Greening IoT with Fog: A Survey

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Greening IoT with Fog: A Survey

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***Abstract*—The current growth in Internet services, mobile devices, and machine-to-machine (M2M) technologies is providing the building blocks for the Internet of Things (IoT) as it is being applied across all industry sectors. With ongoing proliferation of IoT applications, a new platform called Fog/edge computing, in addition to Cloud computing, is being developed to address requirements such as bandwidth, latency and location awareness. As with previous many telecommunication systems, energy consumption concerns in IoT have been deferred to the point that it may become a bottleneck in the future. This work conducts a survey of existing literature addressing IoT energy consumption growth. We firstly highlight the factors and technologies in the system design, application layer and network virtualizations which lead to higher or lower energy consumption of an IoT service. Furthermore, we report strategies that can help to alleviate power consumption of IoT applications and services using Fog computing. Our objective is to provide a survey for network designers and policy makers who wish to gain an insight into deploying energy-efficient IoT applications.**

Keywords—Edge Computing; Fog Computing; Internet of things (IoT); Energy consumption of IoT;

I. INTRODUCTION

In the coming years, a growing number of physical objects are expected to be connected to the Internet at an unprecedented rate, as society and industry deploys the Internet of Things (IoT)[1]. The basic premise in IoT is one of enabling physical objects to collaborate directly without human interference to share information, coordinate intelligent and real-time decisions and ultimately deliver ubiquitous services across the full spectrum of human activity. The IoT is rapidly becoming pervasive in our lives, with the considerable reduction in both size and cost of IoT devices as well as progressive developments in big data and predictive analytics [1].

It is expected in the near future, IoT applications will be delivering a very diverse range of services, supported by a very heterogeneous collection of devices deployed as part of the IoT's infrastructure. Many of these sensors and actuators are anticipated to connect to each other and exchange data and information over the Internet. In this regard, resource management, service creation, service management, service discovery, data storage, and power management would require careful integration of IoT infrastructure and sophisticated coordination of these components. Cloud computing comes into play here [2]. The collected sensor data would be sent to a server located in a Cloud data center for processing to ascertain any required action. Should an action be required, a server would then coordinate the necessary resources based on service requirements. The use of only centralized Cloud computing raises concerns such as bandwidth limitation and delay.

In many applications, IoT devices and sensors collect data in a local network and the actions required in response to the collected data take place in the same local network. Hence, a new platform called Fog/edge Computing [3, 4] has been introduced to serve IoT applications that either cannot be performed in the Cloud due to the requirements of the service, or which do not benefit from the resources of the C loud. Fog computing adds local intelligence (compute and storage) to a cluster of IoT devices forming a localised network. Fog can make possible services requiring low latency, and for other services can mitigate the volume of data that might otherwise need to be sent to a (remote) data center. This platform enables refined and better applications or networking services between the end nodes in an IoT and the traditional Cloud.

Fog computing in IoT is not a replacement of the Cloud; rather they are largely complementary to each other. Indeed, the management and updating of Fog systems may well be handled from the Cloud. Currently, there is a significant effort focusing on improving security, privacy, scalability, mobility and etc. in IoT applications across many industries in which the IoT can be applied. However, there has been less emphasis on the growth of energy consumption of IoT applications, although sensing/acting devices require power to collect, transmit and possibly analyze the data.

In this article, we present a brief overview of published work that has researched the power consumption by Cloud and Fog computing for IoT applications. We discuss the factors in the system design that lead to high power consumption. We also report on strategies that can help to reduce power consumption of IoT applications and services. We highlight factors and technologies that can impact the energy consumption of IoT applications such as the type of access network in the Fog, the idle time of servers located in the Fog and network virtualization. Finally, we discuss the possible use of microgrid resources to power Fog computing in order to reduce the carbon footprint of IoT services.

The goal of this article is to provide insights to assist network designers or policy makers when contemplating the development of energy-efficient IoT applications.

The rest of the paper is organized as follows. In Section II we introduce the Cloud and Fog Computing paradigms and

First and second authors contributed equally.

describe their architecture and characteristics. Section III surveys existing work comparing energy/power consumption of IoT applications based on Cloud computing and Fog computing. In Section IV, we examine the effect of combining Fog computing and microgrids to reduce the carbon footprint of IoT applications and services. Finally, we summarize the paper in Section V and highlight a number of open research directions in the relevant areas that are of significance and require further attention.

II. ARCHITECTURE

IoT applications and services can be run over Cloud platform or Fog platform. The system architecture of IoT applications provided by the Cloud and Fog are explained in the following sub-sections, respectively.

A. Architecture of Cloud-based IoT applications (IoT/Cloud)

Cloud computing provides centralized resources for data processing and storage that may be required for an IoT service ranging from simple personal services (low volume data collection and storage) to “big data” based services. Additionally, the advantages of “pay-as-you-go” Cloud computing will also be available to IoT user services. Similar to conventional Cloud-based applications, the system architecture of IoT applications includes (1) endpoint device (i.e. IoT sensors), (2) modem/gateway, (3) access network such as 3G/4G, Wi-Fi, Low-Power Wide-Area (LPWA) network, (3) Edge network (switch), (4) Core network, and (5) Data Center, respectively.

Although Cloud computing is an efficient solution for processing content in distributed environments, this platform is less suited for those applications which require low latency, mobility support, remote area with limited bandwidth or privacy sensitive applications. Hence, a new platform called Fog computing is being developed to meet these requirements. In the following, we describe how Fog Computing enables new varieties of (IoT) applications and services.

B. Architecture of Fog-based IoT applications (IoT/Fog)

Fog computing [3, 4] refers to distributing traditional Cloud Computing resources and services to the network edge thereby bringing cloud resources nearer to the endpoints (i.e. sensors and other IoT devices). Fog computing resources are located in the local network avoiding the need to send data to (geographically) remote Cloud data centers for processing and storage. However, Fog computing is not totally independent from the Cloud because the related components in the Fog and Cloud exchange important updates and other data in order to remain synchronized. Therefore, Fog computing is complementary to the Cloud computing and can serve applications which may not be well suited to (centralized) Cloud computing. Since Fog is localized, it allows real-time delivery of data and provides services that require better delay performance such as video conferencing, gaming, video streaming and augmented reality (it is assumed the local computation resources in the Fog are sufficient to do the tasks as fast as the Cloud, otherwise the response from Cloud could be quicker). Bandwidth sensitive and privacy sensitive applications are examples of applications that may be better served by Fog computing.

Having hundreds of billions of Internet-connected devices in the IoT, a variety of new wireless access technologies are needed to enable communication between these nodes. IoT devices can be connected to the Internet directly or through a gateway that acts as a bridge between IoT devices, networks and the Internet as shown in Fig. 1. In case of direct connection, 3G/4G or LPWA network connection can be used, while the communication between IoT devices and the gateway is generally via short-range wireless technologies such as Bluetooth, ANT+ or ZigBee. The gateway can be connected to the Internet via an access network modem using either Ethernet, PON (Passive Optical Network),Wi-Fi or 3G/4G network interface. Some of the access network technologies are discussed in the Section III.

The distribution of Fog computing and storage resources throughout the edge network is accomplished by having many, small clusters of servers with limited computation and storage resources. These clusters are sometimes referred to as “nano-data centers” reflecting their size and resource availability [5, 6]. A server in a Fog nano-data center can be a microcomputer such as a Raspberry Pi for low computational load or it can be a cluster of Raspberry Pis, a laptop or a home server if a higher computational load is expected.

The system architecture of IoT/Fog applications includes (1) endpoint device (i.e. IoT sensors) and nano data centers (or Fog servers), (2) local access network (i.e. Bluetooth, ZigBee), (3) IoT gateway, (4) Access network connected to the Internet, (5) Edge network (switch), (6) Core network, and (7) Data Center, respectively. For the sake of simplicity, all Access network, Edge network and Core network is shown as Transport network in Fig. 1.

III. POWER CONSUMPTION OF IOT/CLOUD VERSUS IOT/FOG

As discussed in Section II, some IoT applications can be run on the Cloud platform more efficiently whereas other IoT applications are more suited to the Fog Platform. There are many papers that discuss power consumption of Cloud based services [7, 8]. However, because combining the IoT with Fog computing is relatively new, there is a paucity of papers on the topic of power consumption on this topic.

In this section, we first explain the energy consumption of IoT end devices and their support networks. Then, we discuss the impact of several IoT/Fog system parameter’s on energy consumption of Fog computing.

A. Additional Energy Consumption to Enable IoT-based System

To demonstrate the risk of a substantial increase in global energy consumption with the expected proliferation of the IoT and its services, a report by the International Energy Agency (IEA) based on the Energy Efficient End-Use Equipment (4E) Agreement was recently published [9]. In that report, the authors estimated the annual standby energy consumption for

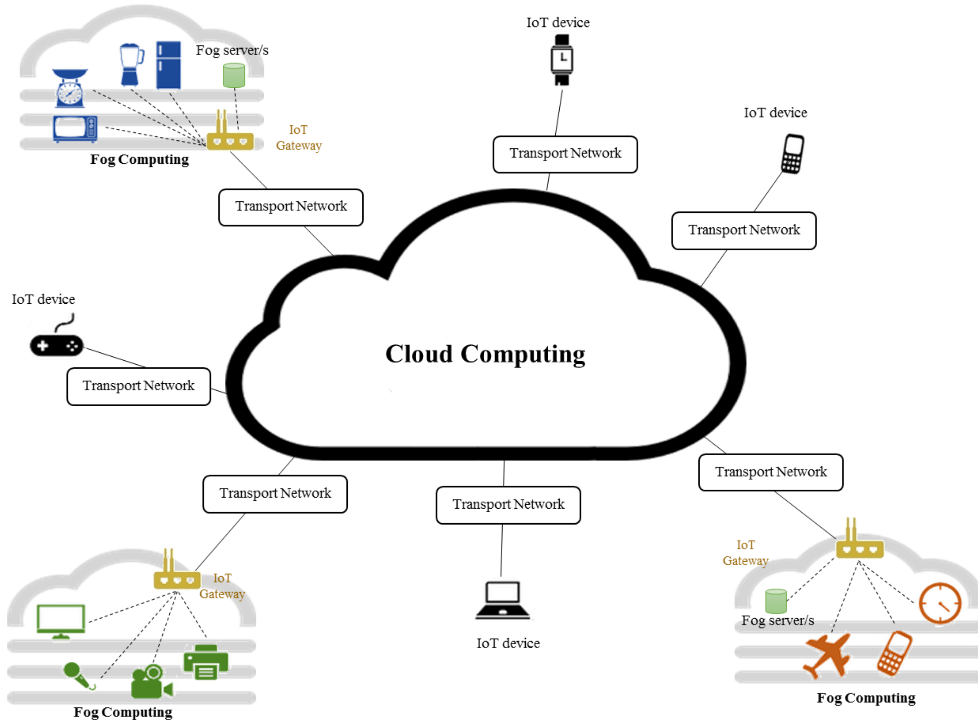

Figure 1. High level architecture of Fog and Cloud computing in IoT

off-the-shelf mains-powered IoT devices and their respective gateways, using market research projections (2015 – 2025) of future IoT device shipments and power measurements of the IoT devices (e.g. smart bulb). The report estimates that the annual global standby energy consumption of five selected IoT application use-cases (i.e. Home Automation, Smart Lighting, Smart Appliances, Smart Roads and Smart Street Lightings) could reach 46 TWh by 2025, with the share of Home Automation and Smart Appliances being 78 % (36 TWh) and 15 % (7 TWh) respectively. The report further classified energy requirement of these application use-cases and provided guidelines for the selection of appropriate communication technologies or protocols (i.e. Bluetooth Smart, ZigBee, Wi-Fi, etc) if standby energy is to be minimized. This report does not include the communication transport energy for the relevant Cloud-based applications. However, since the gateways and other local IoT deceives are included in the estimate, it could give an indication of the annual standby energy consumption if the applications were IoT/Fog-based.

B. Parameters for Greening Fog

Considering the IoT/Fog platform already exists and all additional energy costs paid, there are still factors and parameters that can impact energy consumption of IoT applications running over the Fog platform which are discussed in the following sub-sections.

1) Access Network Technologies:

Focusing on power consumption of Fog and Cloud computing, there are several key differences between the Fog and Cloud. In contrast to Fog data centers, Cloud data centers are typically remote (geographically) from the IoT device network; hence the transport network power consumption using the Cloud will be greater than when using the Fog (Remoteness also has an impact on latency). In some cases the transport network power consumption may be a significant proportion of the overall IoT service power consumption, and must not be ignored [5, 8]. While an IoT Cloud service may consume same amount of energy in both the edge/metro and core networks, its energy consumption in the access network may widely vary depending on the choice of access network technology and the service bit-rate in uplink versus downlink traffic. A further consideration is and the number of other users'/ or services' whose data are is passing through the network equipment at a given time, and against which part of the idle power consumption of network elements would be apportioned .

Gray et al. in [10] provided a model of the power consumption of a range of IoT access network technologies. The authors provided a detailed first-order modeling, analysis and comparison of the power consumption of IoT access network technologies, while considering the network traffic with IoT-like statistics (i.e. 1 kb/s to 1 Mb/s) and dominated by uplink traffic. The authors compared 6 potential state-of-the-art wireline and wireless access network technologies and architectures that may be suitable for future deployment of IoT

Cloud or Fog applications and services. For the wireline access network technologies, the authors considered Passive Optical Network (PON), Point-to-Point Optical Network (PtP) and Very-high-bit-rate Digital Subscriber Line (VDSL2) while Long Term Evolution (4th Generation) or 4G-LTE and Shared & Un-shared/Home Wi-Fi were considered for the wireless access network technologies.

The authors showed that if the network access is shared by a good number of users or services, the power share per user or service is low; hence shared Wi-Fi to gateway connection with PON network access was deemed the most power-efficient. Although the authors showed that VDSL2, PtP and PON architectures were less power- considering IoT-like traffic, their results present indicate huge opportunities for power savings using sleep-mode techniques, because the wireline network access power consumption was dominated by the idle power of their respective modems. Hence the implementation of energy-efficient techniques like sleep-mode and a reasonable choice of access network technology could reduce the energy consumption of IoT Cloud-based services (i.e. reduced transport energy). Depending on the location of the Fog resources, such reduction could be make Cloud-based services a little more attractive as compared to Fog-based services if energy consumption is the yardstick of measurement.

Their results also indicated that dedicated 4G-LTE access can be more power-efficient than any of the dedicated the wireline access technologies for lower data-rates. Even at moderate rates, LTE Access is still efficient compare to wireline during the time of day (busy-hours between 4pm and 10pm) when many mobile users are active, and the energy consumption of the hosting LTE Base Station is shared with other traffic. Importantly, 4G-LTE technology often provides network access to geographically remote locations that may be challenging and costly to provision with wireline access. Furthermore, many IoT services/use-cases (e.g. Smart Farming, Environmental Monitoring) may be deployed in geographically remote areas that could lack the network infrastructure for traditional wireline access. Although the authors showed that VDSL2, PtP and PON architectures may be power-efficient considering IoT-like traffic, their results present huge opportunities for power savings using sleep-mode techniques because the wireline network access power consumption was dominated by the idle power of their respective modems. Hence the implementation of energy-efficient techniques like sleep-mode and a reasonable choice of access network technology could reduce the energy consumption of IoT Cloud-based services (i.e. reduced transport energy). Depending on the location of the Fog resources, such reduction could be make Cloud-based services a little more attractive as compared to Fog-based services if energy consumption is the yardstick of measurement.

LPWA, an emerging access network technology designed for the IoT, was not considered in the Gray et al. study in [5]. However, LPWA could be a more energy-efficient access network technology albeit for low data-rate (i.e. 100 b/s up to 50 kb/s) applications as it was designed for low-power, low bit-rate IoT services.

Jalali et al [5, 6] has also modeled access network power consumption to compare local and remote processing of data. The access networks covered in that paper are common to both IoT/Fog and IoT/Cloud. The authors of [5, 6] showed that energy consumption of Fog computing applications heavily depends on the type of access network attached to server/s or gateway in the local network. The results showed that how the power consumption of a single application varies with different types of access network. For example, power consumption of the application with the Fog server attached to 4G is much higher that the same application with the Fog server attached to Ethernet. It also reveals that depending upon the IoT service data rate, wireline technologies (Ethernet, PON) may or may not be more energy efficient than wireless technologies (LTE, Wi-Fi).

2) Idle Power Consumption of Fog Servers

Another parameter mentioned in [5, 6] is the idle power consumption of local computation devices (i.e. nano servers) in Fog and their active time. Physical servers in Cloud data centers are dynamically shared across many services and users (by virtualization). If an IoT service is inactive for a time, the server can be allocated to other tasks in the Cloud data center. This sharing enables the amount of idle server power consumed by a service to be reduced. Because of the relative size of Fog data centers, this degree of sharing may not be attainable in the Fog. Therefore, if servers in a Fog data center are idle for long periods between a service's tasks, that IoT service may be less energy inefficient in the Fog compared to the Cloud.

A Fog computing data center typically has far less resources (i.e. CPU, RAM, storage, etc) available compared to a Cloud computing data center. Consequently, Fog data centers may be less able to utilize power saving strategies available in large data centers, for example, virtualization and more aggressive use of sleep modes. Also, should the computing load on a Fog data center exceed its capacity, the load will have to be shared with other data centers which will incur inefficiencies due to the need to coordinate and transport data between the data centers. Having all the processing undertaken in a single (Cloud) data center would avoid this problem.

3) Application type

Another determining factor for energy consumption is the type of applications. The authors in [6] indicate that parameters such as the number of downloads, the number of updates and the amount of data pre-loading play a significant role on the energy consumption of the applications. For example, it is shown in [6] that applications require a significant amount of updating traffic or significant computational power may be more energy efficient in the Cloud than the Fog. Their results reveal that the best energy savings using Fog computing come from applications that generate and distribute data continuously in end-user premises, with low access data rate from outside of the Fog and sufficient local computation such as video surveillance applications without facial recognition.

The results in [11] showed that IoT applications with no computation are more energy-efficient when run on Fog platform. Conversely, the paper also showed that applications with heavy computation consume more energy in the Fog, and it is more energy-efficient for such services to be sent to the Cloud. The reason is that the idle power consumption of local computation recourses for heavy local computation applications is very high compared to data centers idle power consumption that can be shared by many other applications. It should be noted that these results are based on the assumption that the IoT system is powered by the centralized grid, not local smart grids (known as microgrids) with renewable energy sources. We will explain in Section IV how the results vary if the IoT system can be powered by microgrids.

Delay sensitive applications are most likely best provided using Fog computing. However, this may increase power consumption of the application. Deng et al in [12] proposed a combined Cloud-Fog platform to improve the trade-off between the system power consumption and the end-user experienced delay.

An advantage of a Cloud platform is the ability to allocate and re-allocate Cloud servers in response to overall processing loads and to the processing and storage requirements of the IoT service, thereby reducing the consumption of the IoT service. For services that significant data processing and storage are not required and for delay-sensitive services, Fog computing will be advantageous in terms of energy and latency. In contrast, the delay-tolerant applications are better to be forwarded to the Cloud for further processing. This policy utilizes network and Cloud resources more efficient and is also improve the power consumption.

The authors in [12] considered the impact of workload allocation on both Fog and Cloud computing operating independently. Their results show that increased workload results in increased power consumption for both Fog and Cloud. However, although the computation delay increases with workload for the Fog, it remains steady for the Cloud due its greater scalability of computation resource.

They also evaluated the power consumption and delay for a combined Cloud-Fog system. It was found that with partial allocation of the workload to the Fog as well as the Cloud, the system delay declines although the power consumption increases. This is due to the fact that in the combined Cloud-Fog computing system, Cloud computing is more computationally powerful and energy-efficient than Fog computing. However Fog computing provides the benefit of close proximity to end users can offer improved latency performance relative to the Cloud by sacrificing some computation resources while saving WAN bandwidth.

4) Virtualization and Network Management

Configuring and managing Cloud/Fog computing infrastructures to provide IoT services, where the services run on many heterogeneous devices is not simple. In fact, the Fog demands heterogeneous devices and services to be managed almost homogeneously, ideally by a fully automated software platform. The utilization of Network Function Virtualization (NFV) and Software-Defined Networking (SDN), the most noticeable technologies in this regard, can simplify the implementation and management and diminish costs, in many aspects of Fog computing, such as resource allocation and VM migration. When it comes to energy savings in the network, NFV and SDN are also promising solutions. NFV attempts to enable dynamic deployment of on-demand network and user services close to where and when needed. Because some network services can be performed by software only, SDN is one of the key components required for NFV. For instance, some gateways can be deployed as virtual machines and their traffic tightly controlled on account of SDN capabilities in a local edge cloud. Overall, the combination of NFV and SDN can help to minimize the total network and data centers server power consumption [13, 14].

Authors in [15] introduced a four layer IoT model to address the energy efficiency in IoT networks supported by Cloud computing. The architecture in this model consisted of IoT objects (e.g. temperature sensors) at the first layer and the networking elements (relays, coordinators and gateways) are hosted within the upper three layers, respectively. These networking elements in each layer aggregate and process the traffic produced by IoT objects and other elements in lower layers. This work suggests a model in which IoT traffic could be processed by Virtual Machines (VMs) hosted by distributed mini Clouds at relays, coordinator and gateway devices with the objective of minimization of the total power consumption.

For this purpose, the authors considered two scenarios; 1) the Gateway Placement Scenario (GPS) in which located the VM in the gateway element only, so that traffic aggregation and processing handled by one mini Cloud at the gateway and 2) Optimal Placement Scenario (OPS) in which VM placement is elastically enabled at relays, the coordinator or the gateway elements. Their results showed that with optimal distribution of mini Clouds in the IoT network, the total power consumption decreased significantly providing power savings of up to 36% compared to processing IoT data in a single mini Cloud hosted at the gateway. The reduced power consumption of OPS resulted from the reduced number of hops traversed by the IoT-to-VM traffic in the IoT network and the reduced number of components and traffic through the IoT network. They also considered the impact of capacity constrained VMs (represented by the number of IoT objects a VM can serve) on total power consumption. They showed that as the number of served IoT objects per VM increases, the number of powered on networking elements decreases there-by improving power efficiency.

IV. LOCALIZING IOT TRAFFIC AND POWER RESOURCES

In the previous section, the factors and parameters that can be modified to reduce energy/power consumption in the current IoT/Fog architecture were discussed. This section focuses on the technologies and systems that can be used in conjunction with Fog computing in order to control energy consumption of IoT applications and services. Authors in [11] propose a new approach to exploiting the capabilities of microgrids in the context of Fog computing in order to reduce the energy consumption of IoT applications and services.

Microgrids are a transformation of the traditional centralized electricity grid, to small-scale energy sources located closer to demand compared to the traditional grid. Because of their closer proximity to end-users, microgrids match local supply to local demand dynamically and permit

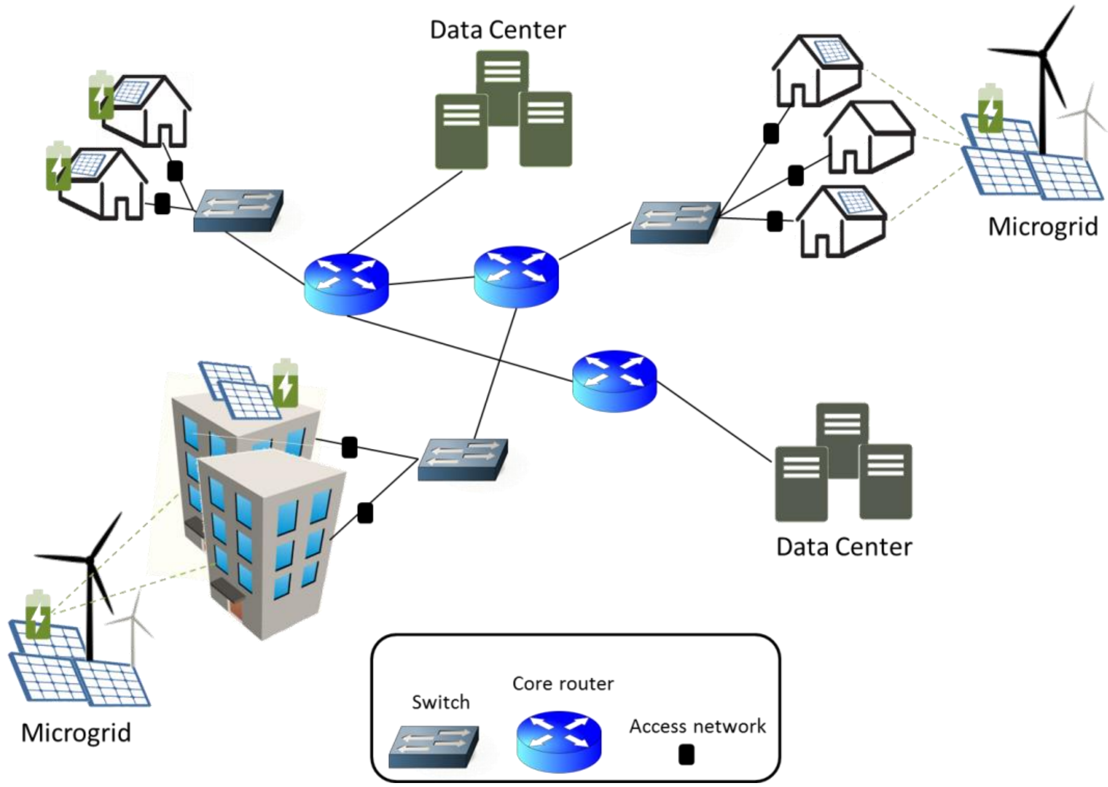

Figure 2. Network architecture of Cloud-Fog System attached to Microgrids

direct customer involvement in electrical power provisioning. Microgrids can operate linked to a traditional centralized grid or they can be detached from the grid and operate independently. Fog computing likewise will help IoT applications take advantage of local processing, computation and storage. As a result, Fog computing and microgrids can cooperate and complement each other to adapt Fog resource allocation to renewable energy availability, since both of them are suited to localized services. As Fig. 2 shows, microgrids are physically connected to end-user premises where Fog is implemented. The results in [11] show integrating microgrids and Fog computing can reduce energy consumption of IoT applications in a range of ways. A system powered with both microgrids and Fog computing can run many IoT applications locally and efficiently in the Fog when local renewable energy is available irrespective of the type of access network, idle power consumption of local servers or type of IoT applications. As more local energy is provided by microgrids more IoT applications can be served efficiently by the Fog computing platform.

V. Summary and Discussion

This article surveyed the current state of the art in energy consumption of IoT applications and services. Our focus was principally on using Fog computing to improve energy consumption of IoT. First, we discussed the additional energy consumption required for current network to be updated to accommodate IoT-based services. We described factors that can impact the energy consumption of an IoT-enabled network when IoT applications run over the Fog and Cloud. Parameters such as the type of access network in the Fog, idle power consumption of Fog servers, type of IoT applications and the availability of microgrids can determine whether or not the Cloud is a more energy-efficient platform than the Fog.

There are several issues to be considered in the future including:

- Energy-harvesting sensors and IoT device use of local energy generation
- Where exactly to locate Fog computation and storage considering microgrids can provide local energy sources for each individual house
- The impact of local energy storage (batteries) and energy sources in a neighbourhood
- Integrating Fog computing and microgrids at different network levels and different locations.

Dynamic, real-time energy management systems will be required to respond to local renewable energy availability, local weather conditions and the type of IoT application. These systems will provide strategies for switching between the Cloud and the Fog resources for the most energy-efficient implementation of IoT applications and the most effective utilization of fluctuating renewable energy sources.

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