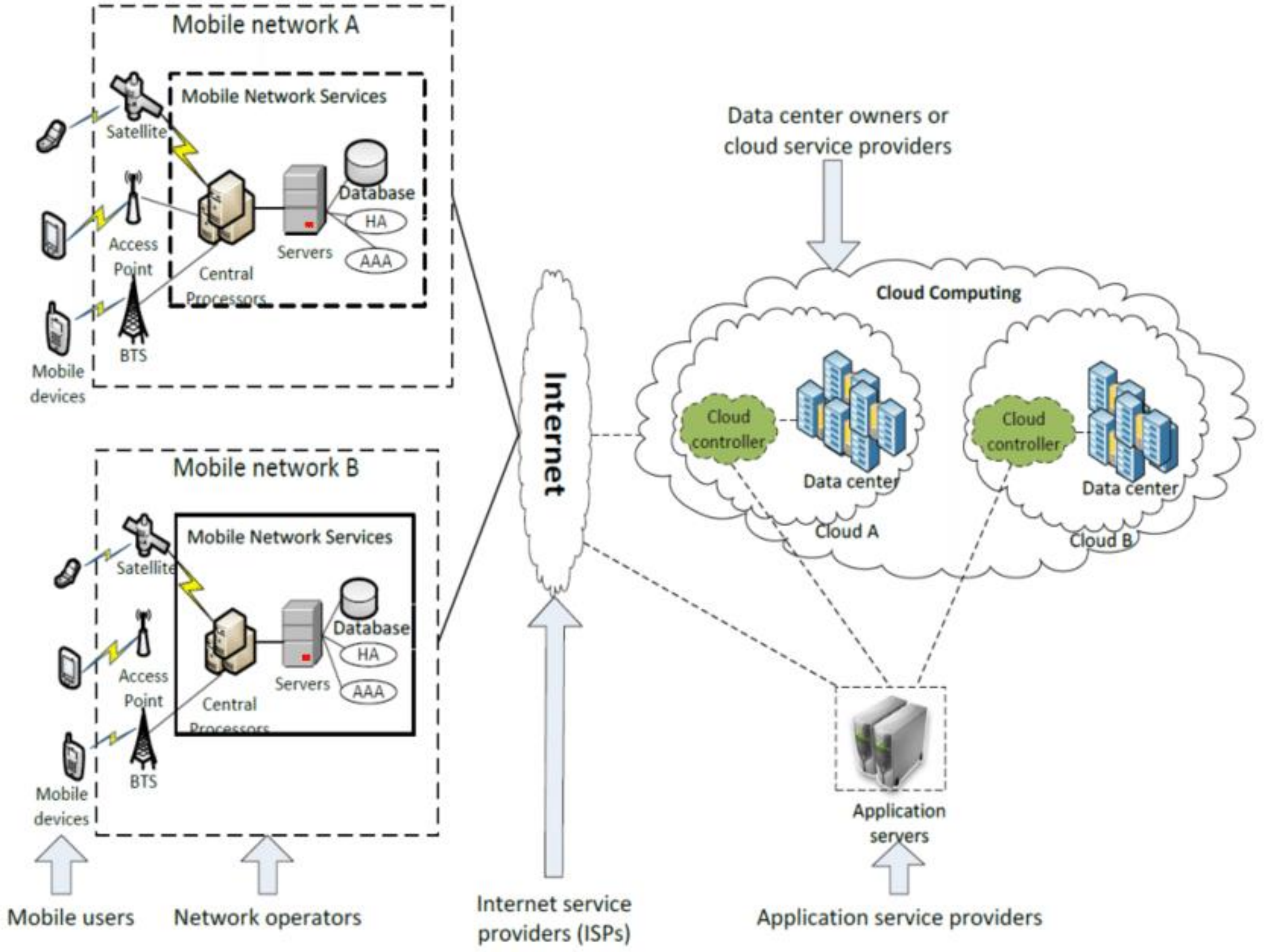


Figure 2

Figure 1. Mobile Cloud Computing (MCC). Retrieved from https://www.researchgate.net/figure/310598856_fig1_Fig1-Mobile-Cloud-Computing-MCC-Architecture-18
Figure 2. Mobile Cloud Processing. Retrieved from http://www.techweez.com/2013/09/24/optimization-offloading-strategies-mobile-cloud-computing/

Cloudlet

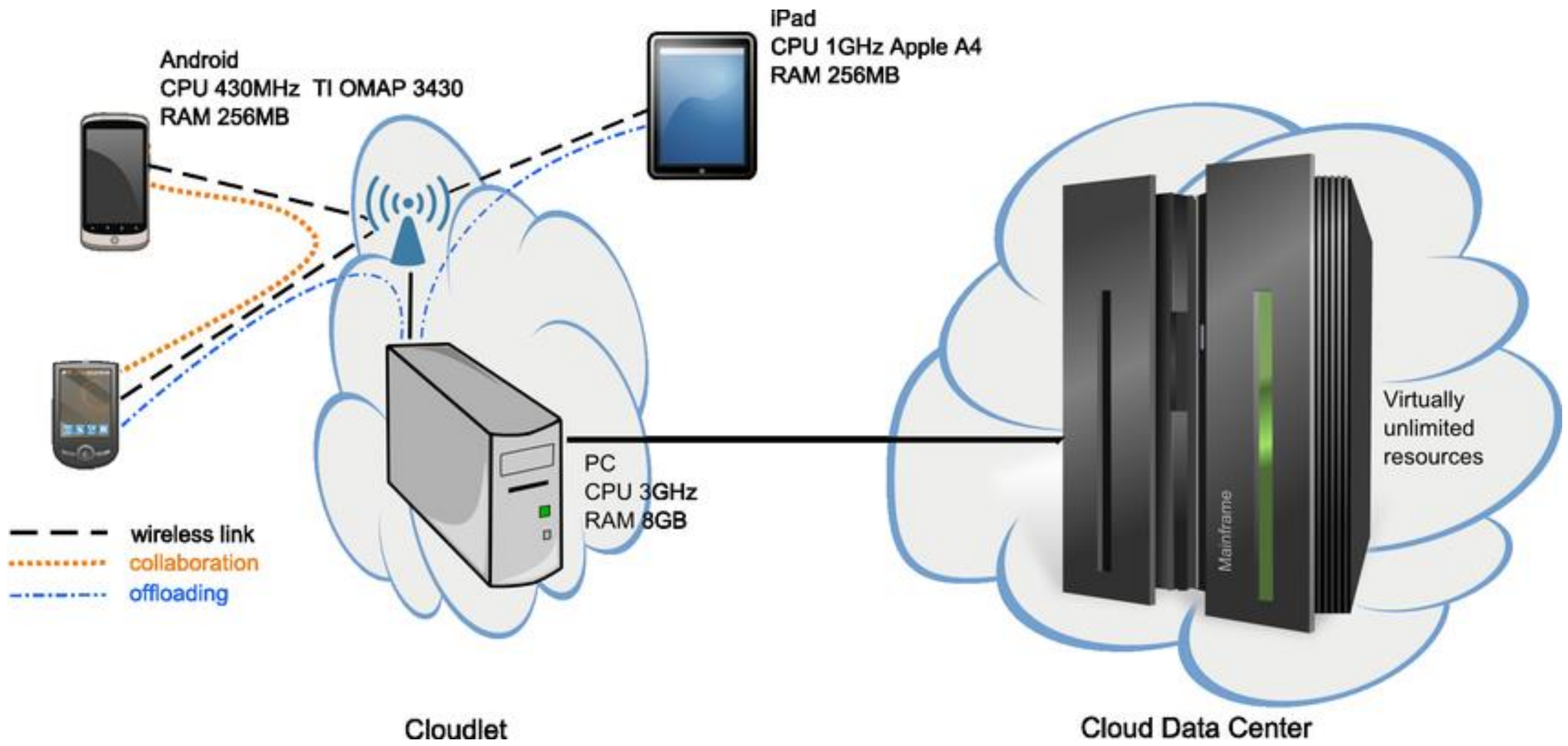


Figure 3

Figure 3. Mobile devices accessing nearby connected cloudlet and large cloud data centers via Internet. Retrieved from https://www.researchgate.net/figure/285321513_fig1_Fig-1-Mobile-devices-accessing-nearby-connected-cloudlet-and-large-cloud-data-centers.

Micro datacenter (mDC)

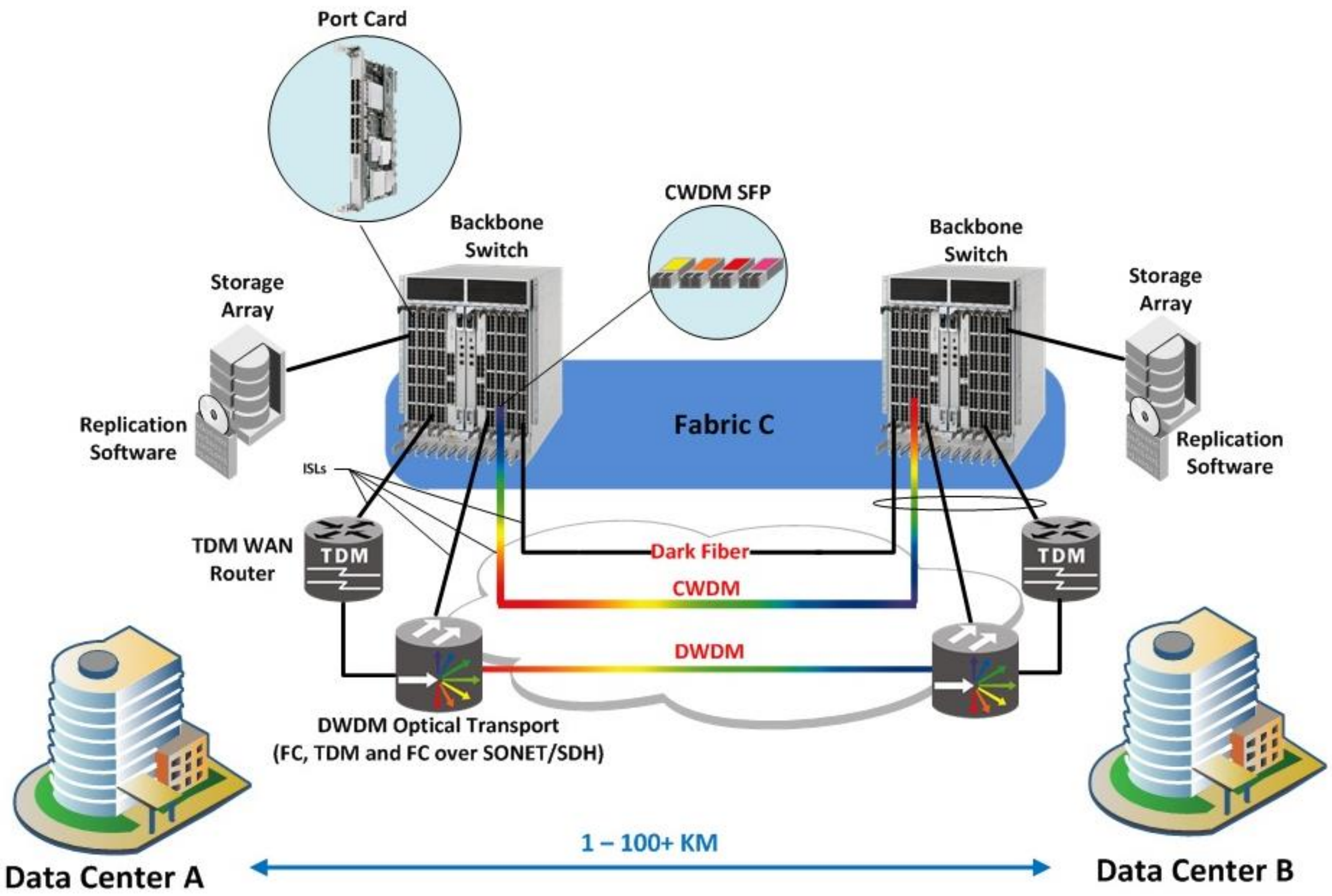


Figure 4

Figure 4. Datacenter infrastructure. Retrieved from https://www.google.com.br/imgres?imgurl=http://community.brocade.com/legacyfs/online/11516_DesignTopology_Base.jpg&imgrefurl=http://community.brocade.com/t5/Design-Build/Data-Center-Infrastructure-Storage-Design-Guide-SAN-Distance/ta-p/36627&h=622&w=922&tbnid=_gxqLAUuOzerOM&tbnh=184&tbnw=273&usg=__TPFaeS4TuRAOx_OlKe5PD9ZB5b8=&hl=pt&docid=UXBhieH1AQrRBM

Mobile edge computing (MEC)

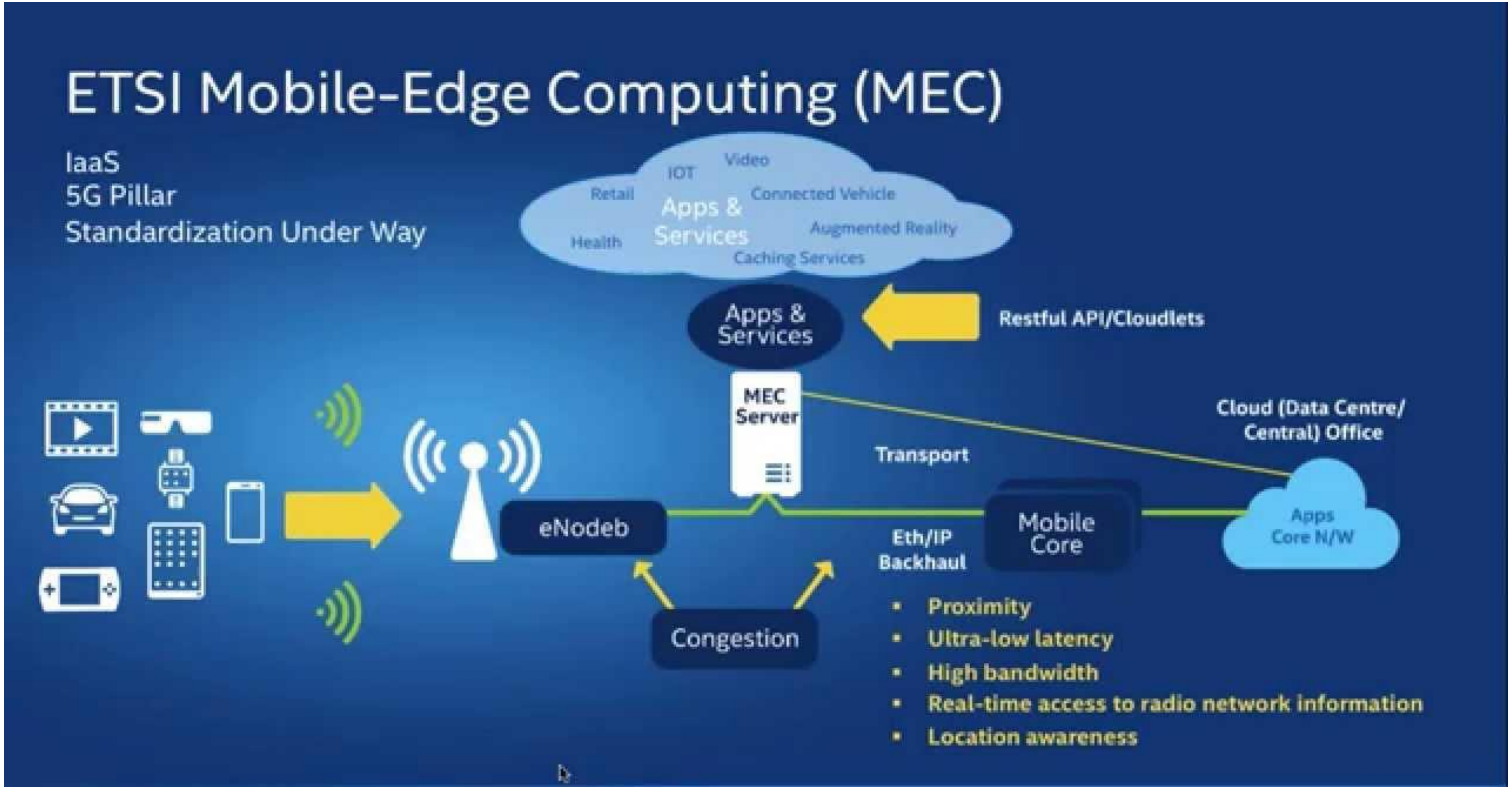


Figure 5

Figure 5. MEC architecture. Retrieved from https://www.youtube.com/watch?annotation_id=annotation_3594496571&feature=iv&src_vid=O2dDxQcuY-0&v=75VWiDM71Wc.

Characteristics for variants of edge computing

	Cloudlets	Fog Computing	Mobile Edge Computing	Micro-Data Centre
Rapid Response	No	Yes	Yes	Yes
Latency	Low	Low	Low	Low
Mobility	Yes	Yes	Yes	Yes
Enterprise User	Local and Smart City Enterprise	Security industry and network providers	Telecommunication and Software Providers	Hardware
Security Provider	None	Service Provider	Service Provider and Hosted enterprise	Service Provider
Service Level Agreement	None	Essential	Essential	Essential
Academic research input	High	Moderate	Moderate	Low

Cloud computing - Architecture

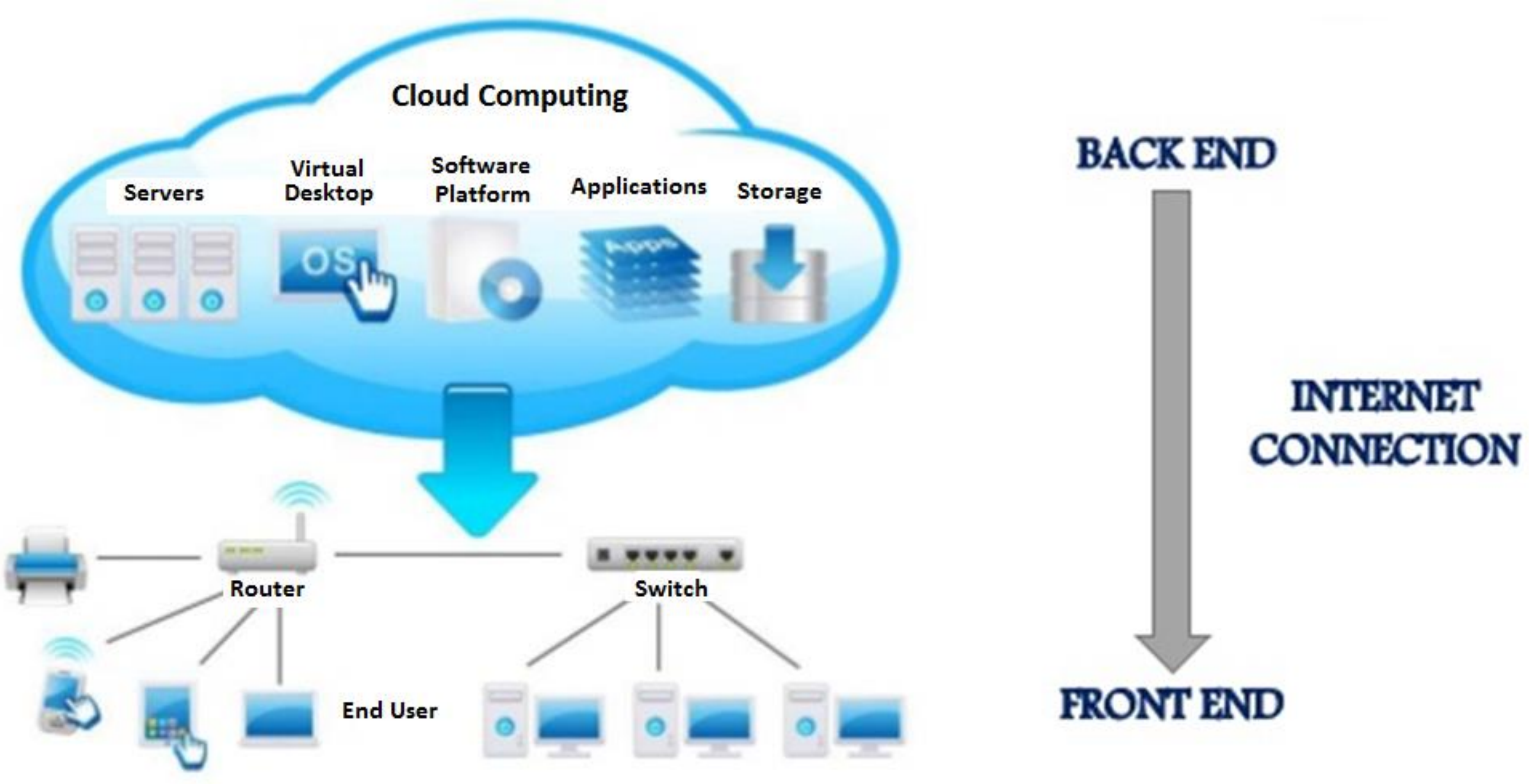


Figure 6

Figure 6. Cloud Computing: A new Trend **https://pt.slideshare.net/DebidattaSatapathy/cloud-computing-a-new-trend**

Cloud computing - Types of cloud

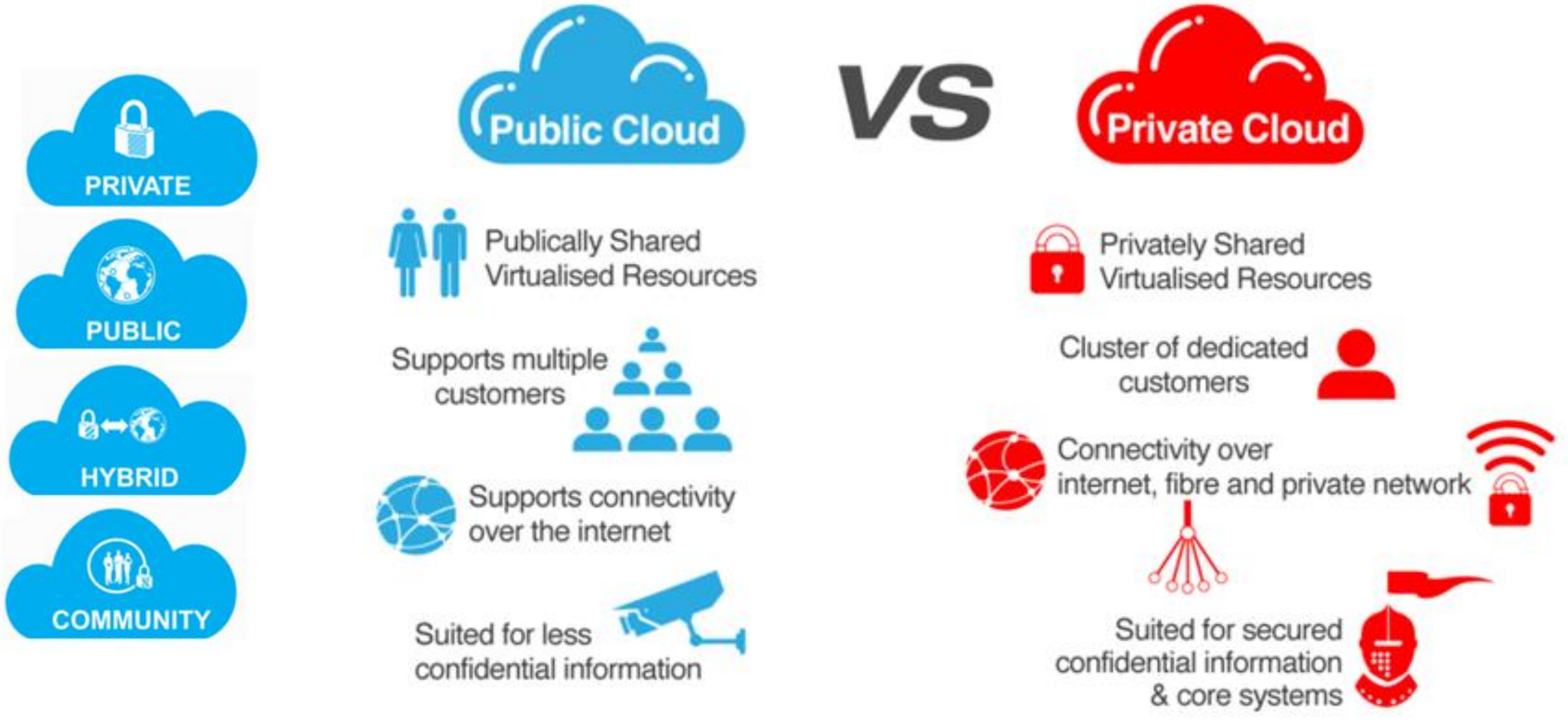


Figure 7

Figure 7. What is a Public Cloud? Discover Top Rated Public Cloud Computing Providers, Services, Security & Technologies. Retrieved from http://cloudnewsdaily.com/public-cloud/

Cloud computing – Public Clouds Vs. Private Clouds

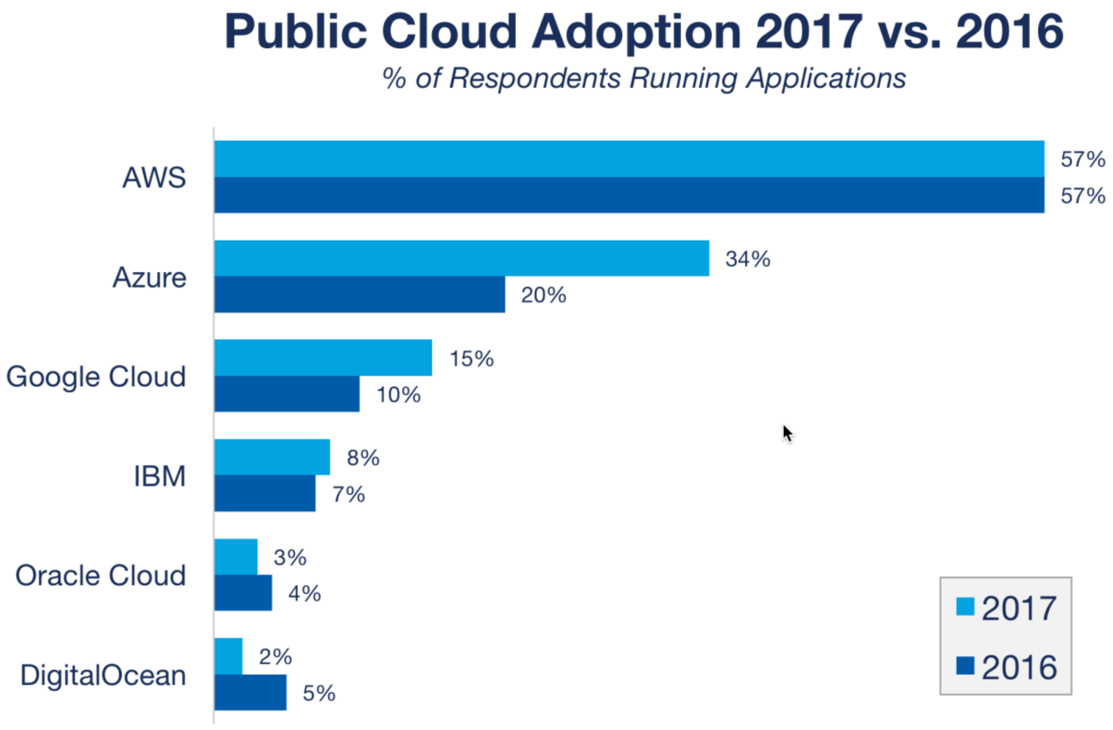


Figure 8.1

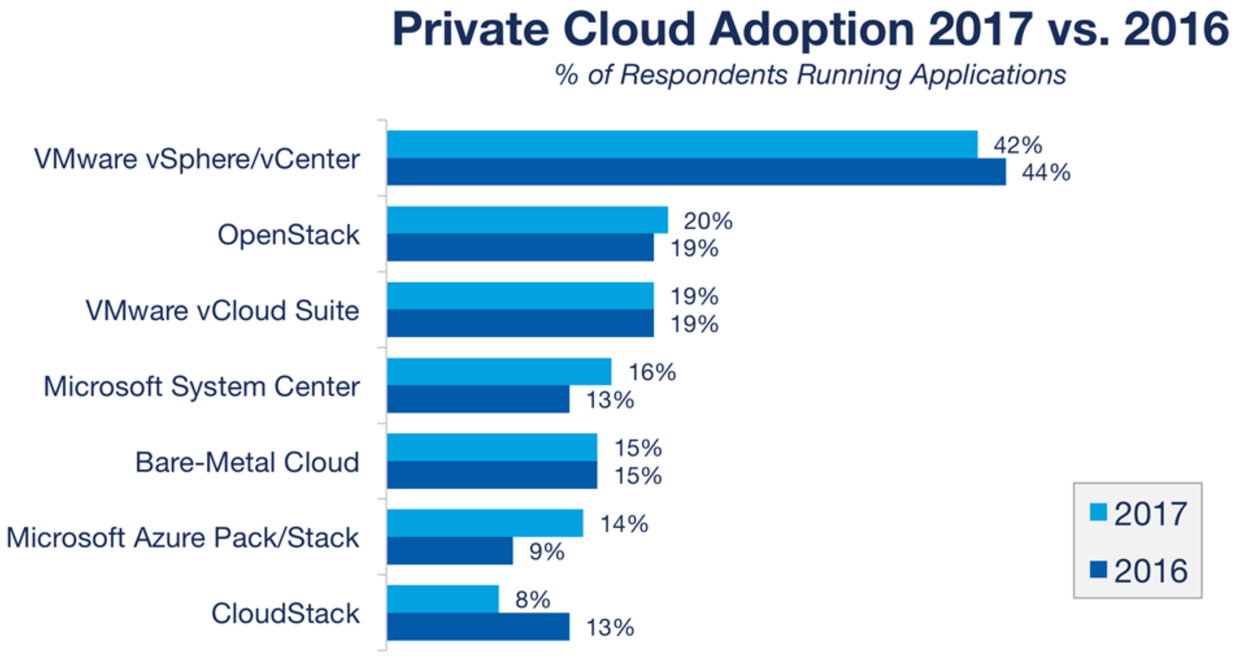


Figure 8.2

Figure 8.1, 8.2. Cloud Computing Trends: 2017 State of the Cloud Survey. Retrieved from http://www.rightscale.com/blog/cloud-industry-insights/cloud-computing-trends-2017-state-cloud-survey

Cloud computing – Services offered

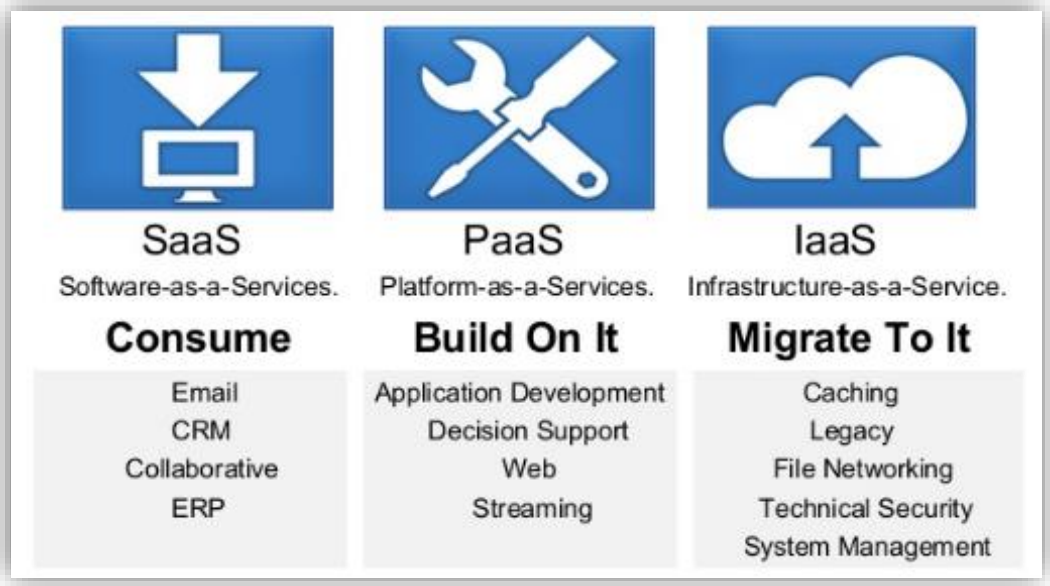


Figure 9.1

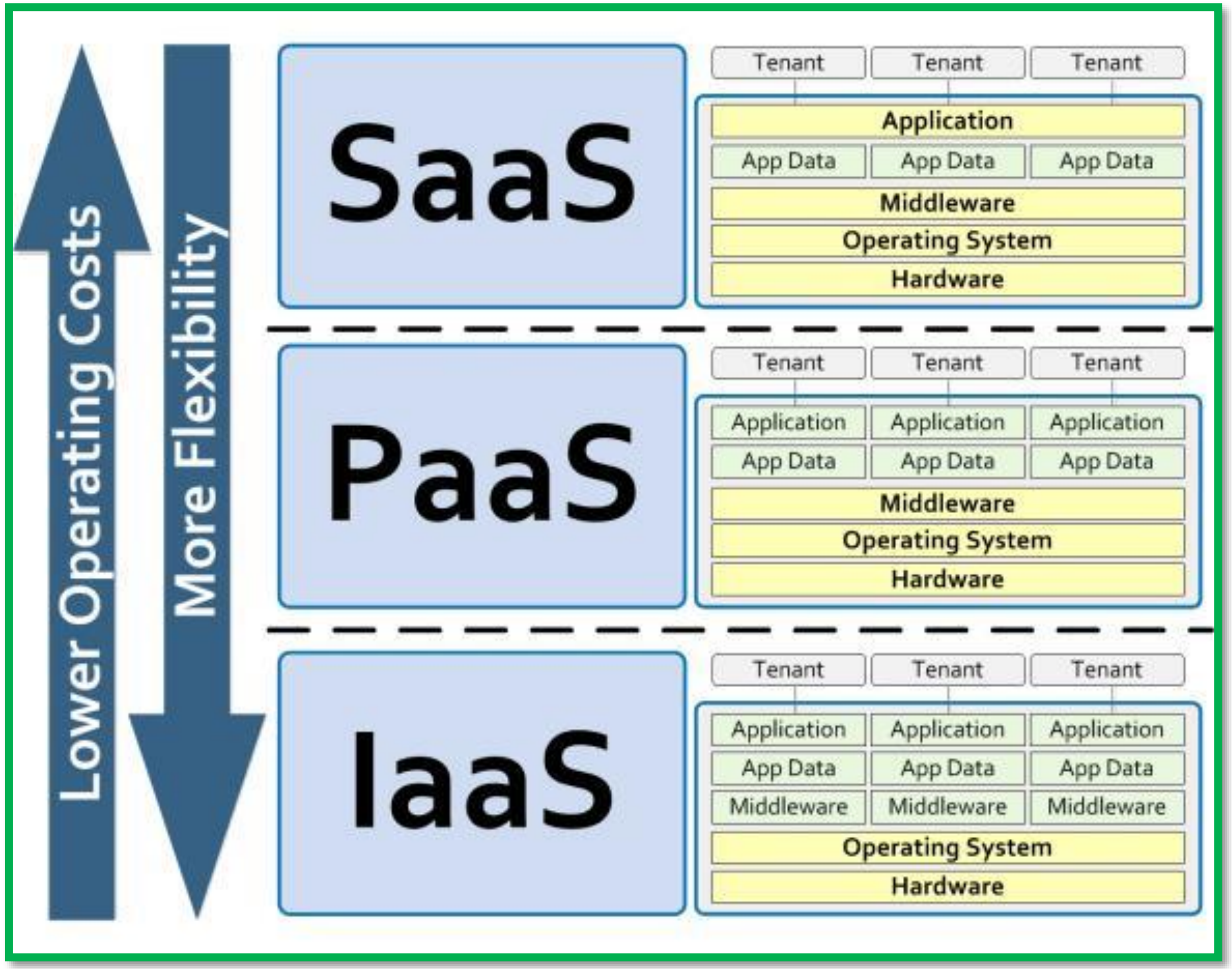
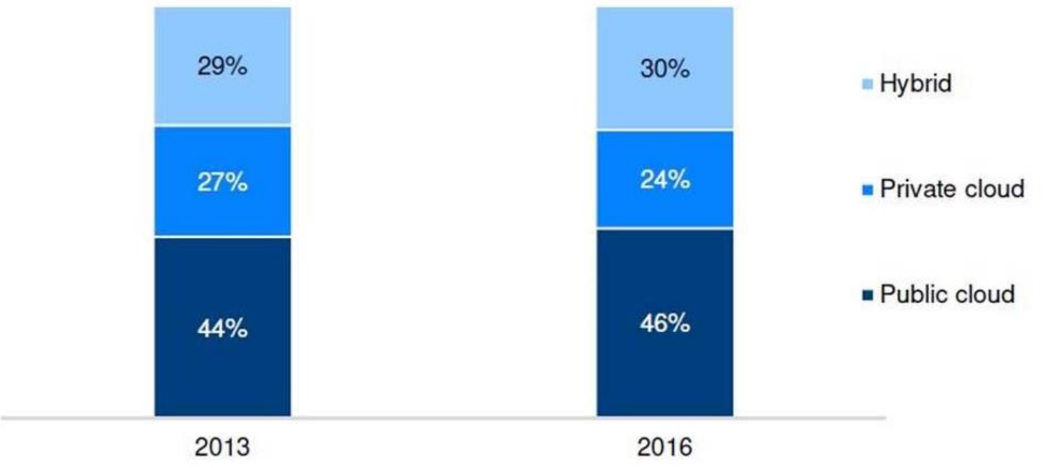


Figure 9.2

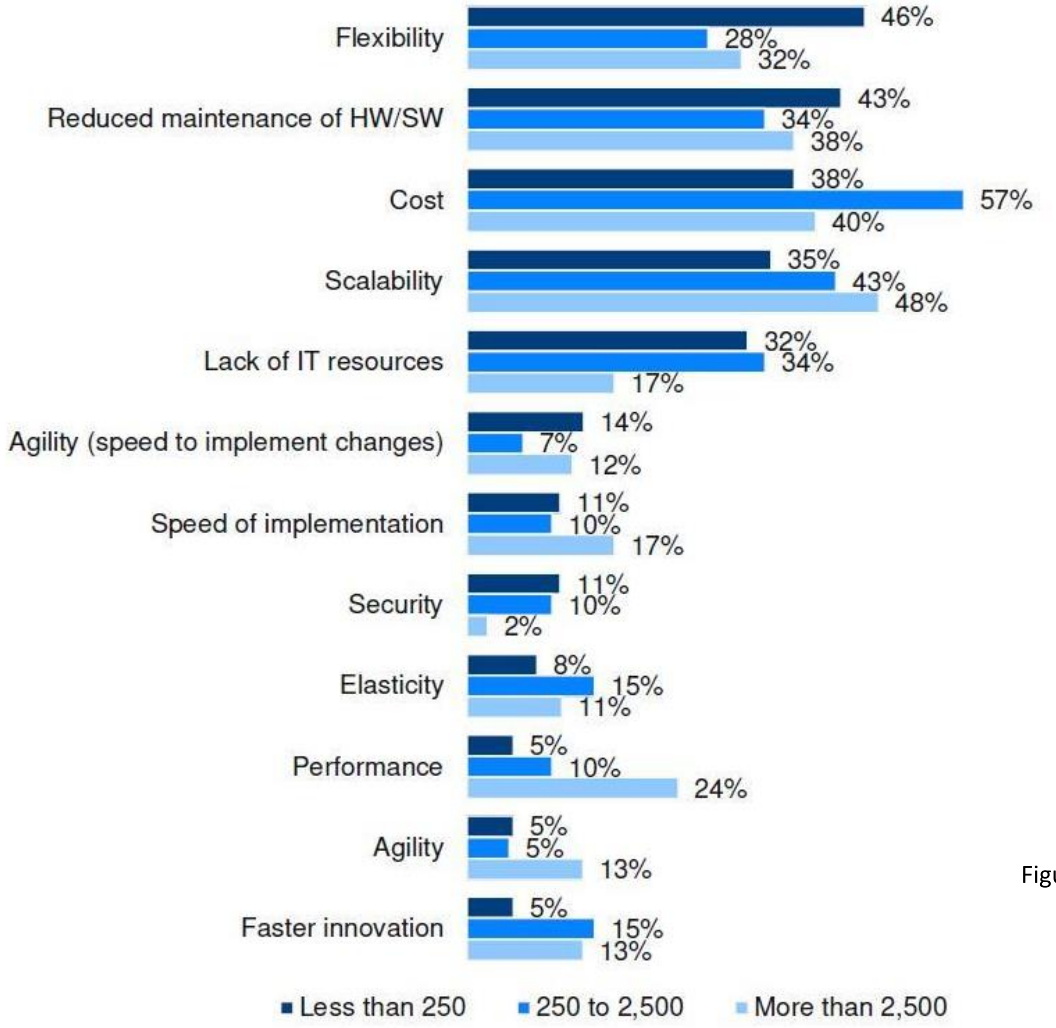
Figure 9.1. Cloud computing. Retrieved from https://www.tcnp3.com/home/cloud-technology/what-is-cloud-computing-infographic/
Figure 9.2 types of Cloud computing. Retrieved from https://www.linkedin.com/pulse/cloud-computing-vs-big-data-synonyms-acronyms-girish-khole

Cloud computing



What type of cloud infrastructure do you use to support your BI and data management initiative? TechTarget 2013 (n=278), BARC 2016 (n=163)

Figure 10.1

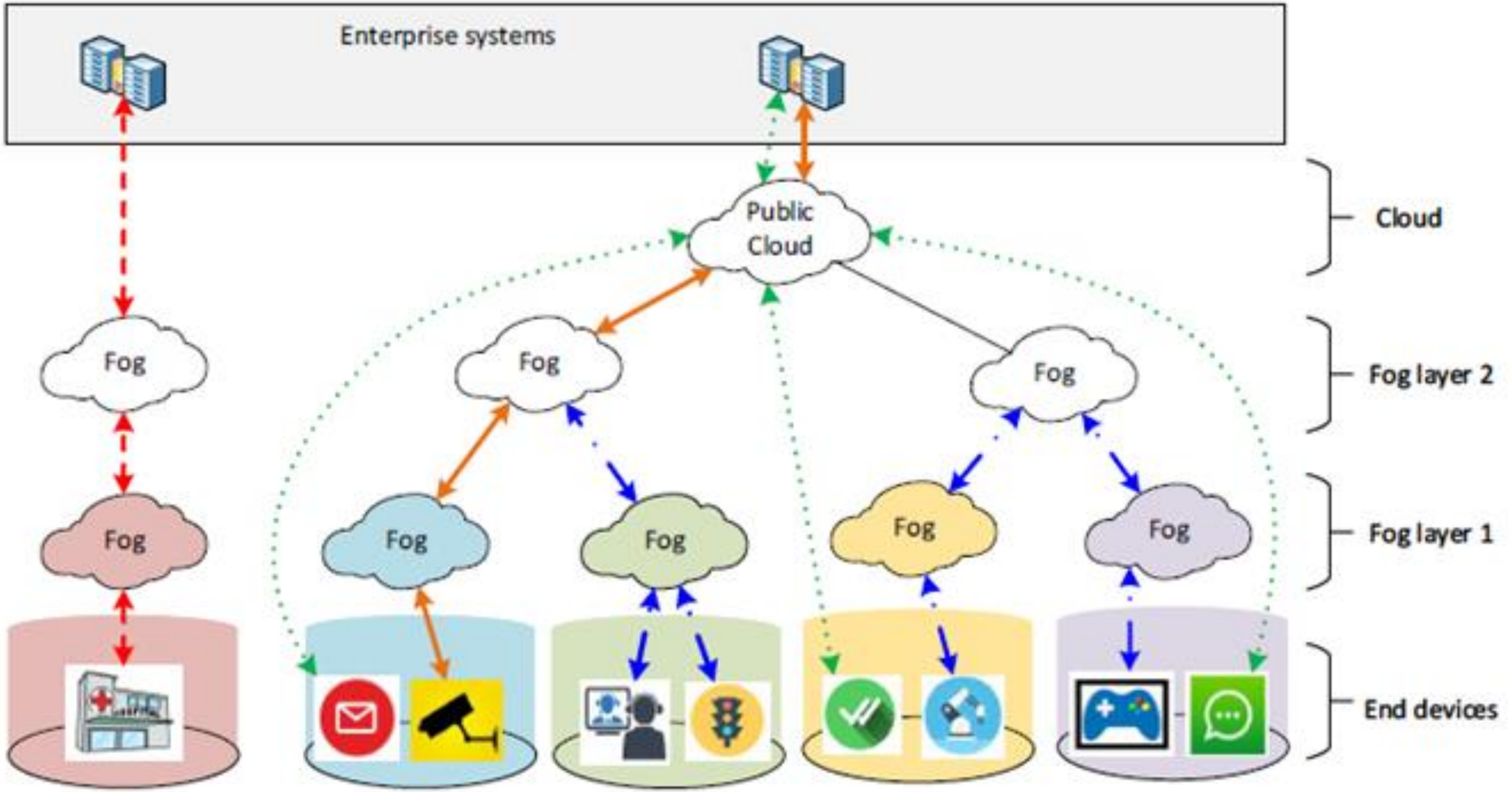


Most important reasons for implementing BI and data management in the cloud by company size (n=162)

Figure 10.2

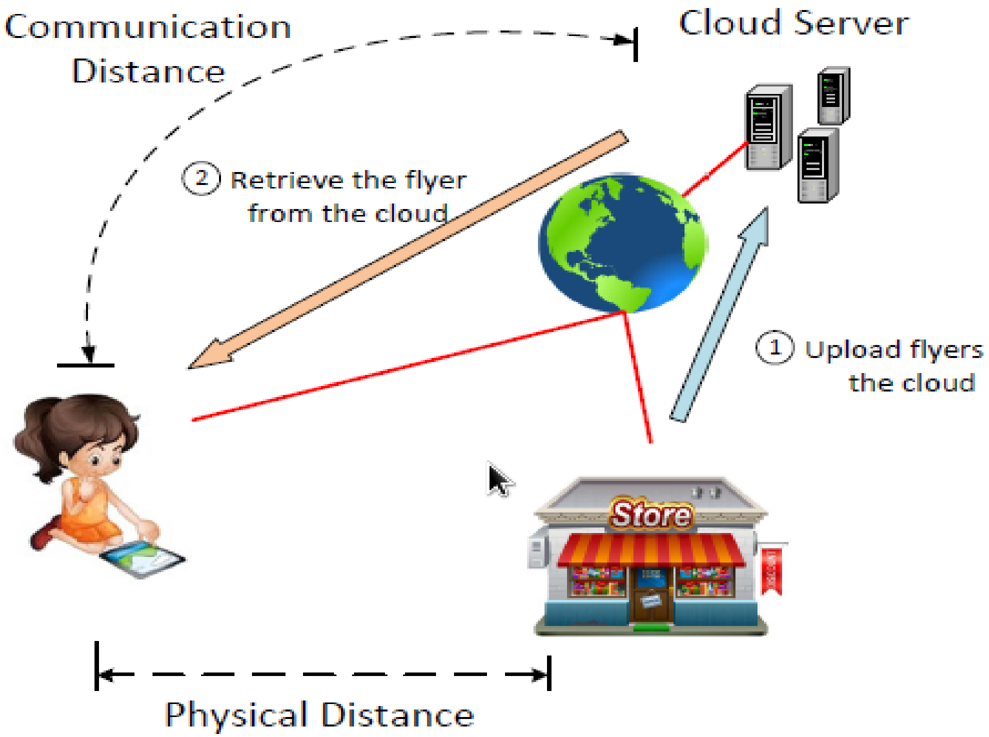
Figure 10.1, 10.2. Business Intelligence And Analytics In The Cloud, 2017 Retrieved from https://www.forbes.com/sites/louiscolumbus/2017/02/26/business-intelligence-and-analytics-in-the-cloud-2017/#2946e0c1a289

Fog Computing – Architecture



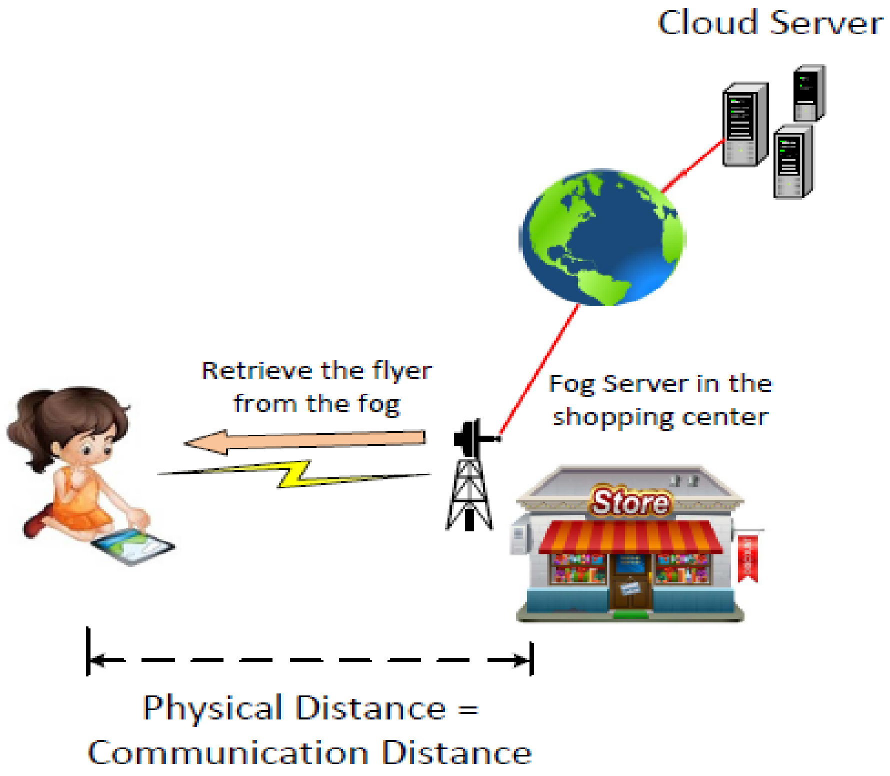
Cloud Computing Vs. Fog Computing

Cloud computing



(a) Retrieving the flyer from the cloud

Fog computing



(b) Retrieving the flyer from the fog

Figure 11

Figure 11. Example: download the flyer of a nearby store. Retrieved from T. H. Luan, L. Gao, Z. Li, Y. Xiang, G. We, and L. Sun, "A View of Fog Computing from Networking Perspective," *arXiv:1602.01509 [cs]*, Feb. 2016.

Fog Computing Vs. Cloud Computing

	Fog computing	Cloud Computing
Size	The size is flexible.	The size is fixed.
Target user	Mobile users	General Internet users.
Service Type	Limited localized information services related to specific deployment locations	Global information collected from worldwide
Hardware	Limited storage, compute power and wireless interface	Ample and scalable storage space and compute power
Distance to users	In the physical proximity and communicate through single-hop wireless connection	Faraway from users and communicate through IP networks
Working environment	Outdoor (streets, parklands, etc.) or indoor (restaurants, shopping malls, etc.)	Warehouse-size building with air conditioning systems
Deployment	Centralized or distributed in reginal areas by local business (local telecommunication vendor, shopping mall retailer, etc.)	Centralized and maintained by Amazon, Google, etc.

Source: T. H. Luan, L. Gao, Z. Li, Y. Xiang, G. Wei, and L. Sun, “Fog Computing: Focusing on Mobile Users at the Edge,” *arXiv:1502.01815 [cs]*, Feb. 2015.

IoT and Fog computing

The Internet of Things (IoT)

Often refers to a set of services and applications

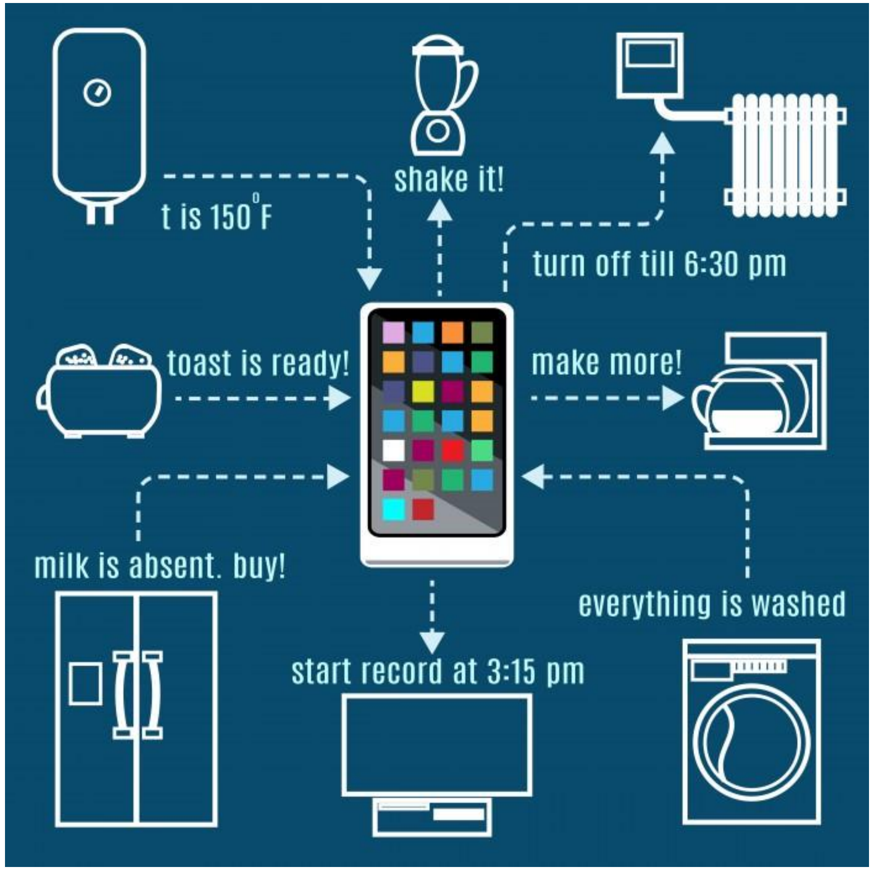
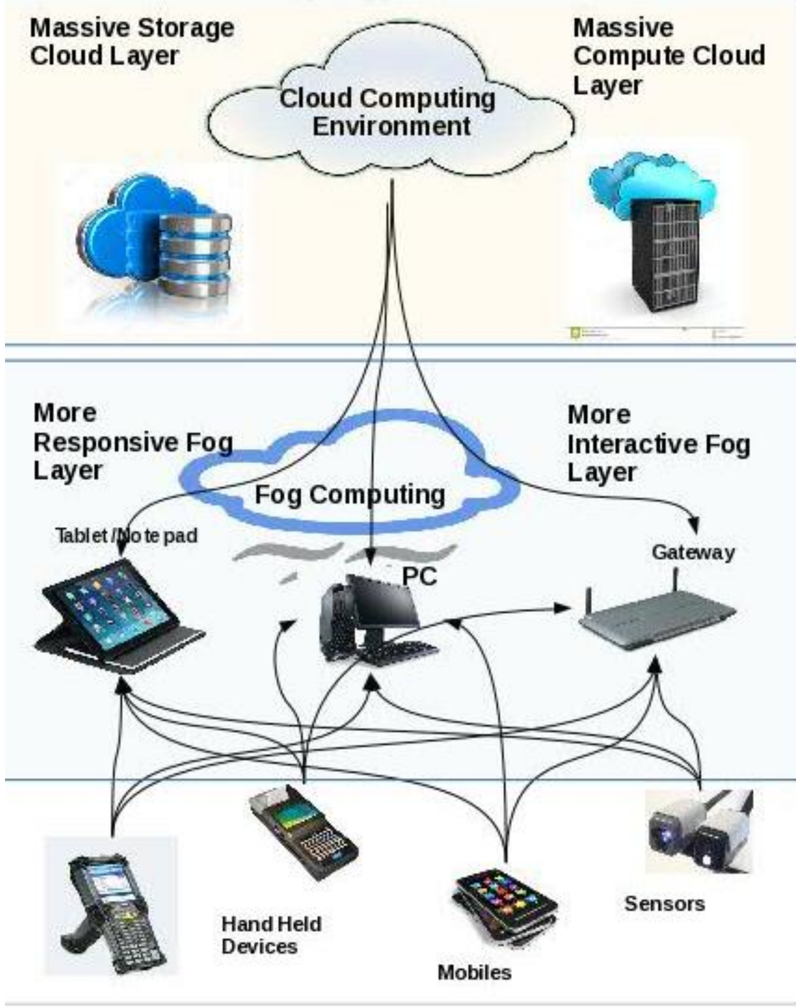


Figure 12

Figure 12. SIoT, Retrieved from http://www.akuaroworld.com/iot-a-world-totally-hyper-connected/

Fog computing

Is a distributed architecture

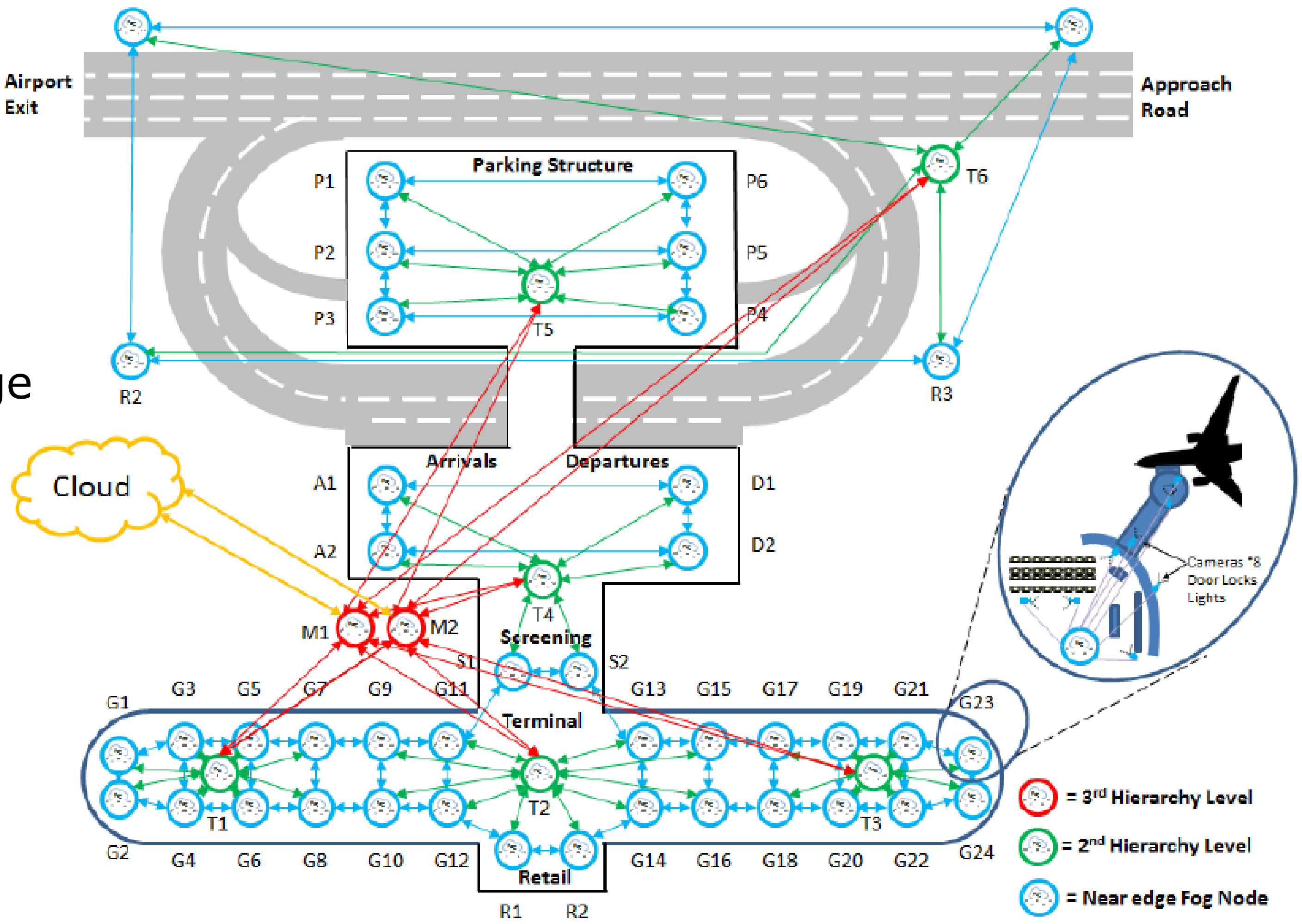


Examples

Use case Airport - Visual security (surveillance): A Fog scenario

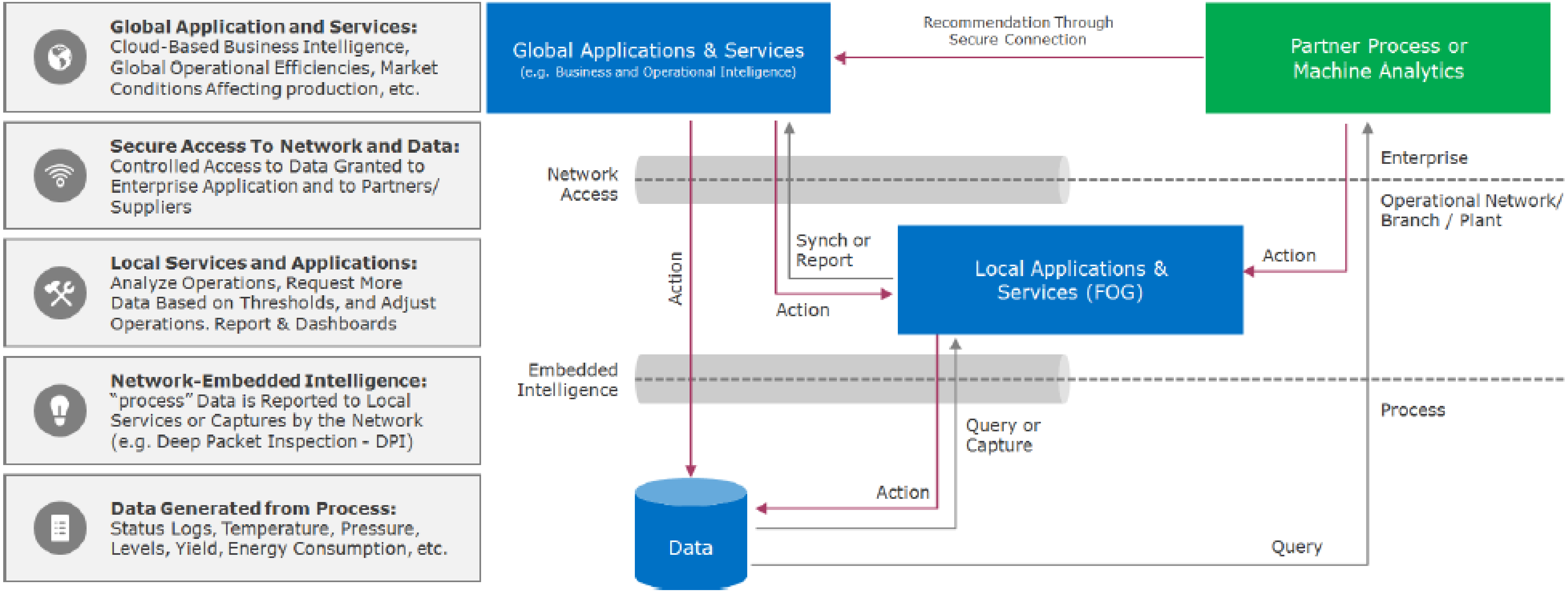
Let's look at the passenger's journey:

- Leaves from home and drives to the airport
- Parks in the long-term parking garage
- Takes bags to airport security checkpoint
- Bags are scanned and checked in
- Checks in through security and proceeds to boarding gate
- Upon arrival, retrieves bags
- Proceeds to rental car agency;
- Leaves airport



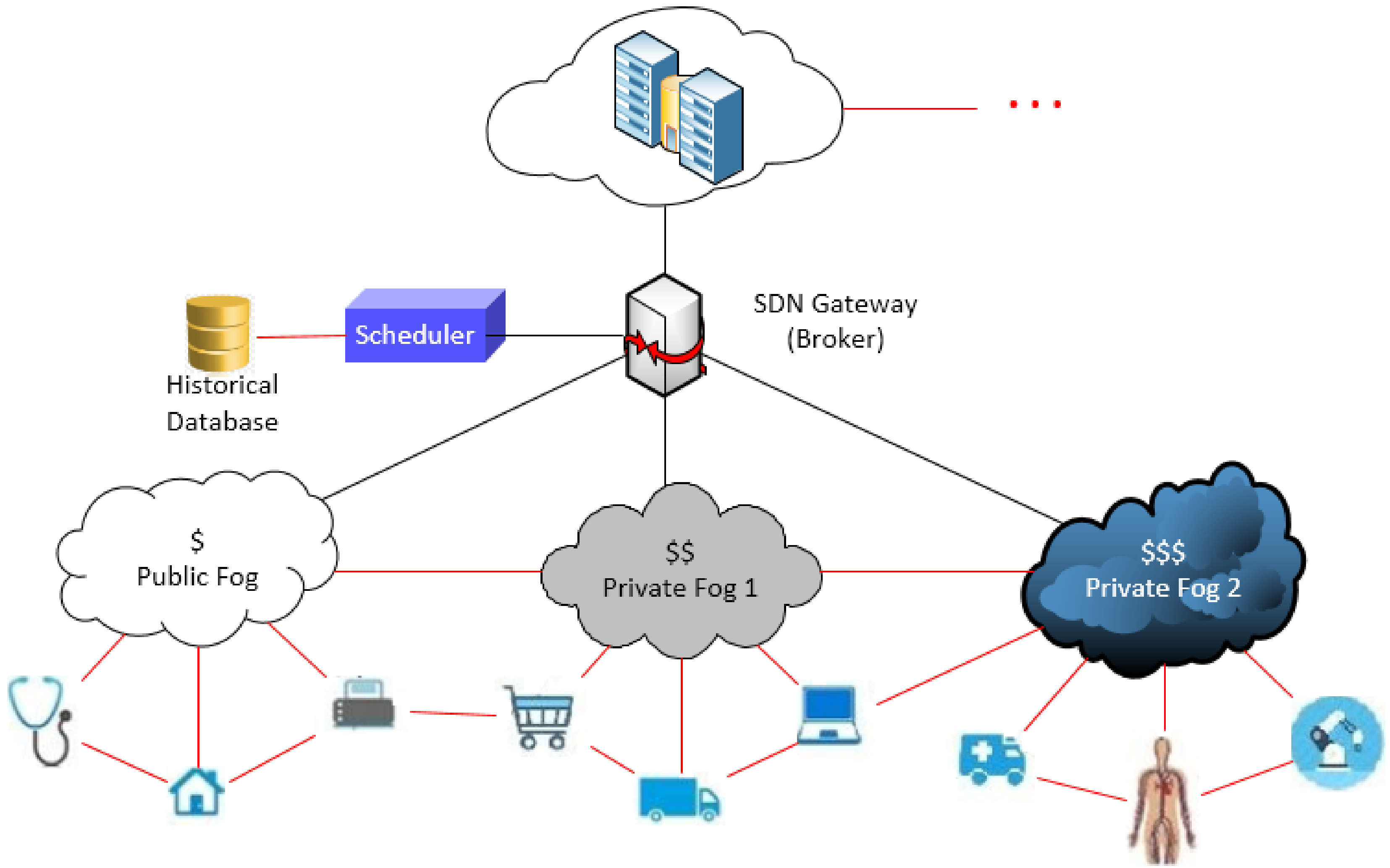
Source: "OpenFog Reference Architecture: OpenFog Consortium". Available: https://www.openfogconsortium.org/ra/ [Accessed: 24/05/2017].

Fog computing – Business Intelligence

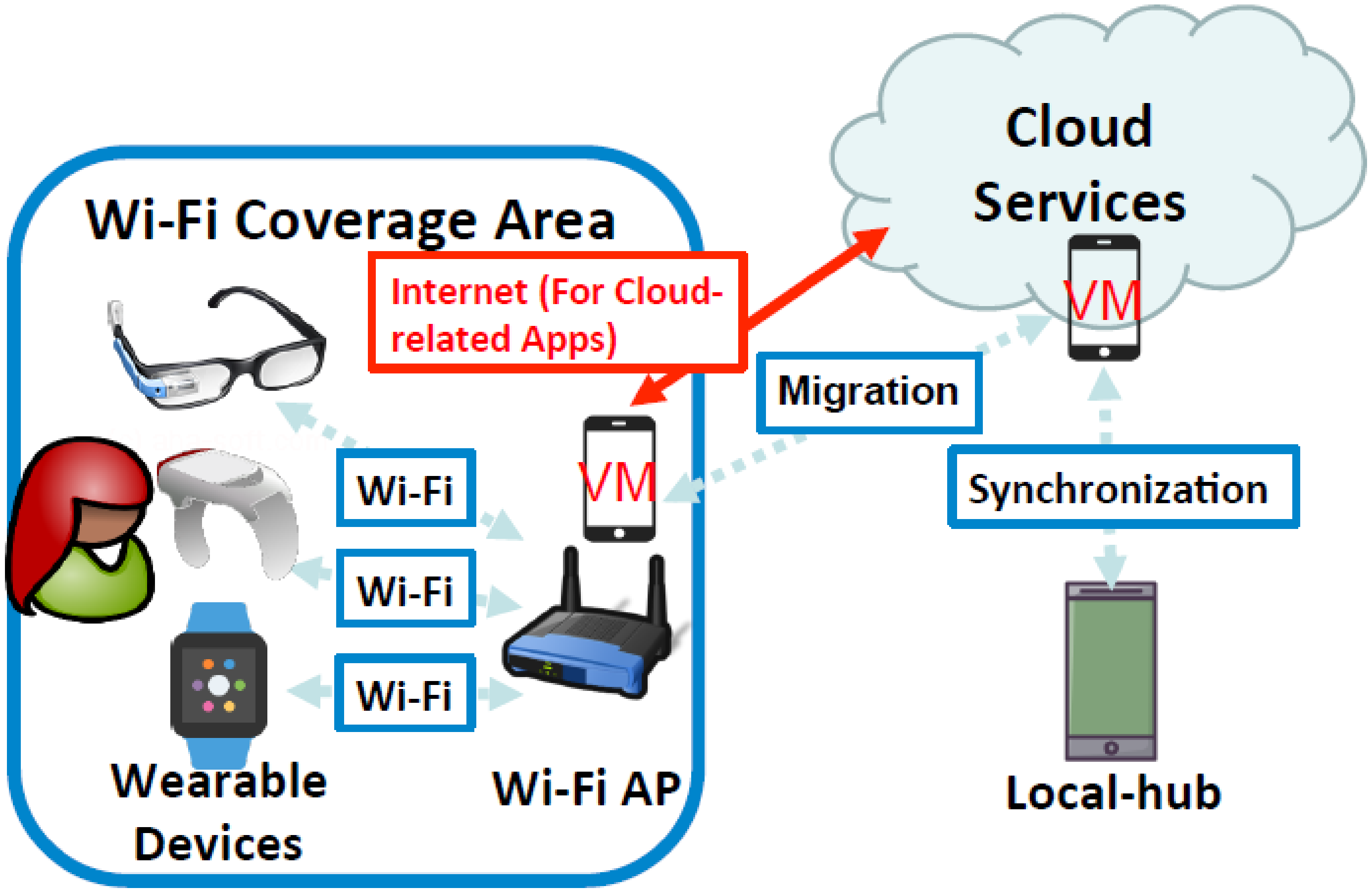


Source: "OpenFog Reference Architecture: OpenFog Consortium". Available: https://www.openfogconsortium.org/ra/ [Accessed: 24/05/2017].

Fog computing, SDN and NFV



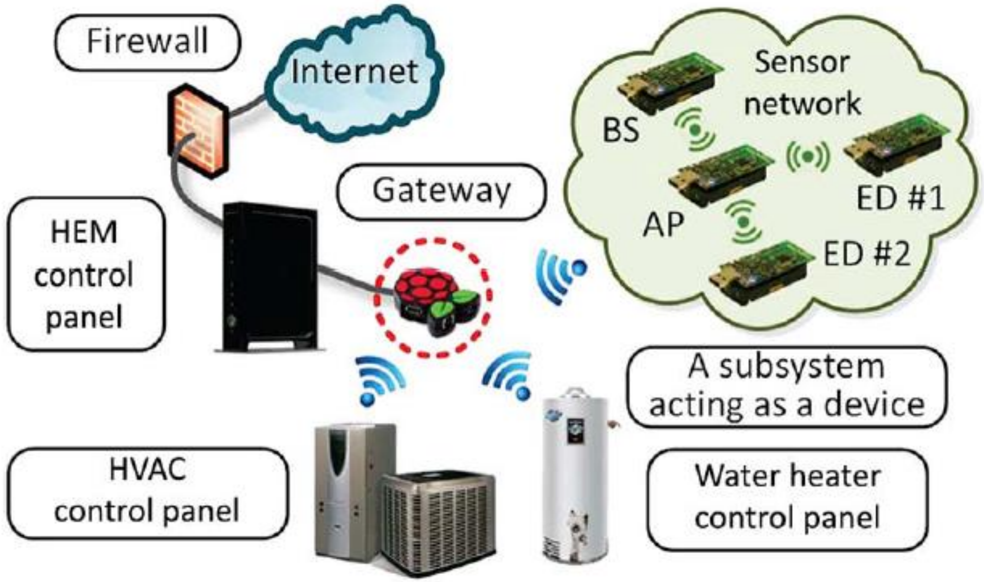
Local Hubs



Wi-Fi Coverage Area
Internet (For Cloud-related Apps)
Cloud Services
VM
Migration
Synchronization
VM
Wi-Fi
Wi-Fi
Wi-Fi
Wearable Devices
Wi-Fi AP
Local-hub

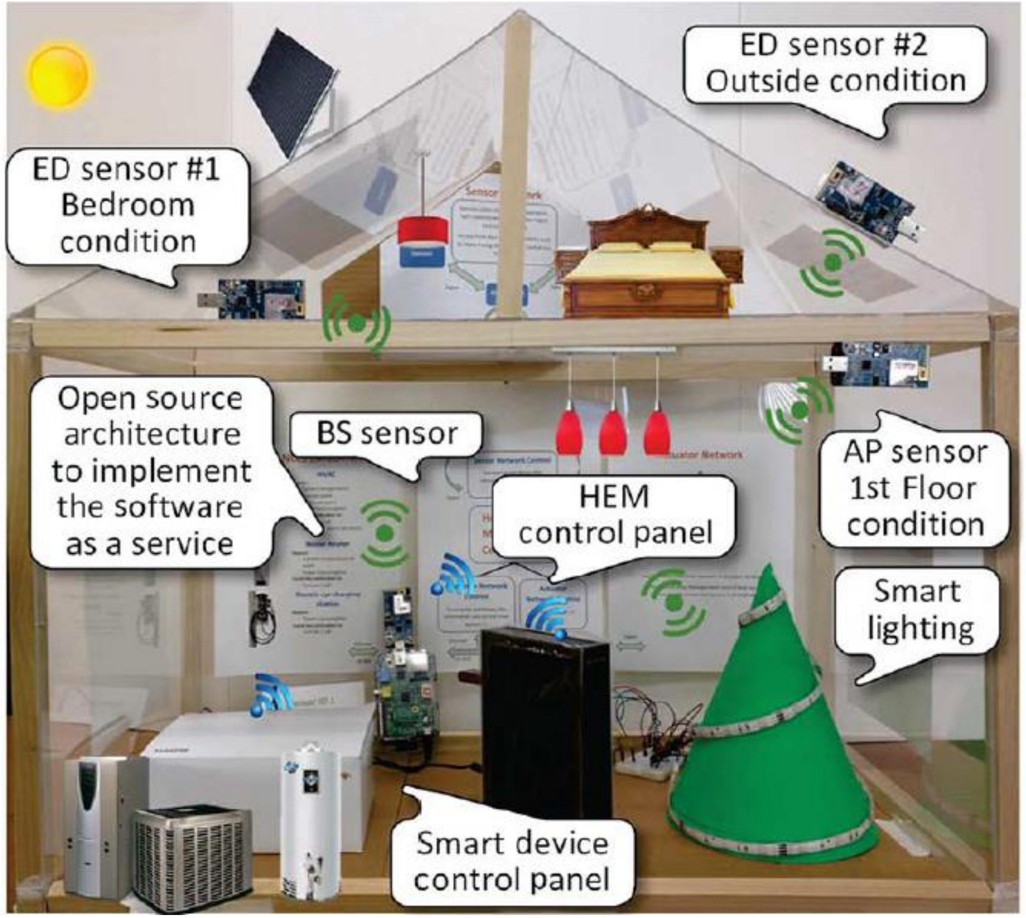
Home Energy Management

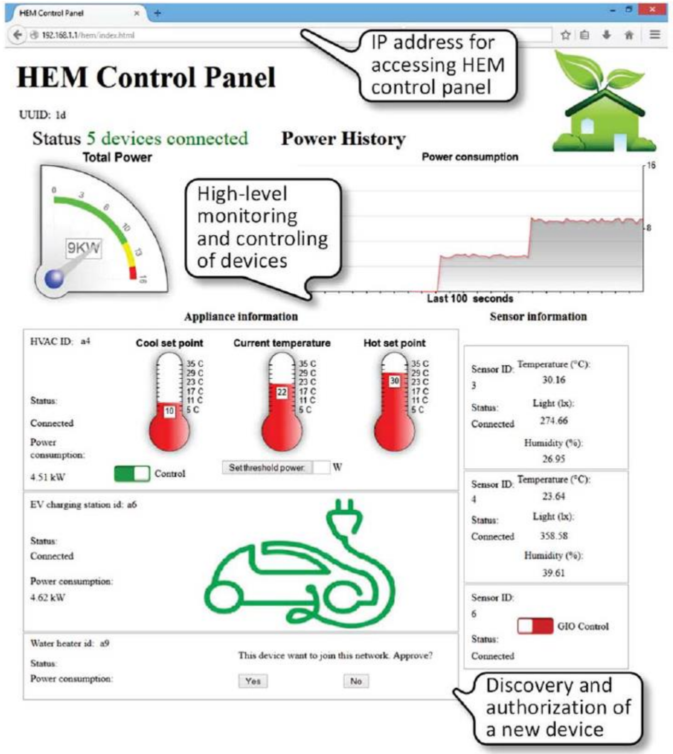
- Cost of implementing the platform such as computing devices, software stack, and communication devices is still high enough that hinders the process of deploying it for ordinary residential users



M. A. Al Faruque and K. Vatanparvar, "Energy Management-as-a-Service Over Fog Computing Platform" ,IEEE INTERNET OF THINGS JOURNAL, VOL. 3, NO. 2, APRIL 2016

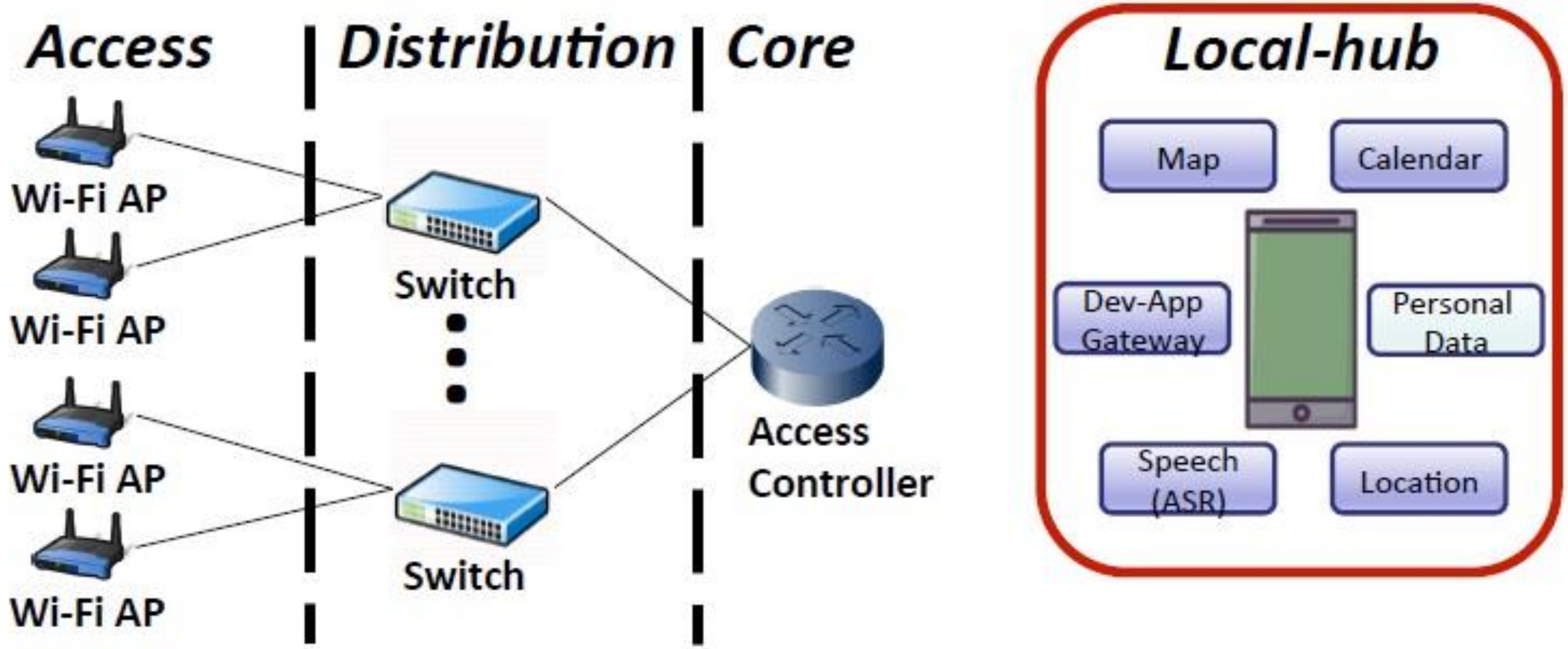
Home Energy Management





M. A. Al Faruque and K. Vatanparvar, "Energy Management-as-a-Service Over Fog Computing Platform" ,IEEE INTERNET OF THINGS JOURNAL, VOL. 3, NO. 2, APRIL 2016

- Shift functionalities of local-hub from smart phone to edge network
  - Pre-install shareable function module on APs



T. Zhang, T. Quek, J.Huang, Ai-Chun Pang, Y. Yang, "Fog Computing and Networking:A New Paradigm for 5G and IoT Applicationns, IEEE ICC 2017

Fog RAN

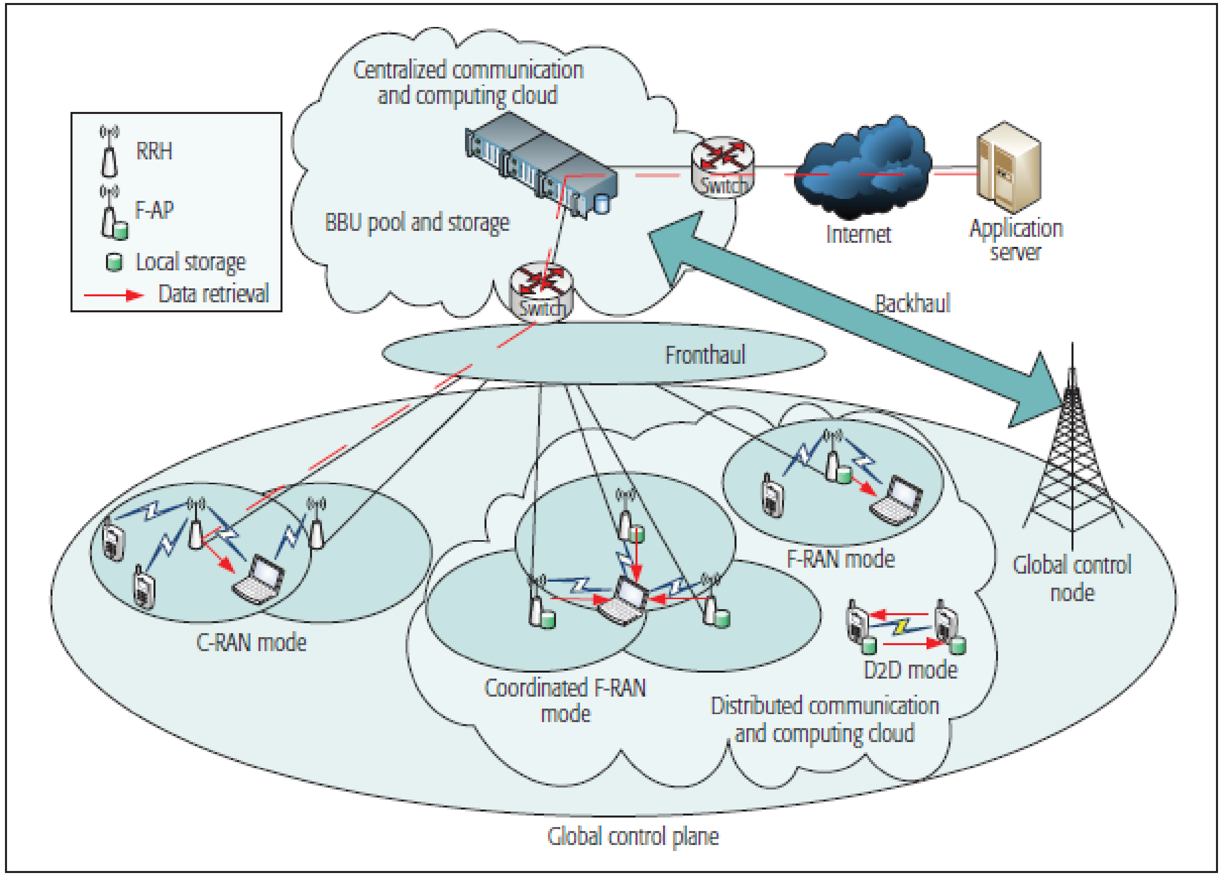


Figure 1. Fog-cloud integrated RAN architecture.

Yu-Jen Ku, Dian-Yu Lin, Chia-Fu Lee, Ping-Jung Hsieh, Hung-Yu Wei, Chun-Ting Chou and Ai-Chun Pang5G Radio Access Network Design with the Fog Paradigm: Confluence of Communications and Computing, IEEE Communications Magazine • April 2017

Fog RAN

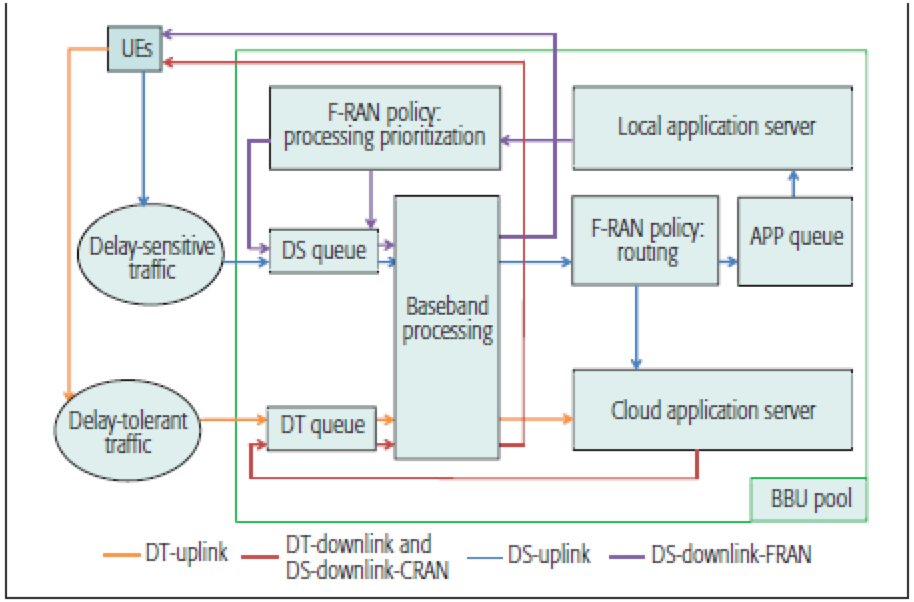


Figure 5. Model of the F-RAN architecture.

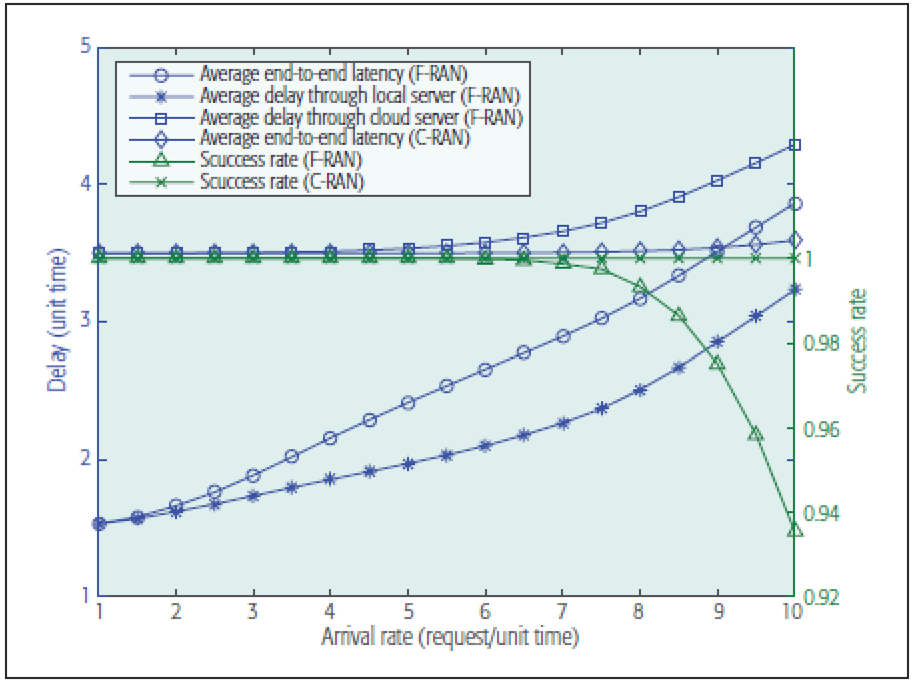


Figure 6. Delay and success rate of DS traffic.

Yu-Jen Ku, Dian-Yu Lin, Chia-Fu Lee, Ping-Jung Hsieh, Hung-Yu Wei, Chun-Ting Chou and Ai-Chun Pang5G Radio Access Network Design with the Fog Paradigm: Confluence of Communications and Computing, IEEE Communications Magazine • April 2017

C-RAN, H-CRAN and F-RAN

- Cloud radio access network (C-RAN) - combination of emerging technologies incorporating cloud computing into radio access networks (RANs). A requirement for centralized processing in the centralized baseband unit (BBU) pool is an interconnection fronthaul with high bandwidth and low latency. Unfortunately, the practical fronthaul is often capacity and time-delay constrained, which has a significant decrease on spectral efficiency and energy efficiency gains.

- Heterogeneous C-RANs (H-CRANs) - user and control planes are decoupled in such networks, where high power nodes (HPNs) are mainly used to provide seamless coverage and execute the functions of the control plane, while remote radio heads (RRHs) are deployed to provide high-speed data rate for packet traffic transmission in the user plane. HPNs are connected to the BBU pool via the backhaul links for interference coordination.

Mugen Peng, Shi Yan, Kecheng Zhang, and Chonggang Wang, "Fog-Computing-Based Radio Access Networks: Issues and Challenges", IEEE Network • July/August 2016

C-RAN, H-CRAN and F-RAN

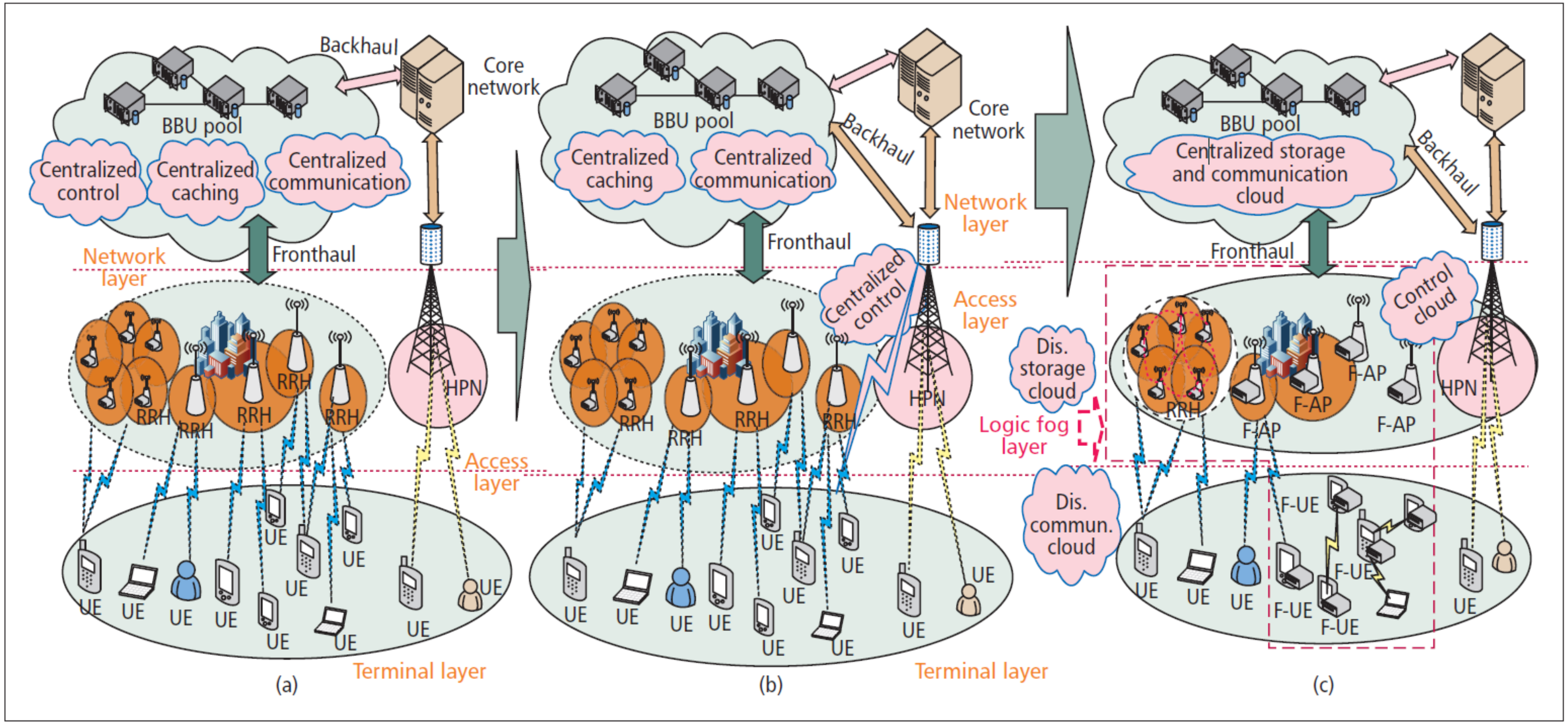


Figure 1. System architecture evolution through F-RANs: a) C-RAN architecture; b) H-CRAN artchitecture; c) F-RAN

Mugen Peng, Shi Yan, Kecheng Zhang, and Chonggang Wang, "Fog-Computing-Based Radio Access Networks: Issues and Challenges", IEEE Network • July/August 2016

C-RAN, H-CRAN, and F-RAN

Items	C-RANs	H-CRANs	F-RANs
Burden on fronthaul and BBU pool	Heavy	Medium	Low
Latency	High	High	Low
Decouple of user and control planes	No	Yes	Yes
Caching and CRSP	Centralization	Centralization	Mixed centralization and distribution
CRRM	Centralization	Centralization, and distribution between the BBU pool and HPNs	Mixed centralization and distribution
Performance gains	Fronthual constraint	Fronthual and backhaul constraint	Backhaul constraint
Implementing complexity	High in the BBU pool, low in RRHs and UEs	High in the BBU pool, low in RRHs and UEs	Medium in the BBU pool, F-APs, and F-UEs
Traffic characteristics	Packet service	Packet service, real-time voice service	Packet service, real-time voice service

Table 1. Advantage comparisons of C-RANs, H-CRANs, and F-RANs .

Mugen Peng, Shi Yan, Kecheng Zhang, and Chonggang Wang, "Fog-Computing-Based Radio Access Networks: Issues and Challenges", IEEE Network • July/August 2016

Summary

Address Challenges in Emerging Systems/Apps (IoT, 5G, Imbedded AI, …)	• Stringent latency/delay requirements • Resource constraints (endpoints, network bandwidth, …) • Intermittent network connectivity • Large # and many types of "Things" • Distributed, remote operations by non-IT experts
Empower the Cloud	• Fog as proxy of Things to connect more Things to Cloud • Fog as proxy of Cloud to deliver services to Things
Enable New Services	• Fog-based services • Fog-enabled 5G • Converged Cloud-Fog platforms and services • User controlled Fog services • Fog-enabled dynamic networking at the edge

T. Zhang, T. Quek, J.Huang, Ai-Chun Pang, Y. Yang, "Fog Computing and Networking:A New Paradigm for 5G and IoT Applicationns, IEEE ICC 2017

Summary

Reshaping Industry Landscape	• Routers, switches, application servers, and storage servers converge into unified fog nodes
Disruptive New Service Models	• Players of all sizes, not just massive cloud operators, build/operate fogs and offer fog services → "WiFi Model" and the rise of local/regional fog eco-systems and operators?
Integrated/Converged Cloud–Fog Services	• For a business to function as a cohesive whole, cloud and fog will converge into one common infrastructure for integrated and unified cloud and fog services: development, deployment, monitoring, management, security, …
Rapid Development and Deployment of Fog Systems and Applications	• Rapid deployment of localized applications → shifting from "build the cloud and see what services we can put on it" to "find what customers want and quickly put together a fog for them"

T. Zhang, T. Quek, J.Huang, Ai-Chun Pang, Y. Yang, "Fog Computing and Networking:A New Paradigm for 5G and IoT Applicationns, IEEE ICC 2017

/

Research Challenges

- How to distribute data between the Fog and the Cloud?
- Which application should be offloaded?
- How to implement Fog nodes with off-the-shelve network switches?
- How F-RAN can minimize traffic congestion in the backhaul?
- How to handle the heterogeniety of data representation?
- Hoe to design an inteoperable, scale, reliable, secure...Fog?