Bus Inf Syst Eng 60(4):351–355 (2018)
https://doi.org/10.1007/s12599-018-0540-6

CATCHWORD

Fog Computing

Complementing Cloud Computing to Facilitate Industry 4.0

Christian Matt

Received: 9 January 2018 / Accepted: 5 April 2018 / Published online: 19 April 2018

1 Introduction

By sharing IT resources over the Internet, cloud computing has led to substantial transformations involving the centralization and translocation of software, platforms, and infrastructure into the cloud. IT resources provided over the cloud are often more elastic and can more quickly adapt to customer requirements, while implementation and usage costs can be reduced (Weinhardt et al. 2009). For many firms these are important benefits, but cloud computing has technological limitations that restrict its use in specific application domains. One of these domains is Industry 4.0, i.e., the advanced digitization within production sites that is directly associated with the Industrial Internet of Things (IIoT), connecting different types of machinery and promising more efficient production as well as new applications and business models (Lasi et al. 2014). In the context of Industry 4.0, cloud computing is confined for several reasons: Firstly, Industry 4.0 leads to substantial amounts of generated data that need to be analyzed, processed, and stored. Owing to limited bandwidth or unreliable Internet connections in production sites, it is often technologically challenging or very costly to transport data to and from the cloud. Secondly, analysis of Industry 4.0 data (e.g., from manufacturing or industrial control systems) often requires real time processing and interactions, which are difficult to guarantee with cloud services (Bonomi et al. 2012). Thirdly, many industry sensors and controllers have limited resources themselves, and therefore require larger computing power in Industry 4.0 scenarios. However, it is often not possible to connect them directly to the cloud (Chiang and Zhang 2016). Lastly, security and privacy have remained important issues in cloud environments. Especially in confidential production environments, manufacturers may not want or may not be allowed to transfer data to the cloud, for instance, due to customer specifications. Owing to these limitations, a technological paradigm beyond cloud computing is required to support the diffusion of Industry 4.0.

Operating on network edges, fog computing is a promising candidate since it "is a cloud close to the ground" (Bonomi et al. 2012, p. 13). Fog computing is a decentralized approach that is based on "an emergent architecture for computing, storage, control and networking that distributes these services closer to end users along the cloud-to-things continuum" (Chiang and Zhang 2016, p. 854). By being closer to end users, fog computing supports applications that require very low latency, high bandwidths, and high security. However, it is not just the technological differences from cloud computing that require specific research attention on fog computing. Beyond its technological realm, fog computing is also likely to have substantial economic and organizational implications for firms and their IT infrastructures. Therefore, fog computing constitutes a promising research area, not only for scholars already engaged in research on cloud computing but for the entire BISE community. This catchword article presents a classification of fog computing, discusses its positioning in firms' IT infrastructures and presents potential application fields, as well as future research opportunities. Arguably, fog computing has also manifold applications in non-industrial (e.g., for specific business services), societal (e.g., for smart cities) and

Accepted after one revision by Prof. Weinhardt.

Prof. Dr. C. Matt (✉)
Institute of Information Systems, University of Bern,
Engehaldenstr. 8, 3012 Bern, Switzerland
e-mail: christian.matt@iwi.unibe.ch

private (e.g., for smart homes) contexts. In the following, however, the focus is on fog computing's potential for Industry 4.0 as a concrete application domain.

2 Key Characteristics of Fog Computing

Fog computing leverages cloud resources as well as firms' own IT infrastructures to provide cloud-like services mainly at the edges of a network (Dastjerdi and Buyya 2016). The proximity of fog computing to cloud computing is also indicated in other definitions, stating that fog computing provides various "services between end devices and traditional cloud computing data centers, typically, but not exclusively, located at the edge of network" (Bonomi et al. 2012, p. 13). The so-called fog nodes are the main building blocks of fog computing (Marin-Tordera et al. 2016). Virtually any device that offers computing power, storage capacity, and network connectivity can be considered a fog node (Cisco 2015). Fog nodes can be used to conduct fog analytics and recognize deviations, failure prediction, machine learning, and system optimization. Especially data that requires fast analysis and responses (e.g., control loops) is processed on the fog nodes closest to the data generating objects. Data that is less time-sensitive and only needs interaction in the next minutes is analyzed and further processed on intermediate aggregation nodes (Cisco 2015). The latter includes simple analyses or the visualization of data as typical application scenarios. Data that does not require time-sensitive processing is mainly still analyzed, processed and stored in the cloud to perform historical and big data analyses. Therefore, the intended use of fog computing differs from cloud computing. Although there are also private clouds residing in firms'-data centers and not shared with others, these usually provide more computing-intensive services for a number of devices or even the firms' entire IT infrastructures, but at the same time private clouds may still have higher latency compared to fog computing. Further, especially small or medium-sized firms might not have the capabilities to manage their own private clouds. Fog computing allows them to build up IT resources to automatize and control their production without running their own cloud or transmitting large amounts of data to public clouds. Figure 1 illustrates how distributed data processing in a fog computing environment can take place. IoT sensors can be deployed in different environments including roads, medical centers, farms, and energy supply. Collected

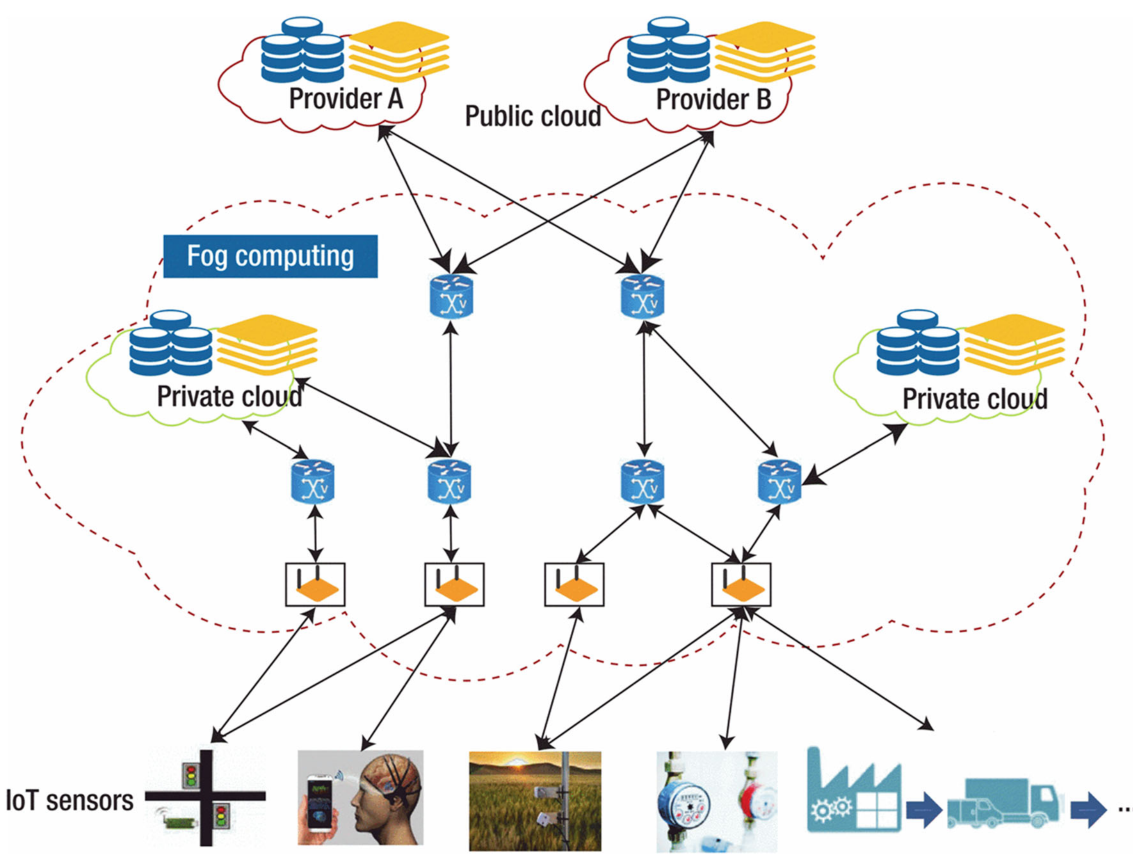


Fig. 1 Fog computing and cloud computing in Industrial IoT (Dastjerdi and Buyya 2016)

information from the sensors is directly processed by the nearest fog nodes and if necessary transferred to other aggregation nodes or private/public clouds.

Another related concept is edge computing which only refers to data processed close to where it is created (e.g., IoT sensors implemented in production machines) and therefore can be seen as a component of fog computing. Fog computing comprises edge processing and the network infrastructure needed to transmit data from the edge to the cloud. Rather than replacing, fog computing therefore connects edge with cloud in the cloud-to-things continuum (OpenFog 2017).

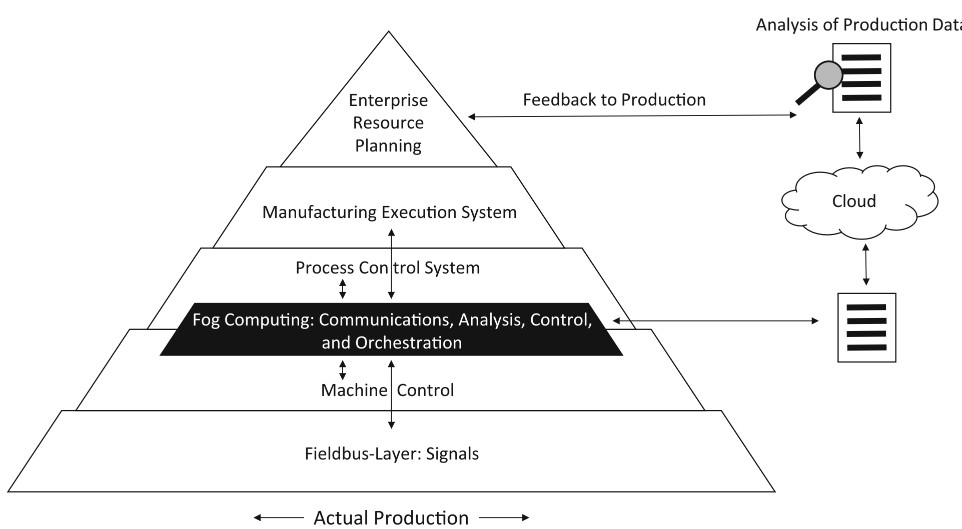
Compared to cloud computing, fog computing offers the additional advantage of allowing for location awareness and the mobility of the involved devices. This is for instance important for connected vehicles, for which the location of objects needs to be tracked and the objects are connected through wireless, while low latency and real-time responses need to be assured. Fog computing is therefore well-suited for geographically distributed wireless sensor networks that are usually characterized by low power, low bandwidth and limited processing capability.

However, fog computing also involves certain challenges for firms. Firstly, there is often substantial technological heterogeneity concerning firms' current IT and machinery infrastructures, comprising various standards and interfaces that make the integration of fog nodes challenging. However, there are ongoing efforts to provide interoperable fog microservices that can be executed on various types of fog infrastructures (OpenFog 2017). Secondly, since fog computing is frequently implemented in geographically wide-spread areas, it is often too expensive to provide extensive resources to all individual fog nodes. However, certain applications (e.g., batch processing jobs) are less delay-sensitive but require many resources, so they will probably continue to rely on cloud services (Mohamed et al. 2014). Splitting larger applications into individual microservices may also allow for sharing resource utilization across several fog and non-fog resources. Thirdly, achieving real-time interactions is possible but difficult in many scenarios, since it usually requires a calibrated coordination of multiple devices. When relying on real-time interactions, even small delays can have significant negative impacts on dependent processes and lead to substantial costs (Dastjerdi and Buyya 2016). Fourthly, owing to the potentially high number of fog nodes, their management may require substantial time and effort. While fog computing must be able to constantly add and remove resources, most data-processing systems have static configurations, making fog computing's full integration difficult. Lastly, the potentially high number of fog nodes and associated service providers can imply new forms of security and privacy risks, and fog computing's specific characteristics restrict the direct transferability of field-tested measures from cloud computing (Dastjerdi and Buyya 2016).

3 Integration of Fog Computing and Current Applications in Industry 4.0

Among others, Industry 4.0 seeks to improve production sites' efficiency, flexibility, and security (Lasi et al. 2014). As one of the three key elements of Industry 4.0, fog computing serves as a connector between the cloud and machinery (Nebbiolo Technologies 2017). In the industrial automation architecture, fog computing builds a new layer between the existing layers of machine control and process control systems (Fig. 2).

Fig. 2 Fog computing in the industrial automation architecture (based on Nebbiolo Technologies 2017)



Fog computing is not just achieved by making machines smarter and more powerful; it establishes a new layer to connect existing layers and elements of firms' IT infrastructures. By connecting cloud computing and machinery, fog computing serves as a technological enabler of Industry 4.0 applications and, at the same time, offers firms the opportunity to consolidate important operational functions that are currently often processed in isolated systems. For this integration, suitable interfaces need to be developed that bridge the differences between the usually more static enterprise applications and the dynamic fog computing environment, in which resources need to be added or removed easily. The so-called OpenFog Reference Architecture provides a suitable medium- to high-level view of system architectures for fog nodes and networks (OpenFog 2017).

In Industry 4.0, fog computing can be used in various application scenarios. For instance, for Cyber-Physical Production Systems (CPPS), numerous interconnected communicating devices are integrated into cloud datacenters, but some of the data need to be processed in real-time in order to reach full automation of end-to-end manufacturing lifecycles (Georgakopoulos et al. 2016). The fog nodes preprocess such data for the cloud, where the more complex analyses take place, for instance, using business analytics. Fog computing can add the required local resource virtualization, security, and application management for real-time Industry 4.0 applications (Nebbiolo Technologies 2017). This is also important to enable machines to become increasingly self-aware and self-maintained, for instance in the context of predictive maintenance. Predictive maintenance relies on algorithms that cannot only point out which parts of machinery wear out faster, but also provide solutions for rearrangement or redesigns for the optimization of machine use. A large number of sensors continuously monitor machine operations and collect the underlying data for the algorithms. Such sensor data can easily become so large in size that their processing is more efficiently handled by fog nodes than by the cloud.

Another fog computing application scenario in the context of Industry 4.0 is real-time video processing and analytics. Using augmented reality, additional information about the real world can be added to the video content on digital screens. For example, workers can receive repair instructions by wearing augmented-reality glasses and looking at an object that needs repair, or they could receive virtual training enhanced by augmented reality. To provide this real time information in a way that is directly applicable to the current view of the workers, voice sequence algorithms and other inputs such as sensor data are often used in addition. Fog computing can make a difference in this processing-intensive environment by providing more computing power and reducing latency.

4 Future Directions

In order to connect the cloud with industrial production and add a new layer to existing IT infrastructures, fog computing requires substantial technological efforts from firms. Foremost, there is the technological integration of fog nodes into firms' IT infrastructures, including the direct interfaces with machinery and the cloud, but also the indirect connections and processing of fog data by other systems. Since Industry 4.0 fundamentally relies upon connectivity between machinery that is not necessarily in the same physical location or even owned by the same firm, the integration into dynamic value-creation networks is of high importance, and leaves multiple open questions concerning standardization as well as concerning the design of adequate user interfaces for fog computing applications.

The integration of fog resources will presumably require high management effort as well as new IT governance principles and processes, which need to guarantee highly dynamic access to fog resources within and beyond firms' boundaries. Therefore, research should develop suitable IT governance architectures to enable and facilitate the integration of fog computing. Fog computing will also impose new challenges concerning resource optimization. New optimization methods for scheduling and resource access could help reduce fault tolerance as well as resource overprovisioning and underprovisioning.

To avoid threats to their production infrastructures, firms have a pressing interest to prevent any privacy and security vulnerabilities arising from fog computing. The BISE community should build upon the recent advancements in IT security and privacy research and extend these to fog computing, focusing on the challenges on a firm and on an individual level. This concerns the direct use of fog resources as well as machinery supported by fog resources, which potentially allow for a more precise recording of employee productivity.

By building the technological basis to enable Industry 4.0 operations and business models, fog computing potentially implies major economic and organizational transformations. For instance, fog computing allows for better interconnectivity and smarter processes within supply chains as well as for new forms of manufacturing, such as built-to-order processing. This in turn enables firms to adopt their current operations and create new products or services. While first assumptions about the effects of fog computing in the context of Industry 4.0 exist, more research is needed to analyze its concrete economic implications. Such research should not be limited to a single firm, but also analyze firms' possibilities to better cooperate and interact with other firms by using and sharing fog resources, hence making these opportunities an essential parameter of business model design.

Fog computing provides new prospects for firms to directly or indirectly monetize novel Industry 4.0 data, not only by optimizing business processes but also by creating industrial data platforms. Currently, very little is known about potential data-driven business models and pricing strategies for fog computing services. Research can contribute by identifying the strategic role of fog computing for firms and its position in digital transformation strategies, IT strategies and other corporate strategies, both from the perspectives of companies that use fog computing, as well as for vendors of fog computing resources.

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