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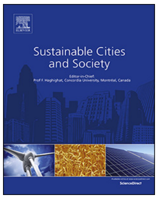

Fog computing for sustainable smart cities in the IoT era: Caching techniques and enabling technologies - an overview

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ABSTRACT

In recent decade, the number of devices involved with the Internet of Things (IoT) phenomena has increased dramatically. Parallel to this, fog computing paradigm has been introduced in order to support the computational demand of latency-sensitive and real-time IoT applications. The main support the fog paradigm can provide for these applications is through enabling computing at the edge of the network closer to the end users and IoT devices. Moreover, in sustainable smart cities, fog computing can be utilized as an efficient framework to reduce delays and enhance energy efficiency of the system. This article considers possible fog computing applications and potential enabling technologies towards sustainable smart cities in the IoT environments. In addition, different caching techniques and the use of Unmanned Aerial Vehicles (UAVs), and various Artificial Intelligence (AI) and Machine Learning (ML) techniques in caching data for fog-based IoT systems are comprehensively discussed. Finally, the potential and challenges of such systems are also highlighted.

1. Introduction

Over the past decade, the IoT (Alabady, Salleh, & Al-Turjman, 2018) has transformed the use of Internet and become a popular term among researchers. The IoT allows people and things (e.g. sensors, actuators, and smart devices) to be connected anytime and anywhere, with anyone and anything. Most of these objects and devices are expected to have sensing capabilities. They can sense and collect data from the environment around us and then share the data across the Internet where it can be processed for different purposes. Connecting a large number of physical objects with sensing capabilities (e.g. sensors) to the Internet introduces the concept of "big data" which needs efficient and smart storage (Al-Fuqaha, Guizani, Mohammadi, Aledhari, & Ayyash, 2015) and its analysis can be the basis for designing and planning of sustainable smart cities (Khan, Babar, Ahmed, Shah, & Han, 2017; Malik, Sam, Hussain, & Abuarqoub, 2018). Clearly, connected objects require efficient mechanisms to store, process, and retrieve data (Al-Fuqaha et al., 2015). However, with millions of interconnected devices, the big data generated can be significantly extensive compared to traditional data traffic. Hence, it is not possible to use the available hardware environments and software tools to manage and process data with acceptable response time (Al-Fuqaha et al., 2015). Therefore, big data is usually considered with respect to the cloud computing paradigm (Perera, Qin, Estrella, Reiff-Marganiec, & Vasilakos, 2017). Cloud technology allows organizations and individuals to utilize many resources remotely and at a reasonable cost (Al-Fuqaha et al., 2015). Nowadays, cloud computing is broadly used in both industry and academia. However, it still has some limitations. The most basic limitation is related to the connectivity between the cloud and the end devices which is set over the Internet and is not appropriate for a large number of cloud-based and latency-sensitive applications such as connected vehicles and smart grid (Mouradian et al., 2017). Moreover, cloud-based applications are usually distributed and consist of multiple components (Mouradian et al., 2017). Therefore, the separate deployment of application components over multiple clouds is quite common. However, this makes the latency even worse as a result of the overhead caused by inter-cloud communications. Fog computing is a paradigm introduced to deal with these limitations.

Fog computing is an architecture that extends the architecture of cloud computing to the edge of the network and distributes computation, control and storage of data closer to the end users (Chiang & Zhang, 2016). The relevance of the fog technology can easily be revealed when the limitations of the traditional cloud technology as well as the new opportunities introduced through the emergence of the IoT and 5 G-related technologies are considered (Chiang & Zhang, 2016). With fog computing, the processing of cloud-based and latency-sensitive applications can take place at the edge of the network while other delay-tolerant applications can be handled in the cloud (Mouradian

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et al., 2017). Moreover, fog technology provides low latency by allowing the processing tasks to be handled close to the end devices, at the edge of the network. In addition, through access points, proxies, and routers located at the edge of the network and close to the sources, fog computing offers heavily distributed points for collecting data generated by the end devices (Mouradian et al., 2017). Fog computing can also ensure higher availability. It is less reliable to connect to the cloud because of various connectivity issues (Stojmenovic & Wen, 2014). Fog computing can reduce the dependency on cloud architecture and provide a mechanism for edge devices to operate without interruption for a reasonable period of time even if the connection to the cloud is no longer available and lost. Additionally, it supports data aggregation from heterogeneous devices such as multiple health-care related sensors, and provides security and data protection for private information and sensitive data such as location and medical-related data (Aazam, Zeadally, & Harras, 2018). Moreover, fog computing provides better real-time response than the cloud-based models (Omoniwa, Hussain, Javed, Bouk, & Malik, 2018). In studies such as Bonomi, Milito, Zhu, & Addepalli (2012) and Bonomi, Milito, Natarajan, & Zhu (2014), it is broadly stated that cloud computing is not suitable for most of the IoT applications and consequently fog computing can be used as an alternative. However, the data delivery from smart devices (e.g. sensors) to cloud becomes a bottleneck due to the poor communication abilities of Wireless Sensor Networks (WSNs), particularly for cloud-based delay-sensitive IoT applications. This bottleneck can degrade the performance of the applications and limits their future development (Zeng, Wang, Lai, Liang, & Chen, 2016).

Moreover, fog computing is a paradigm utilized by specialists in smart environments in order to design efficient information processing data. For instance, in sustainable smart cities where the aim is to integrate various IoT technologies by providing many opportunities for management, development, and governance of user services, fog computing techniques are used to manage resource consumption, reduce costs, improve performance of the system, and connect the IoT devices more effectively (Bangui, Rakrak, Raghay, & Buhnova, 2018). Similarly, fog computing was utilized for sustainable smart cities as an efficient framework in Perera et al. (2017) and Naranjo, Pooranian, Shojafar, Conti, & Buyya (2019) to reduce delays and save energy. Moreover, there is a wide range of potential use-cases which can be considered by the integration of fog computing into smart cities. These use-cases include enhanced operation and services for water, energy, and waste management, improved transportation using direct Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communications, and embedded connected devices for monitoring and providing accurate treatments in social services and healthcare domain. Therefore, fog computing can help to create sustainable smart cities (Saroa & Aron, 2018). In this paper, we present an overview of the fog computing, critically considering the main services as well as potential enabling technologies towards sustainable smart cities in the IoT era. Moreover, we compare various caching techniques in fog-based IoT systems and discuss their strengths and weaknesses in details. In addition, the use of UAVs and various AI/ML techniques in caching for the fog-based IoT systems are highlighted.

1.1. Comparison to similar surveys

In this section, we critically overview various published survey papers related to fog computing paradigm in the IoT environment. For example, a review on fog computing technology is presented in Al-Doghman, Chaczko, Ajayan, & Klempous (2016) however, the study lacks discussion on various important features and topics such as architecture, protocols and applications as well as research issues. Similarly, a comprehensive survey on fog computing is presented in Hu, Dhelim, Ning, & Qiu (2017) covering various aspects such as architecture, enabling technologies, applications and research issues. However, this study does not cover discussions around the communication protocols of the fog-based IoT infrastructures. In Lin et al. (2017), a survey on fog computing-based IoT is presented discussing various topics such as architecture, enabling technologies, security and privacy, and applications. However, research issues and protocols are not covered in this study. The authors in Chiang & Zhang (2016) discuss the opportunities and challenges of fog paradigm, mainly focusing on the networking context of the IoT. However, the study does not cover topics related to protocols, services, and enabling technologies of the fog technology. The study in Bonomi et al. (2012) argues various characteristics that make the fog technology an appropriate platform for differeent critical IoT applications and services such as smart cities, WSNs, smart grid, and connected vehicles. However, a number of important aspects such as protocols and research issues are not covered. Moreover, the key enabling technologies, research issues and typical IoT applications benefitting from fog computing are investigated in Pan & McElhannon (2017) but the paper does not cover services and protocol issues. In Bilal, Khalid, Erbad, & Khan (2018), the authors present a detailed overview of potentials, trends and challenges of fog computing. The study in Aazam & Huh (2016) presents an overview of the architecture of fog paradigm in the IoT era without discussing other important issues such as protocols and services. Moreover, the security related issues of the fog-based IoT infrastructures are comprehensively discussed in Ni, Zhang, Lin, & Shen (2017) and Alrawais, Alhothaily, Hu, & Cheng (2017). An overview of the core issues, challenges and future research directions in fog-enabled systems for IoT services is presented in Wen et al. (2017). However, this study does not cover issues related to architecture, communication protocols and applications. The study in Atlam, J.Walters, & Wills (2018) presents an overview of fog computing and its integration with IoT by discussing benefits and implementation challenges. The focus of this review paper is on the architecture of the fog paradigm and emerging IoT applications. In addition, state of the art and research challenges related to fog computing are highlighted in a comprehensive survey in Mouradian et al. (2017). The authors critically discuss the fog-enabled architecture and various application domains. However, other critical issues such as communication protocols and services are not discussed in this paper. Similarly, another comprehensive survey paper related to fog computing-based IoT is presented in Omoniwa et al. (2018) where the authors discuss various topics related to fog paradigm such as architecture, services, protocols and enabling technologies as well as research challenges. A summary of the topics covered in the studies discussed in this section is presented and compared to our study in Table 1.

Although, there are several published survey papers that cover various aspects of the fog computing paradigm in the IoT era, but none of them considers the use of UAVs and AI/ML techniques in caching data in the fog-based IoT systems. Therefore, the contributions of this paper relative to the recent literature in the field can be summarized as follows:

- To the best of our knowledge, this study is the first survey paper that provides a summary of the use of UAVs and AI/ML techniques in caching data for improving data delivery in the fog-based IoT systems.
- We provide a classification for the fog computing services in the IoT era while focusing on caching data in the fog-based IoT applications.
- We present and compare various simulation tools which enable researchers to understand the actual characteristics of the model in lower cost where the fog-based IoT devices are deployed.
- We provide tabular summaries about
  - The existing survey studies in the fog-based IoT systems,
  - The strengths and weaknesses of different studies in caching data for the fog-based IoT systems,
  - Tools used for simulating the fog-based IoT environments.
- Finally, we discuss some challenges and research issues that must be carefully studied regarding the utilization of fog paradigm in the IoT

Table 1
Summary of the review/survey studies in the fog-based IoT Environments.

Ref	Architecture	Services	Security	Protocols	Enabling Technologies	Applications	Caching	Use of UAVs and AI/ML in caching	Research Challenges
(Mouradian et al., 2017)	X	–	–	–	–	X	–	–	X
(Chiang & Zhang, 2016)	X	–	–	–	–	X	–	–	X
(Bonomi et al., 2012)	X	–	–	–	–	X	–	–	–
(Al-Doghman et al., 2016)	–	–	–	–	X	–	–	–	–
(Hu et al., 2017)	X	–	–	–	X	X	–	–	X
(Lin et al., 2017)	X	–	–	–	X	X	–	–	–
(Pan & McElhannon, 2017)	X	–	–	–	X	–	–	–	X
(Bilal et al., 2018)	–	–	–	–	X	X	–	–	–
(Aazam & Huh, 2016)	X	–	–	–	–	–	–	–	–
(Ni et al., 2017)	X	–	X	–	–	X	–	–	X
(Alrawais et al., 2017)	–	–	X	–	–	X	–	–	X
(Wen et al., 2017)	–	X	–	–	–	–	–	–	X
(Atlam et al., 2018)	X	–	–	–	–	X	–	–	X
(Omoniwa et al., 2018)	X	X	X	X	X	X	–	–	X
***	X	X	X	X	X	X	X	X	X

- = Not Considered, X = Considered.
*** = Our Study.

era.

In order to assist the readers, Table 2 provides a list of abbreviations along with brief definitions used throughout this study. The rest of this paper is organized as follows. Section 2 discusses the role of cloud and fog computing in green IoT. The feasible fog computing services in the IoT era are presented in Section 3. Section 4 discusses standards, protocols and enabling technologies in the fog-based IoT systems. Fog computing applications in support of the IoT paradigm are presented in Section 5. A classification of caching techniques in fog computing paradigm together with the use of UAVs in caching data in the fog-based IoT systems are presented in Section 6. An overview of the used AI/ML techniques in caching data for the fog-based IoT applications is discussed in Section 7. Section 8 provides a summary of the tools used for simulating the fog-based IoT environments. Section 9 discusses some open research issues and gives future research directions. Finally, Section 10 concludes this survey paper.

2. The role of cloud and fog computing in green IoT

IoT is a concept which aims to connect billions of "things" with each other. The IoT smart devices sense, gather, and transmit crucial information from the environment nearby. This exchange of massive amount of information among billions of smart devices such as smart phones, sensors, etc. creates a huge energy need. Green IoT basically gives special attention to the energy efficiency in the IoT environments. It is defined as the energy efficient approaches to reduce and/or get rid of the green-house effect generated by existing IoT applications (Arshad, Zahoor, Shah, Wahid, & Yu, 2017). Cloud computing and fog computing play a significant role in the implementation of Green IoT (Arshad et al., 2017). Fig. 1 shows the role of cloud computing and fog computing in delivering various IoT services to the end users. The architecture in Fig. 1 includes three layers named cloud layer, fog layer, and smart devices layer. The fog layer contains of fog domain which includes gateways, and the smart devices layer contains IoT smart devices such as smart phones. The communication between fog layer and

Table 2
Abbreviations.

Abbreviated	Name	Abbreviated	Name
6LoWPAN	IPv6 over Low Power Wireless Personal Area Network	LTE-A	Long Term Evolution
AI	Artificial Intelligence	M2M	Machine-to-Machine
API	Application Programming Interface	ML	Machine Learning
BLE	Bluetooth Low Energy	MMA	Man-in-the-Middle Attack
BS	Base Station	MMN	Machine Neural Network
CD	Content Delivery	NB-IoT	NarrowBand IoT
CF	Collaborating Filtering	NFC	Near Field Communication
CNN	Convolutional Neural Network	P2P	Peer-to-Peer
CoT	Cloud of Things	PER	Packet Error Rate
D2D	Device-to-Device	QoE	Quality of Experience
DDoS	Distributed Denial of Service	QoS	Quality of Service
DDPG	Deep Deterministic Policy Gradient	RAN	Radio Access Network
DL	Deep Learning	RFID	Radio Frequency IDentification
DNN	Deep Neural Network	RNN	Recurrent Neural Network
DQL	Deep Q-Learning	RR	Randomized Replacement
DRL	Deep Reinforcement Learning	SDN	Software Defined Networking
IoT	Internet of Things	TEDS	Transducer Electronic Data Sheets
IPSec	Internet Protocol Security	UAV	Unmanned Aerial Vehicle
ITS	Intelligent Transportation System	UE	User Equipment
KNN	K-Nearest Neighbor	V2I	Vehicle-to-Infrastructure
LAN	Local Area Network	V2V	Vehicle-to-Vehicle
LoS	Line of Sight	VM	Virtual Machine
LPWA	Low Power Wide Area	WAN	Wide Area Network
LRU	Least Recently Used	WISP	Wireless Identification and Sensing Platform
LR-WPAN	Low-Rate Wireless Personal Area Networks	WSN	Wireless Sensor Network

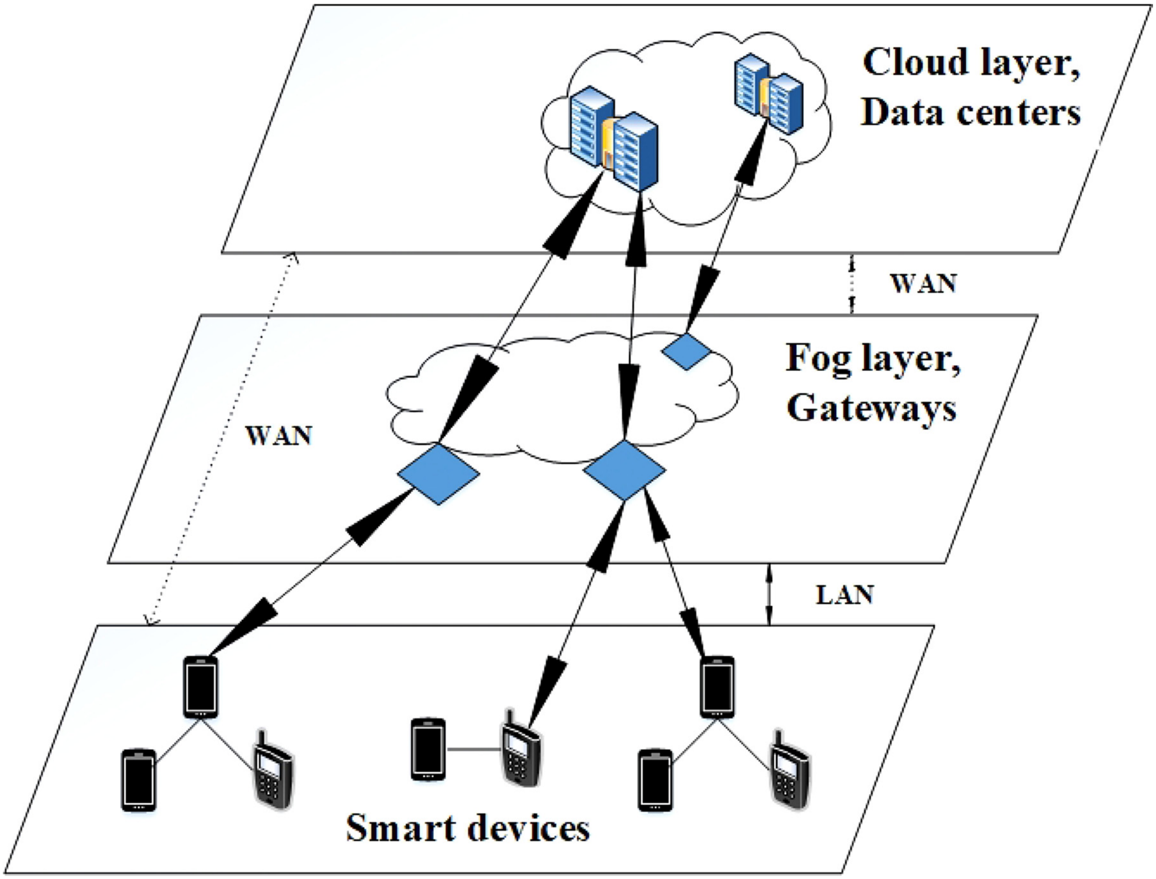

Fig. 1. Overview of fog-based IoT.

smart devices layer is done through Local Area Network (LAN). However, the communication between smart devices layer and the cloud layer is done using Wide Area Network (WAN) either directly or through the fog layer.

Cloud computing provides a new management scheme for big data which offers easy and on-demand access to a shared pool of resources such as networks, applications, servers, storage, and various services (Arshad et al., 2017). However, there are some challenges which make the implementation of cloud computing a difficult task for the Green IoT. For example, synchronization between various cloud vendors as well as standardization of cloud computing present significant challenges for IoT cloud-based applications (Al-Fuqaha et al., 2015). Another challenge in employing cloud computing for the IoT is related to the security issue due to the fact that the security mechanisms between the cloud platforms and IoT devices are different. Cloud computing and IoT systems have different resources and components, therefore, managing cloud computing and IoT is also a challenging factor in employing cloud platforms for the IoT. Due to these challenges, the implementation of cloud computing for the Green IoT is not an easy task. As an alternative, fog technology can be utilized to increase the overall performance of the IoT applications by trying to perform part of the service offered by cloud computing inside the local resources (Al-Fuqaha et al., 2015).

Fog computing is a paradigm which enables computing at the edge of the network closer to the end user and IoT devices (Mouradian et al., 2017). It can act as a link between IoT smart devices and cloud computing and storage devices. Fog computing is an extension of cloud technology in which cloud computing services are extended to the edge devices of the network. Compared to the cloud computing, operational costs and energy consumption in the fog paradigm are less since the fog layer is placed closer to the end user and therefore, distance between the users and fog devices can be less than a few hops (Hu et al., 2017; Mahmud, Koch, & Buyya, 2015). This in turn causes less communication latency in the fog paradigm. On the other hand, real-time interaction can be a challenging task for the cloud technology due to its high latency, but this issue can be easily solved by fog computing (Naha et al., 2018). It has the potential to provide services that have better delay performance compared to the cloud data centers due to their closeness to the end users. Therefore, fog computing can serve as the most suitable choice for the IoT designers regarding the implementation of the Green IoT (Al-Fuqaha et al., 2015). For instance, fog resources are located between smart devices and cloud data centers which provide better delay performance. Moreover, compared to cloud computing, fog technology is based on micro centers which have limited processing, communication, and storage capabilities (Al-Fuqaha et al., 2015). Therefore, it is possible to deploy many micro centers near to the end devices which in turn provides efficient deployment financially. If the number of end devices increase in the network, more fog micro centers can be deployed to deal with the increasing load. In addition, since fog resources are positioned near to the end devices, they can act as a mobile cloud in order to support mobility. Fog technology has also the potential to improve the performance of the real-time interactive applications and can interoperate with different cloud providers (Rao & Sree, 2018). Last but not least, using fog resources, instead of sending raw data to the cloud, partially processed data can be sent to the cloud data centers for further processing. A summary of the mentioned features of the fog technology in the Green IoT era is illustrated in Fig. 2.

3. Fog computing services in the IoT

The features of fog layer in Fig. 1 have already been highlighted in Fig. 2. These features can be utilized to provide various services in a

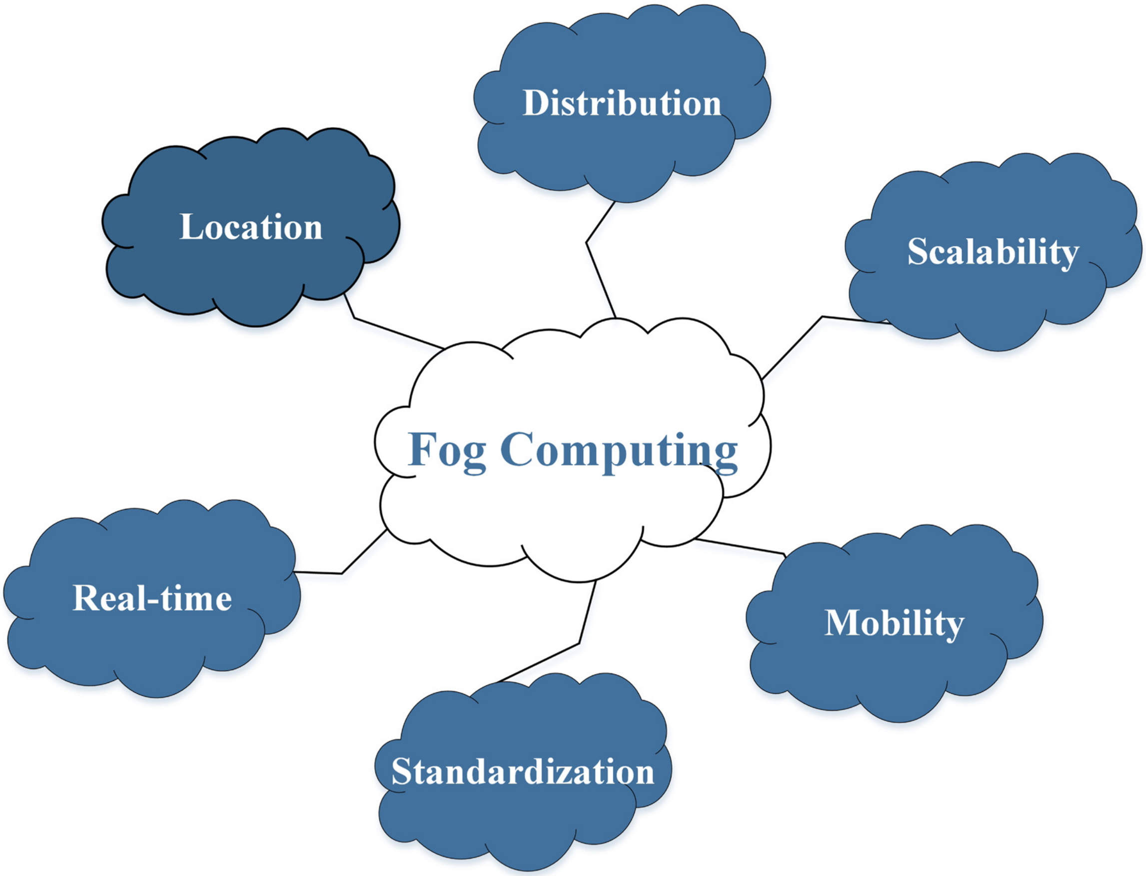

Fig. 2. Features that make fog computing an optimal choice for the IoT designers.

way that the overall requirements of the systems are satisfied. The fog layer in Fig. 1 is close to the smart devices' layer which consists of smart phones, sensors, tags, etc. and this proximity provides unique services that are possible only at this layer. These feasible services at the fog layer can be classified into three categories; computing services, storage services, and communication services (Rahmani, Liljeberg, Preden, & Jantsch, 2017).

Computing Services: In the cloud-based systems, the processing tasks can be brought down from the cloud layer to the fog layer for localized processing and quick response (Datta, Bonnet, & Haerri, 2015; Hu, Ning, Qiu, Zhang, & Luo, 2016). In this regard, many configurations of sharing the computing loads among various layers of the cloud-based IoT systems can be considered and the processing requirements may differ according to the actual work. For example, for a system which carries out data processing to learn a certain pattern, the distribution of the workload should be in such a way that the localized patterns can be recognized in the fog layer and the generalized ones are only available in the cloud layer. In addition to data management, because of the proximity of this layer to the end devices, it would be easier to handle events to respond in real-time and improve the reliability of the system.

Storage Services: In IoT systems, a massive amount of data can be generated using billions of sensor devices in the environments. These devices are not capable of storing the generated data even for one day. Moreover, it is not necessary to push all the data directly to the cloud if there is redundancy or irrelevance in data. Therefore, the sensible approach would be to store data in the fog layer temporally (Rahmani et al., 2015). Together with computing services, storage services can filter, analyze, and compress data for efficient transmissions. They can also help to learn local information regarding the behavior of the system. The storage services can also help to improve the reliability of the system by providing appropriate system behavior for end devices in such cases where the communication is not robust. Such characteristics of the fog layer are presented in (Sarkar, Chatterjee, & Misra, 2015) where the authors assess the suitability of fog computing in the context of IoT.

Communication Services: Wireless protocols control the communication in the IoT systems. These protocols are improved for narrow-band transmission, low-power operation, or longer range of coverage because of the resource constraints in the smart devices' layer. The fog layer illustrated in Fig. 1 is placed in a location where it can organize these wireless protocols to combine their communications into a single communication utilized by the cloud layer. This would help to manage subnetworks of smart devices such as sensors and actuators to provide security and improve the reliability of the system. Moreover, the fog layer can provide interoperability of several various protocols by trying to list and interpret the representation format. In addition, non IP-based devices would be easily accessible through the Internet using fog layer (Rahmani et al., 2015).

4. Standards, protocols & enabling technologies in fog-based IoT systems

Fog-based IoT systems require interacting with the cloud systems, with each other, and with a large number of smart devices as well. Therefore, the successful adoption of fog computing with the current IoT systems will depend on new standards. Although fog computing can take advantage from the existing standards, new standards may also be needed especially in the following areas (Chiang, Ha, Chih-Lin, Risso, & Zhang, 2017):

Unification of fog/cloud-based IoT systems: In order to enable unified fog/cloud-based applications and service platforms, new interfaces and protocols are required for the fog and the cloud to communicate with each other. These interfaces and protocols can help to move computing functions between the fog and the cloud, and to manage the life-cycle of the fog-based applications.

Support of distributed and hierarchical fog-based IoT systems: New interfaces and protocols will be required for different hierarchical levels in a fog-based system to communicate with each other, and also for various fog platforms at the same hierarchical level to interact, collaborate and serve as a backup for each other.

Data processing and management: One of the most important enablers of fog computing is local data management. Since data comes from a broad range of sources (e.g. sensors, actuators, and smart phones), new standards may be needed to store, access, and secure the data in the fog and the cloud.

Access to fog-based services: A broad range of new services will be enabled by proximity of fog layer to end devices in a fog-based system. New standards will be needed for the smart devices to communicate with the fog system to discover, request, and receive fog services.

Security: A distributed fog-based IoT system may introduce security challenges which are not present in centralized systems. In order to address these new challenges, new standards are required. For instance, fog computing will require to have different set of local hardware platforms. Therefore, new interfaces and protocols may be needed for fog software to properly communicate with different hardware platforms as well as to automatically detect security compromises in order to respond them remotely and automatically.

4.1. Protocols & enabling technologies

Generally, standards are important factors for efficient and cost-effective deployment of fog-based IoT systems. By considering the distributed architecture of the fog-based IoT shown in Fig. 1, there are still some challenging issues such as mobility and scalability for heterogeneous devices. In order to support fog-based IoT applications with this demanding heterogeneous requirement, it is necessary to consider protocols and technologies to support devices which have limited bandwidth and energy. In this section, we explore some of the most important enabling technologies that can be used for efficient communication of IoT devices in fog-based IoT architecture. These technologies and protocols include Radio Frequency IDentification (RFID), Wireless Identification and Sensing Platform (WISP), WSN, Bluetooth Low Energy (BLE), Near Field Communication (NFC), IEEE 802.15.4, IEEE 802.11 ah, Z-Wave, Long Term Evolution-Advanced (LTE-A), LoRaWAN, IPv6, IPv6 over Low Power Wireless Personal Area Networks (6LoWPAN), NarrowBand IoT (NB-IoT), and SigFox. In addition, we briefly present some of the available standards such as IEEE Std 1905.1a and IEEE 1451 which are useful to improve interoperability among various technologies, applications and topologies.

The RFID systems operate on a frequency band of 125 KHz and require a 12 V power supply. They are generally made up RFID tags and readers. RFID tags use a technology to reflect back the radio wave and then pass on the data to the readers (Lim, Sim, & Mansor, 2009). RFID readers can read and extract the stored information inside the RFID tags. RFID-based systems have the ability to pick up tag IDs automatically from a distance without considering the Line of Sight (LoS) operations. Moreover, they are able to scan multiple items at the same time without the need to scan them independently. They can also scan the tags quickly typically in milliseconds. Two of the most common applications of RFID-based systems are in commercial stores and hospitals (Omoniwa et al., 2018). For instance, for safety monitoring, an RFID bracelet can be attached to a psychiatric patient (e.g. on the hand of the patient). If the patient attempts to leave the predefined restricted area by passing the door equipped with an RFID reader, an alarm message can be sent to the staff over the wireless network in order to take immediate actions.

WISP is a battery-free and wireless platform used for the purposes of sensing and computation. WISP devices are powered by ultra-high frequency RFID readers. WISP-based systems use the same communication technology as in the RFID-based systems. However, they are unique with a fully programmable micro-controller (Smith, Sample, Powledge, Roy, & Mamishev, 2006). In addition, WISP-based cameras can be used for battery-free imaging (e.g. capture and transmit images) by utilizing low-power communication technology and harvesting wireless power (Naderiparizi, Parks, Kapetanovic, Ransford, & Smith, 2015). Moreover, WISP has recently attracted too much attention in the area of security and cryptography (Smith, 2013).

WSNs consist of small nodes with sensing capabilities. They can be easily deployed into the existing IoT infrastructures with no (or little) modifications since IoT supports interoperability of various networks including WSNs (Gaur, 2015). For example, the authors in Khalil, Abid, Benhaddou, & Gerndt (2014) investigated the integration of WSNs into IoT by deploying real-world wireless sensors in order to monitor appliances in a sustainable and energy efficient smart building (Yu, Haghighat, & Fung, 2016; Mirzaei, Olsthoorn, Torjan, & Haghighat, 2015). Another attempt to integrate WSNs with IoT is presented in Laubhan et al. (2016) where the sensor nodes collect various environmental parameters such as temperature, humidity, and air quality from the environment and store them on the cloud so that the user can access them universally. Different from the RFID-based systems which need a reader, WSNs communicate in a Peer-to-Peer (P2P) manner. However, based on the configuration and algorithm of the WSNs, sink nodes can be utilized to collect sensed data from the other nodes in the network.

BLE is a wireless technology for short-range communication that operates on the 2.4 GHz frequency band (Gomez, Oller, & Paradells, 2012). It can be easily integrated into classic Bluetooth and therefore, can benefit from the use of Bluetooth technology as well. BLE can be utilized in various IoT scenarios such as in medical monitoring (Omre & Keeping, 2010), public transportation systems (Narzt, Mayerhofer, Weichselbaum, Haselbock, & Hoer, 2015), and monitoring industrial environments (Gomez et al., 2012). For example, BLE can be used in industrial and process automation in order to help obtain the data wirelessly from the control room and therefore, facilitates the process of data collection and storage.

NFC (Want, 2011) has a very short-range communication and operates on a frequency band of 13.56 MHz. This standard enables devices to communicate to each other only in close vicinity (e.g. in the range of about 10 cm). The targets of NFC technology can be simple devices such as stickers and cards. Moreover, it also allows P2P communication in which both devices must be powered. NFC can be used for financial transactions (Schamberger, Madlmayr, & Grechenig, 2013; Husni, Basjaruddin, Purboyo, Purwantoro, & Ubaya, 2011). In addition, other applications benefiting from the NFC are social networking (Fressancourt, Herault, & Ptak, 2009), museums (Ceipidor, Medaglia, Volpi et al., 2013), and mobile ticketing systems (Ceipidor, Medaglia, Marino et al., 2013).

The IEEE 802.15.4 standard provides low-cost and low-power wireless communication within short ranges (usually up to 20 m) which makes it appropriate for the use in WSNs, Machine-to-Machine (M2M) communications and IoT. It defines the characteristics of physical and data link layers for Low-Rate Wireless Personal Area Networks (LR-WPANs) products (Atzori, Iera, & Morabito, 2010). The physical layer of the IEEE 802.15.4 standard is responsible for transmitting and receiving data, link quality indication, discovering the levels of energy in the current channel, and clear channel assessment (Karapistoli, Pavlidou, Gragopoulos, & Tsetsinas, 2010). On the other hand, the data link layer of this standard is responsible for frame validation, channel access mechanism, and acknowledgment of delivered frames as well as beacon management (Omoniwa et al., 2018).

IEEE 802.11 ah (Aust, Prasad, & Niemegeers, 2012) is the competitor standard of IEEE 802.15.4. It is an improvement to the widely utilized IEEE 802.11 standard and uses the frequency band of 900 MHz to provide extended network coverage. The performance of the IEEE 802.11 ah reveals that it performs better than IEEE 802.15.4 in case of congested networks. However, IEEE 802.15.4 outperforms IEEE 802.11 ah in terms of energy consumption (Olyaei, Pirskanen, Raeesi, Hazmi, & Valkama, 2013). Moreover, the study in (Akeela & Elziq, 2017) shows that the IEEE 802.11 ah is suitable for M2M, Vehicle-to-Vehicle (V2V), and IoT applications which require long-range communication and long battery life.

Z-Wave (Yassein, Mardini, & Khalil, 2016) is a low power MAC protocol that operates on the frequency band of 908 MHz and is utilized by small data packets within the range of 30 m at low speeds up to 100 kbps. However, it is not suitable for transmitting or streaming of time critical data due to its low data rate (Al-Sarawi, Anbar, Alieyan, & Alzubaidi, 2017). The ZWave solution can be extensively used in smart home automation where the protocol runs over various appliances with smart sensors, smart lighting, smart air-conditioning, etc.

LTE-A is the enhanced version of LTE which provides higher throughput and lower latencies as well as improved coverage. It supports higher bandwidth up to 100 MHz aiming to obtain a higher level of system performance (Wali & Das, 2014). LTE-A has important characteristics such as carrier aggregation, support for relay nodes, and enhanced use of multi-antenna techniques which make it suitable for the use in fog-based IoT infrastructures. This is because fog-based devices may be used to offer relay services to end-devices or other fog nodes in the network.

LoRaWAN is a Low Power Wide Area (LPWA) technology which supports low power and low data rate (e.g. from 0.3 kbps to 50 kbps) as well as long-range operations. In fog-based IoT, LoRa technology can be used by end-devices in order to communicate with gateways using a single hop. Moreover, the LoRaWAN technology can solve the connectivity problem of billions of smart devices in the IoT era in the next few years (de Carvalho Silva, Rodrigues, Alberti, Solic, & Aquino, 2017).

IPv6 is the Internet protocol introduced to overcome the shortcomings of IPv4. It can handle scalability by providing a unique address to a large number of IoT devices. IPv6 supports Internet Protocol Security (IPSec). It also offers supports for neighbor discovery which enables neighboring nodes to communicate and determine the presence of each other. These features make IPv6 a suitable protocol for fog-based IoT systems where fog-based devices share the information on how to reach each other and how to relay information through the available device. 6LoWPAN is a standard defined to support IEEE 802.15.4 low-power wireless networks in the frequency band of 2.4 GHz (Olsson, 2014). It enables IPv6 connectivity for constrained embedded devices that utilize IEEE 802.15.4 low-power wireless communications (Mamo & Sikora, 2015).

NB-IoT is a low power cellular technology specifically designed for IoT in order to provide improved coverage with respect to LTE. With NB-IoT, it is possible to connect different objects that need small amount of data over long periods (Zhang, Li, Wen, Xun, & Liu, 2018). This technology has been utilized in different smart cities' applications such as intelligent parking and smart hospitals (Zhang et al., 2018). The integration of NB-IoT and fog computing can save network bandwidth, ensure the quality of data analysis, improve the response time, and enhance the efficiency of data storage compared to traditional cloud computing models (Qin et al., 2019).

SigFox is a network protocol that provides M2MWAN communication solutions that operate on the 868 MHz frequency band. It is especially designed to meet the requirements of massive IoT applications in order to enhance the network capacity, increase life cycle of the device, reduce cost of devices, and improve communication range as well as minimize energy consumption (Lauridsen et al., 2017). SigFox is a software-based communication solution where all the computing tasks are managed in the cloud. SigFox will have better potential in fog-based IoT systems because of capability of fog-based devices to perform some of the tasks closer to the network edges (Omoniwa et al., 2018).

In addition to abovementioned protocols and technologies, IEEE Std 1905.1a and IEEE 1451 are two available standards that can be utilized to improve interoperability among various technologies, topologies, and applications in fog-based IoT systems. IEEE Std 1905.1a is a standard that supports a common interface, by defining an abstraction layer, in order to deploy multiple networking technologies at smart homes (IEEE Standard for a Convergent Digital Home Network, 2015). The abstraction layer provides a platform for improving network range, guaranteeing security for network connections, and establishing various network management functionalities such as Quality of Service (QoS) negotiation, discovery, and path selection. IEEE Std 1905.1a can be easily deployed to fog-based IoT systems with different characteristics such as load balancing, aggregated throughput, self-install, and the support for simultaneous and multiple streams (Omoniwa et al., 2018).

IEEE 1451 (Wobschall, 2007) is a set of standards developed to integrate various protocols and standards to support interoperability among different applications and technologies. An important characteristic of IEEE 1451 standard is that Transducer Electronic Data Sheets (TEDS) of all transducers and the data communicate on the Internet in the same way for all sensors and actuators regardless of the type of the network which can be either wired or wireless.

5. Fog computing applications in support of the IoT

Fog computing plays a significant role in the next generation of mobile networks (5 G) in support of the IoT. Various applications can make use of different services introduced by fog technology to enhance the overall performance of the network. In this section, we describe and list some typical ones of these applications. Fig. 3 illustrates various applications of fog computing in support of the IoT.

5.1. Smart agriculture

Agriculture is a vital part of any sustainable smart city projects as it contributes to the food supply chain significantly (Perera et al., 2017). In the smart agriculture domain, sensors deployed in field vehicles can be used to collect information regarding the plant growth and climate conditions in the field. In addition, air balloons can be utilized to sense the field from the sky. Fog computing can play an important role in doing the aforementioned sensing tasks more efficiently. For example in Guardo, Di Stefano, La Corte, Sapienza, & Scata (2018), a fog computing-based solution is proposed for the smart agriculture where the computing is distributed to balance the computational load and reduce the waiting time in the actuation phase of an event. The infrastructure can easily manage agricultural lands and track the alarm notifications from the sensor nodes.

5.2. Smart traffic light and intelligent transportation systems (ITS)

A smart traffic light system is a network of connected traffic lights which helps to minimize traffic congestion, prevent accidents, and reduce noise and fuel consumption. This in turn, can provide a better driving experience for people. For example, in case of health monitoring systems, street cameras that sense the flashing lights of an ambulance can change the street-lights for the ambulance to pass through the traffic. In this domain, street-lights communicate with sensors and detect the presence of vehicles and pedestrians, and adjust the lighting accordingly. Fog devices can coordinate to provide green traffic wave and send warning signals to vehicles approaching the traffic. Moreover, in the context of ITSs (Al-Turjman & Malekloo, 2019), transportation data would be huge and can cause large delays if a central system is responsible to analyze the data. In this regard, fog-based devices placed at certain intersections can be used to analyze local data and inform people of the updated information about the routes which in turn reduces the delay significantly.

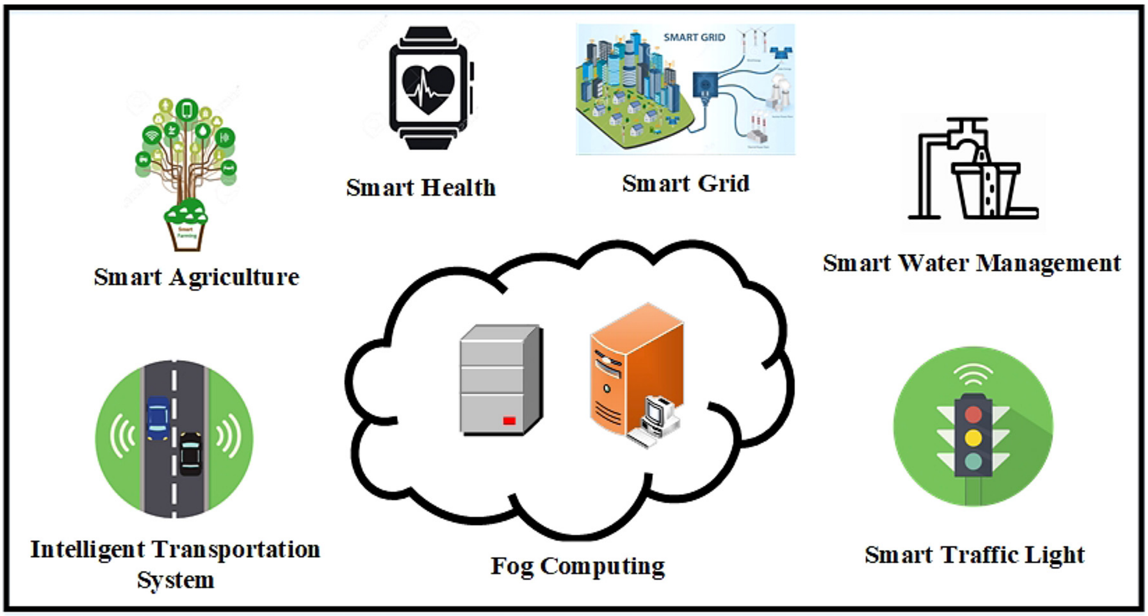

Fig. 3. Applications of fog computing in support of the IoT.

5.3. *Smart health*

Fog computing can be utilized in healthcare domain in which it is crucial to perform processes in real-time. For instance, fog technology can be used to detect, predict, and prevent falls for stroke patients. In Cao, Chen, Hou, & Brown (2015), a pervasive fall detection for stroke mitigation is employed for similar purposes using fog computing technology to investigate and develop new algorithms for designing a real-time fall detection system based on new filtering and non-linear time series analysis techniques. Experimental results show that using fog computing improves the performance of the system in terms of response time and energy consumption compared to cloud-only approaches. Moreover, a fog-based smart healthcare system provides mobility support, low latency, and location and privacy awareness (Stantchev, Barnawi, Ghulam, Schubert, & Tamm, 2015).

5.4. *Smart water management*

One of the most important aspects regarding future sustainable smart cities is related to smart water management. Cost-effective and energy efficient transportation and use of water are important in this regard (Perera et al., 2017).

A smart water management system helps to monitor water consumption, transportation, and anticipation of future water use. In addition to all of these features, the smart water management system can reduce water losses in the city and improve the city water system by analyzing data collected from the sensors deployed in the system. In this regard, fog-based infrastructures together with other wireless technologies and protocols such as IPv6, 3 G, 4 G, and LTE will help to achieve the mentioned enhancement in the smart city's water system. Moreover, fog computing can enhance the Cloud of Things (CoT) services which can be utilized to implement smart water networks in order to make them more sustainable, more reliable and more efficient (Mohamed, Lazarova-Molnar, & Al-Jaroodi, 2017). In addition, the CoT with the help of fog technology can monitor the quality of water, and provide information on the presence of toxins or pollutants in the water in real-time.

5.5. *Smart grid*

In sustainable smart cities, smart grids are important since they provide efficiency, availability, and reliability in electricity management in the city (Abujubbeh, Al-Turjman, & Fahrioglu, 2019). A smart grid system is expected to improve transmission efficiency of electricity, minimize operation costs, and provide better integration with renewable energy systems in order to save electricity for future usage. Therefore, it will be of great importance to build better electricity networks and reduce the electricity bills in the cities. In this regard, fog computing plays a significant role in support of a successful smart grid in smart cities. In a fog-based smart grid, data generated by fog devices and sensors can be processed by fog collectors. They can also filter the data to be locally processed and send it to cloud for real-time visualization and analysis. For example, the study in Moghaddam & Leon-Garcia (2018) proposes a fog-based architecture for Transactive Energy (TE) management system where fog nodes are used as retail energy market\ server providing energy services to the users. In the proposed architecture, customers avoid buying energy from the power grid which is more expensive at the peak times and instead, buy energy from each other. The performance evaluation of the proposed architecture reveals that the fog-based architecture outperforms the cloud-based model in terms of total bandwidth and delay especially when the communication channel is not ideal.

6. Caching in fog computing

In the fog paradigm, services and resources of the cloud are closer to the users which facilitate them in the edge networks. With the significant growth of data gathered by smart devices (e.g. sensors), the demand for efficient data collection and delivery in the IoT era has become extremely important. Caching is a technique which usually comes with data delivery, and plays a significant role in improving the performance of the network in terms of various factors such as reliability and response time. In fog-based IoT systems, caching at the fog nodes can reduce the computational complexity of the cloud as well as the network load (Balevi & Gitlin, 2018). In this paper, we review available caching techniques in the literature and discuss their strengths and weaknesses in fog-based IoT systems. We classify these techniques based on the following parameters: functionality, location, and content. A comparison of these techniques is presented in Table 3.

Caching based on functionality: In the content-oriented networks, in order to increase its potential as much as possible, the content must be stored in the control level instead of guessing it at the data level

Table 3
A comparison of different caching techniques in fog-based IoT systems.

Ref	Caching Technique	Strength	Weakness
(Wang et al., 2012)	Functionality-based	Efficient in terms of latency	Not sufficient for fog systems since some content types would probably be handled more efficiently using devices such as smartphones at the edge of the network.
(Ming et al., 2014)	Functionality-based	Efficient in terms of latency and consumed bandwidth	Requires knowledge of in-network nodes' capabilities which contradicts with the fog paradigm.
(Eum et al., 2012)	Location-based	Efficient in terms of availability, adaptability, diversity, and robustness	Makes a geographical bottleneck for the node in the network.
(Hail et al., 2015)	Location-based	Lower delay, higher value of successfully received packets	Interactions between caching and various routing protocols are not considered.
(Sourlas et al., 2012)	Content-based	Efficient in terms of energy and environmental metrics	Higher cost of additional message exchanges and computational efforts.
(Al-Turjman, 2019)	Content-based	Reduces data publisher load	Not suitable for fog systems since the authors did not consider multiple gateways.

(Wang et al., 2012). For example in Wang et al. (2012), the authors studied the relationship between caching the content in distributed IP-based systems and the new content-oriented designs in the fog-based systems. They considered a combination of real-time traffic from various sources such as the web and multimedia streaming, and concluded that addressing cached content in the control level is more efficient than guessing them at the data level. Moreover, in Ming, Xu, & Wang (2014), the authors proposed

an algorithm in which a cluster of caches is considered with various leafs connected by a parent node. In order to fetch the data from the parent node, an inter-level cache cooperation is used. This technique provides more cost effective solution in terms of latency and consumed bandwidth, and significantly reduces network delay and traffic. However, this approach would not be ideal for fog-based systems since other types of contents would probably be handled more efficiently with other devices such as smart phones at the edge of the network (Al-Turjman, 2017).

Caching based on location: Location-based caching is another category for caching in fog-based systems. In this category, data is stored in a node with the highest probability of getting a cache-hit (Al-Turjman, 2017). For instance, a caching policy is proposed in Eum, Nakauchi, Shoji, Nishinaga, & Murata (2012) where a node for caching is selected as long as the node has highest connectivity degree according to its geographical position. However, this makes a geographical bottleneck for the node in the network. In Hail, Amadeo, Molinaro, & Fischer (2015), a location-based caching policy is proposed by utilizing a combination of probabilistic caching method and geo factors. The method also considers device energy, storage capability, and data freshness as well as a probabilistic least recently used approach. The results obtained by the authors reveal that the proposed algorithm enhances the performance of the system in terms of data retrieval and energy efficiency.

Caching based on content: Caching based on content is another approach for caching in fog-based systems. In Sourlas, Flegkas, Gkatzikis, & Tassiulas (2012), an approach is proposed by the authors suggesting that the Least Recently Used (LRU) approach would probably be the most suitable candidate for caching in cloud-based networks. Through a comparison between the pure LRU approach and three other approaches named; the probabilistic LRU, the pure randomness, and the probabilistic caching method, the authors concluded that the LRU method improves the performance of the system in terms of energy and environmental metrics. Moreover, the authors in Al-Turjman (2019) proposed two popularity-based caching approaches from the basis of optimal replica replacement trying to reduce the data publisher load and increase the in-network cache-hit. This approach may not be suitable for fog-based systems since the authors did not consider multiple gateways in the network as they can be used in fog paradigms.

6.1. *The use of UAVs in caching data in the fog-based IoT systems*

Drones or Unmanned Aerial Vehicles (UAVs) can be used to improve connectivity in terrestrial wireless communications (Zeng, Zhang, & Lim, 2016). They can also enable Line of Sight (LoS) communication to the User Equipment (UE) on the ground and therefore, enhance the overall performance of the network. The efficiency of caching from the edge of the network has been extensively analyzed in the literature especially for wireless Content Delivery (CD) networks (Ji, Caire, & Molisch, 2015; Altieri, Piantanida, Vega, & Galarza, 2015; Wang, Zhang, Song, & Letaief, 2017). However, none of these studies considers mobility of the CD nodes, and the temporal and spatial dynamics of storage and transmission capacities. Therefore, the user who requests a content file cannot be served efficiently if the requested fille is not cached at the node or if the user moves outside of the area where the caching node provides service. To overcome this challenge, a number of studies considered the use of UAVs to store and deliver contents to the user on the ground (Xu, Zeng, Guan, & Zhang, 2018; Zhao et al., 2018]. Considering mobility of UAVs and their easy implementation, this can facilitate many efficient, cost-effective, and reliable solutions. For example, UAVs can be used to increase the coverage of the static CD nodes, and dynamically extend the transmission and storage capacities. In Asheralieva & Niyato (2019), the authors consider the operation of the cloud-based CD networks with Device-to-Device (D2D) and UAV-enabled caching which can improve scalability, reliability, and elasticity compared to the traditional CD networks (Networking, 2016). Moreover, the work in Chen et al. (2017) studies the problem of proactive deployment of cache-enabled UAVs in order to optimize the Quality of Experience (QoE) of wireless devices in a cloud-based Radio Access Network (RAN). However, little research has been carried out so far to adapt UAV communications with the fog-based systems for caching data from the fog. The only attempt in Khoshkholgh, Navaie, Yanikomerogluy, Leung, & Shin (2019) proposes a UAV-enabled fog-based system supported by caching and cooperative communications. In the proposed system, the UAVs placed in a cooperation zone contribute in a cooperative transmission approach to the users on the ground. In addition, the authors, using stochastic geometry, develops an efficient probabilistic content placement algorithm. The results of this study reveal that the developed algorithm performs better than classical caching techniques in terms of energy efficiency.

7. AI/ML techniques in caching data for the fog-based IoT systems

To address the huge amount of multimedia data traffic and requirements of user QoE in the next generation of mobile networks (5 G) (Yang, Fan, Ren, Zhao, & Alam, 2019), it is of vital importance to develop and design efficient content caching techniques at the edge of the network which is considered as a key strategy for 5 G (Hou, Feng, Qin, & Jiang, 2018). Recent developments in fog computing and Machine Learning (ML) provide efficient caching techniques for 5 G which can reduce service latency by providing computation and storage capacity at the network edges. Moreover, caching at the edge of the network is considered as a promising solution to reduce the redundant data transmission and improve the QoE (Han et al., 2019). In this section, we overview the used AI/ML techniques in caching data for the fog-based IoT paradigm.

In Tanzil, Hoiles, & Krishnamurthy (2017), the authors present an adaptive caching technique based on the extreme-learning Machine Neural Networks (MNNs) to estimate the popularity of the content based on the content's features, behavior of the users, and the available statistics requested from the users. The scheme also uses a mixed-integer linear programming to select the physical cache sizes and estimate the location of the content in the network. Finally, the authors show that the proposed caching technique improves the users' QoE as well as the performance of the network compared to industry standard caching techniques. The study in Bastug, Bennis, & Debbah (2014) proposes a networking paradigm where network nodes, using a proactive approach, cache wisely selected contents at the edge of the network. In this regard, Collaborating Filtering (CF) strategies are utilized to predict the file popularity matrix. Nevertheless, CF learning techniques are suboptimal primarily due to data sparseness and cold-start problems which are important challenges among the ML experts (Lee, Sun, & Lebanon, 2012). Similarly, the authors in Bastug, Bennis, & Debbah (2015) utilize transfer learning for popularity estimation where the most popular contents are cached in a proactive manner at the small Base Stations (BSs) until the storage is full at the BSs. However, there may be redundant caching since each BS caches the most popular content independently, and therefore, the same content may be cached by several small BSs. This in turn results in low caching efficiency. Moreover, in Han et al. (2019), a proactive caching strategy is proposed based on mobile edge computing to minimize the average transmission cost and increase the cache hit rate. The authors propose a transfer learning-based approach to predict content popularity and utilize a greedy algorithm in order to solve the problem of cache content placement. The results of this study reveal that the proposed caching mechanism performs better in terms of average content delivery, transmission cost and latency as well as cache hit rate compared to other content caching schemes such as Randomized Replacement (RR) and popularity-aware greedy strategy.

Traditional caching techniques generally need a large number of online optimization iterations to define content delivery and placement. Therefore, they are considered as high computational complexity methods. However, by using Deep Neural Networks (DNNs) for the optimization of caching at the edge of the network, offline training would be used to avoid online heavy computation iterations. This only requires Deep Learning (DL) interface which provides optimization strategies. A DNN can be trained with techniques provided by heuristic or optimal algorithms to define the cache policy (Chang, Lei, Zhou, Mao, & Ristaniemi, 2018). This can result in avoiding online optimization iterations. In addition, since there are some patterns for the output of the optimization problem related to partial cache refreshing, a multi-layer perceptron can be trained to accept the current content popularity and the last content placement probability as input to provide the cache refresh policy (Yang, Zhang et al., 2019). Therefore, according to Chang et al. (2018) and Yang, Zhang et al. (2019), DNNs can be utilized to reduce the complexity of the optimization algorithms. However, techniques based on DNNs can only be used when the optimization algorithms for the original caching problem is available. Therefore, these methods cannot be considered as self-adapted and their performance is restricted to fixed optimization algorithms. Moreover, DL can be used for customized caching at the edge of the network. For example in Ndikumana, Tran, & Hong (2018), a multi-layer perceptron is deployed in the cloud in order to anticipate content popularity to be requested and minimize delay for content downloading in self-driving cars. The outputs of the multi-layer perceptron are then sent to the nodes at the edge of the network and based on these outputs, each node caches the contents which have the higher probabilities to be requested. On self-driving cars, Convolutional Neural Networks (CNNs) can be used to predict the gender and age of the owner (Ndikumana et al., 2018). As soon as these features are identified, other ML algorithms such as binary classification algorithms and K-means clustering (Kanungo et al., 2002) can be used to define which contents should be downloaded from the nodes at the edge of the network to the car.

In addition, by considering the fact that users' willing to access the contents at various environments is different and changing (Tang, Guo, Ma, Shen, & Chi, 2019), Recurrent Neural Networks (RNNs) can be utilized for the prediction of the users' trajectories. According to these predictions, all the contents of the users' interest can be cached on the node at the edge of the network of each predicted location in advance.

Besides DNNs, Deep Reinforcement Learning (DRL) can be used to maximize the long-term caching performance dealing with the whole optimization problem (Adelman & Mersereau, 2008). The advantages of DRL are in the fact that DNNs can learn main features from the raw observation data. By combining DL and RL, the integrated DRL can enhance the methods related to cache management in fog/edge computing paradigm directly from high-dimensional observation data. For instance in Zhong, Gursoy, & Velipasalar (2018), a Deep Deterministic Policy Gradient (DDPG) is utilized to train a DRL agent in order to enhance the cache hit rate and make appropriate decisions regarding cache replacement. In this study, a single base station scenario is considered such that the DRL agent makes decision to cache required the contents or replace the cached contents. In addition, in Dulac-Arnold et al. (2015), the authors propose an algorithm to deal with the large action space challenge. In this regard, K-Nearest Neighbor (KNN) algorithm is used to map the set of practical action inputs into one integrated input. Therefore, the action space is narrowed down in an intended way without missing the optimum caching policy. The results reveal that the proposed algorithm outperforms in the terms of cache hit rates and runtime compared to the algorithms based on Deep Q-Learning (DQL) which search the whole action space instead. Another study on the use of DRL for caching in the fog-based IoT is presented in Zhou, Peng, Yan, & Sun (2018). In this study, a DRL-based algorithm is proposed for coded caching scheme in fog RANs. In this regard, the network controller allocates limited cache spaces of the fog access points to various coded files according to the users' historical requests. The simulation results show the performance improvement of the proposed algorithm in terms of successful transmission probability compared to other ML algorithms such as Q-Learning.

8. Simulation environments in the fog-based IoT systems

Simulations are valuable techniques for development of the IoT-based systems and are considered as an alternative approach to design a working prototype of the model since they can describe the actual characteristics of the testbeds where IoT devices are installed and configured. Moreover, simulations provide opportunity for developers and researchers to conduct and repeat experiments in lower cost, and allow them to collect data which can be used to validate the results obtained by other evaluation techniques such as analytical modelling. A fog-based IoT simulation tool has to provide high accuracy for various heterogeneous scenarios and support complex network designs. In addition, it should provide scalability and extensibility as well as mobility based on realistic scenarios. Although, there are a broad range of simulators for cloud computing such as iCanCloud (Nunez et al., 2012), OMNeT++ (Varga, 2010), CloudSim (Calheiros, Ranjan, Beloglazov, De Rose, & Buyya, 2011), GreenCloud (Kliazovich, Bouvry, & Khan, 2012), and CloudAnalyst (Wickremasinghe, Calheiros, & Buyya, 2010), there are only few tools that can be utilized to simulate fog computing scenarios in the IoT era. In this section, we briefly discuss and compare the most common simulation tools used for simulating the fog-based IoT frameworks. A summary of the main characteristics and capabilities of these simulation tools is also presented in Table 4.

FogNetSim++: It is a simulation tool designed on top of OMNeT+

Table 4
A comparison between different tools for simulating the fog-based IoT systems.

Attributes	FogNetSim + +	iFogSim	FogTorchII	EmuFog	Fogbed
Latency	–	–	X	–	–
Bandwidth	X	–	X	–	X
Delay	X	–	–	–	–
Handover	X	–	–	–	–
Resource Consumption	X	X	X	X	X
Power Consumption	–	X	–	–	–
Mobility	X	–	–	–	–
Scalability	X	–	–	–	–

- = Not Considered, X = Considered.

+ (Varga, 2010) to simulate a large fog network in the IoT era (Qayyum, Malik, Khattak, Khalid, & Khan, 2018). It enables researchers to consider fog scheduling algorithms and mobility models as well as handover mechanisms in their simulation environment. The effectiveness of FogNetSim + + can be evaluated in terms of memory usage and CPU using a traffic management system. Moreover, FogNetSim + + supports Packet Error Rate (PER), latency, handover, and execution delay. However, it does not yet support Virtual Machine (VM) migration among fog nodes.

iFogSim: Another tool for simulation of fog computing infrastructures is iFogSim (Gupta, Vahid Dastjerdi, Ghosh, & Buyya, 2017). This simulation toolkit allows users to measure performance of fog computing environments in terms of energy consumption, network usage, and latency. iFogSim is based on CloudSim (Calheiros et al., 2011) and enables simulation and modelling of fog computing infrastructures in order to evaluate scheduling and resource-management policies. Moreover, iFogSim integrates simulated services for resource management and power monitoring at application scheduling and placement layers to support multiple deployment scenarios such as cloud-only deployment and edge-ward placement (Moysiadis, Sarigiannidis, & Moscholios, 2018). In addition, it is possible to extend simulation models to support the design of data placement strategies based on certain goals such as reducing energy consumption and network congestion as well as minimizing the service latency (Naas, Boukhobza, Parvedy, & Lemarchand, 2018). However, iFogSim does not support mobility and its scalability is restricted since it is limited to discrete event simulation.

FogTorchII: FogTorchII (Brogi, Forti, & Ibrahim, 2017) is an open source simulator based on Java that supports application deployment in the fog. It is capable to model software capabilities such as programming languages and OS, and hardware capabilities including RAM, storage and CPU cores, as well as QoS metrics such as bandwidth and latency. FogTorchII implements variations in communication links used as inputs, and then, the outputs contain results in terms of fog resource consumption and QoS assurance which can be obtained by evaluation of the storage and consumed RAM. However, the main limitation of the FogTorchII is related to its scalability (Brogi et al., 2017).

EmuFog: This is an emulation framework appropriate for fog computing scenarios (Mayer, Graser, Gupta, Saurez, & Ramachandran, 2017). EmuFog enables the design of fog computing environments and emulation of applications in large scale, and allows users to evaluate and implement the behavior of their models in the network topology. Besides the advantages and usefulness of the EmuFog, it does not support hierarchal fog infrastructures. Furthermore, it does not support mobility for both fog nodes and clients.

Fogbed: Fogbed (Coutinho, Greve, Prazeres, & Cardoso, 2018) is an emulator designed on top of the network emulator Mininet (De Oliveira, Schweitzer, Shinoda, & Prete, 2014). It provides opportunities to design and evaluate cloud and fog testbeds. The Application Programming Interface (API) of the Fogbed allows the users to add, connect and remove containers from the network topology in a dynamic way, which in turn enables the emulation of real-world fog infrastructures. However, Fogbed does not yet support some of the important aspects of fog computing such as scalability, fault-tolerance, security, and reliability management.

9. Open research issues

Despite of many research studies carried out in fog computing and the recent development in the IoT, there are still many challenges and research issues that must be carefully studied regarding the utilization of fog paradigm in the IoT era.

9.1. Standards & programming languages

Initially, fog computing has been utilized to extend the cloud-based services closer to the IoT devices. Since the structure of fog and cloud are different, it is highly required to modify and improve the existing standards and related programming languages in order to enable cloud-based services in fog paradigm. In addition, it is extremely important to develop efficient networking protocols and user interfaces for management of a large number of connected devices in fog-based IoT systems.

9.2. Scalability

Scalability is a crucial issue that has to be considered by researchers for large-scale systems such as fog-based IoT applications. The lack of real-world data on fog-based systems may result in algorithms that are not suitable for real-world scenarios. Therefore, it is beneficial to investigate on optimal algorithms that describe complexity of the fog-based systems. Moreover, the local interactions within the fog-based IoT networks can result in instability of global states in most distributed systems. Mechanisms to overcome this challenge will significantly enhance the performance of the fog-based IoT networks. Furthermore, in fog-based systems, only necessary and urgent requests are managed by the fog and the other tasks are sent out to the cloud for further processing. Therefore, it is important to determine the point where the fog achieves the optimal resource utilization based on the type of service, the number of users, and available resources.

9.3. Resource utilization

Fog devices provide an efficient platform for multiple heterogeneous technologies offering various services to the end-users in the IoT era. However, an important challenge is how to link resources across multiple platforms. Therefore, it will be extremely important to investigate on efficient algorithms, regarding scheduling, matching and synchronization tasks, for proper resource utilization of resource-constrained IoT devices.

9.4. Deployment

Deployment is an important issue in fog-based IoT systems as it may cause latency if it is not done properly. The decision regarding the deployment of fog layer in the IoT architecture should be made according to different requirements such as the number of sensors, type and amount of task that will be carried out in the fog layer, and the capability of fog devices. It is of utmost importance to investigate how these requirements will be fulfilled. Moreover, another important issue during the deployment is related to application and resource scaling. According to the requirement of the application and resource, scaling and shrinking can be utilized if they do not interrupt the existing services. In this regard, placement may affect the deployment of fog computing paradigm (Naha et al., 2018).

9.5. Power management

Fog nodes have to handle a vast number of services coming from various end devices (e.g. sensors). One approach in this regard is deployment of fog nodes in the environment based on the demand. However, this solution will dramatically increase the number of computationally active fog nodes and hence, increase the total power consumption of the system. Therefore, in fog networks, efficient power management is crucial in dealing with the large number of available services. In addition, for the power management within fog network, it can be an effective solution to consolidate fog nodes by moving jobs from one node to another in some applications. Therefore, it is important to investigate toward the techniques regarding this issue in fog-based systems. Moreover, fog devices are often power-constrained. Therefore, it is important to manage energy usage within the fog-based IoT ecosystem using optimal power control techniques. As the communication in the fog-based IoT ecosystem is mostly machine-oriented, it results in drastic increase in energy consumption of IoT devices. Therefore, further research need to be carried out in order to improve energy efficiency within the framework of fog-based IoT.

9.6. Security & privacy

Security and privacy are also one of the most important challenges in the realization of fog-based systems. Since fog nodes are located between end users and cloud data centers, the security vulnerability of fog computing is relatively high. For instance, in some cases, data which are coming from end devices (e.g. sensors) are related to users' situations and interests. Therefore, one of the most important concerns regarding security in fog computing is related to appropriate privacy assurance that needs be thoroughly investigated. One of the most dangerous attacks in fog-based IoT architecture is Distributed Denial of Service (DDoS) attack. DDoS attacks may be generated from IoT end-devices. For instance, different malicious devices may start many fake service requests simultaneously. This makes it impossible for the IoT end-devices to handle real service requests due to limited processing capabilities since they are busy with those fake service requests. Another important security attack in fog-based IoT environments is Man-in-the-Middle Attack (MMA). This attack easily utilizes fog-based IoT infrastructures to reveal private and sensitive information such as the identity and location of the IoT end-devices (Mukherjee et al., 2017). It is also possible to physically compromise hardware components such as IoT end-devices, sensor devices, and RFID tags. This type of attack is called physical attack. The capability of physical attacks depends on the location of deployment and the level of protection given to such devices (Abomhara & Koien, 2014).

9.7. Blockchain & software defined networking (SDN)

The Blockchain technology is capable of delivering a secure foundation for regulating data as well as information transactions between independently functioning devices in fog-based IoT environments. Blockchain introduces secure transmission and storage by digitally signed documents in order to enhance privacy and protection. Therefore, it is very important to research more into this technology in order to provide and enhance mechanisms regarding transferring data directly among IoT devices for secure communication using a reliable method such as a time-stamped contractual handshake (Tariq et al., 2019).

In addition, Software Defined Networking (SDN) is a technology that can be integrated with fog technology to provide efficient data sharing and reliable resource cooperation. SDN can also add more functionalities such as intelligence to the fog-based IoT networks (Khan et al., 2019). Moreover, SDN can be used to secure fog-based IoT architectures. For example, the authors in (Sharma & Park, 2018) proposed a hybrid network architecture utilizing SDN and Blockchain for smart cities. Therefore, it would be beneficial to conduct research into SDN and its integration with Blockchain to provide efficient architecture towards sustainable smart cities.

9.8. Latency management

In fog computing, latency management is necessary in order to ensure an acceptable level of Quality of Service (QoS). Therefore, research into various latency management approaches will help to provide lowest latency in service delivery and ensure better QoS in the entire system. Another important issue in fog computing is related to resource estimation. It helps in allocation of computational resources based on different policies so that proper resources for further computation can be allocated. Therefore, extensive research into various resource estimation policies in terms of different factors such as user characteristics and experienced QoE would be beneficial in order to achieve desired QoS.

9.9. Sustainability & interoperability

Sustainability is referred to the use of renewable energy resources, energy harvesting and energy efficient designs to decrease the total carbon footprint (Khan et al., 2019). This is an important requirement when designing fog-based IoT architectures for smart cities. In smart cities, it is expected to have dense IoT end-devices and fog computing servers. Thus, the infrastructure design of smart cities would face significant energy limitations. Therefore, it is extremely important to conduct research into various ways to improve the energy efficiency of fog-based IoT systems without degrading QoS. This can be done using energy efficient caching techniques (Luo et al., 2017).

Interoperability is another important requirement to turn the vision of fog-based IoT and sustainable smart cities into reality. The challenge of interoperability for fog-based IoT systems in sustainable smart cities arises because of huge number of heterogeneous IoT devices operating with different protocols. The fog-based IoT architecture should be able to provide interoperability in order to enable seamless operation in such a way that different systems and devices can understand and use each other's functions properly. Therefore, further research need to be conducted in order to design frameworks that support interoperability for fog-based IoT systems in sustainable smart cities.

10. Conclusion

Nowadays, the emerging paradigm of the fog computing can act as a link between IoT smart devices and cloud data centers in order to provide services that have better delay performance. In this article, through a comprehensive investigation on the existing studies related to fog computing, we provided an overview of the fog paradigm, its services and potential enabling technologies in the IoT era. We also classified and described various available caching techniques in fog-based IoT systems and compared their strengths and weaknesses in details. Moreover, we listed and described some of the typical applications of fog computing in the IoT environments. Although various studies in existing literature consider surveys that cover various aspects of fog computing in the IoT era, to the best of our knowledge this work is the first one to consider the use of UAVs and AI/ML techniques in caching data for better data delivery in the fog-based IoT applications.

Declaration of conflicting interest

The authors declare that there is no conflict of interest regarding the publication of this article.

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