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Cloud *versus* Edge: Who Serves the Internet-of-Things Better?

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Summary

Usually announced to the ICT community as rivals in the Internet-of-Things (IoT) context, cloud and edge could work together according to their respective capabilities. Today's IoT applications cannot be dependent on a single technology (either SQL or noSQL) nor a single operation model (either centralized or decentralized). The challenges are multiple including complexity of user scenarios, multiplicity of things, sensitivity of data, etc. This paper raises the question of who serves IoT better? Cloud, only; edge, only; or both together. To answer this question, clouds' and edges' duties are identified and then a set of collaborative scenarios are discussed with respect to these duties.

KEYWORDS:
cloud computing, edge computing, internet-of-things.

1 | MOTIVATIONS

The ICT community is known for marketing new solutions using multiple buzzwords that, usually, trigger debates, sometimes heated, among these solutions' advocates and opponents. Buzzwords include, but not limited to, Everything-as-a-Service (*aaS), edge (sometimes referred to as fog) computing, blockchain, big data, deep learning, and, lately, Internet-of-Things (IoT). IoT is about allowing people to have anywhere and anytime control over their cyber-physical surroundings such as homes, offices, and malls. IoT-compliant things (things for short) could be anything ranging from white goods and wrist watches to RFID tags and moisture sensors. According to Gartner (http://goo.gl/J2TwR6), 6.4 billion connected things were used in 2016, up 3% from 2015, and will reach 20.8 billion by 2020. Smart city (e.g., Smart Dubai: http://smartdubai.ae) is one of the highly-cited examples that illustrates the potential benefits of IoT to governments and citizens. To what extent could IoT achieve the dreams of those who advocate for smart homes, smart cars, smart farms, smart robots, etc.? Achieving these dreams would require a strong IT infrastructure upon which future IoT user-applications can tackle the complexity of user-scenarios, the multiplicity of things, the sensitivity of IoT data, and the diversity of IoT devices, protocols, and standards. Such an IT infrastructure could, for instance capitalize on the strengths of certain technologies like cloud and edge, though some treat cloud and edge as rivals. "*Enterprises and vendors that don't focus on new demands driven by edge computing will become non-competitive. The edge will eat the cloud*" (http://goo.gl/nxTNZ2).

Prior to the rise of edge computing (1), the cloud has been the model of choice for exposing resources (traditionally software, platform, and infrastructure) as services, which means shielding users from the complexity of the cyber-physical world's resources, describing resources in a machine-readable format so they can be discovered, and shifting the burden of managing resources internally to cloud providers in-return of a fee (pay-as-you-go). Gartner states that "*by 2021, more than half of global enterprises already using cloud today will adopt an all-in cloud strategy*" (http://goo.gl/m9MQXc). However, despite cloud computing's potentials, it falls short of meeting some non-functional requirements (e.g., high latency and sensitive-data exposure) imposed on certain IoT applications (e.g., in the medical domain where data freshness is a must-have). Indeed, data transfer from things to clouds could take time, be subject to interceptions, alterations, and misuses, and depend on network availability and reliability. Contrarily, it happens that storage and/or processing facilities exist "next" (or nearby) to where data is being collected minimizing its transfer and avoiding its exposure to unnecessary risks (2, 3). This is the essence of edge computing: store and process next to data.

The question we raise, here, is who serves IoT better? Cloud, only; edge, only; or both together. To answer this question, we define the duties of 3 potential stakeholders forming an IoT ecosystem namely, thing, cloud, and edge. Duties are what a stakeholder does and how it helps peers accomplish their duties, too. We, also, discuss some collaborative scenarios showing how combining stakeholders' duties is sometimes necessary.

2 | BACKGROUND

Internet of things is an Internet-based information architecture (4) providing technical means (e.g., RFID and 4G) for interconnecting "things" and enriching them with different capabilities. According to (5, 6), these capabilities include: communication and cooperation, addressability, identification, sensing, actuation, embedded information processing, localization, user interfaces, monitoring, control, optimization, and autonomy. And, according to (7, 8), cited by (9), *"The IoT refers to an emerging paradigm consisting of a continuum of uniquely addressable things communicating to one another to form a worldwide dynamic network"*.

Cloud computing is a consumption and delivery model of IT resources based on Internet protocols. According to NIST (10), cloud computing has 5 essential characteristics that are behind its success: on-demand self-service, broad network access, resource pooling, rapid elasticity, and measured service. More and more companies are adopting the cloud model. For instance, in the RightScale's 8th seventh annual state of the cloud survey (http://goo.gl/mxpMw2) conducted in 2018 on 997 IT professionals, 96% of respondents said they use cloud.

Edge computing is a response to some of cloud computing's limitations such as high latency and sensitive-data exposure (3). Edge computing puts a substantial amount of communication, storage, and processing at the edge of the IT infrastructures as opposed to establishing dedicated communication channels to a more centralized remote cloud infrastructure. It is reported that out of the $500 billion in growth expected for IoT through 2020, McKinsey estimates that about 25% will be directly related to edge technology (http://goo.gl/RqqQ2t).

3 | DUTIES OF THINGS, CLOUDS, AND EDGES

We define things' duties around 3 functions: sensing (in the sense of collecting/capturing data), actuating (in the sense of processing data), and communicating (in the sense of sharing/distributing data). These duties are either enabled or disabled according to the under-development IoT application ((0,1) in Figures 1 , 2 , and 3). From a duty perspective, (*i*) a thing is meant for sensing the cyber-physical surroundings so that it generates (raw) data; this sensing could be performed either continuously or intermittently; (*ii*) a thing is meant for actuating data including those that have been sensed; this actuating could be performed either in batch (until a certain amount of data is available) or continuously (as soon as data is available); and (*iii*) a thing is meant for communicating with the cyber-physical surroundings the data that are sensed and/or actuated; this communication could be performed either continuously or intermittently.

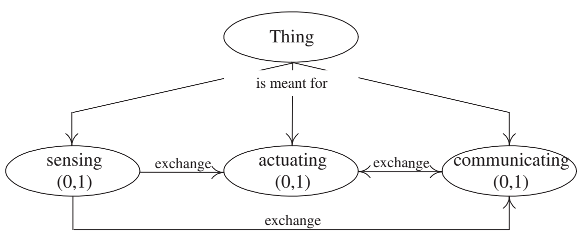

FIGURE 1 Duties associated with thing

A thing's sensing, actuating, and communicating duties form 5 independent lifecycles showing a certain chronology of events as per the following details:

1. Sensing→Actuating→Communicating: sensed data are passed on to actuating; and the data that result from this actuating are passed on to communicating for distribution.

2. Sensing→Actuating: sensed data are passed on to actuating; and the data that result from this actuating are finals.

3. Sensing→Communicating: sensed data are passed on to communicating for distribution.

4. Actuating→Communicating: data that result from actuating are passed on to communicating for distribution.

5. Communicating→Actutaing: external data to the thing are passed on to actuating.

We define edges' duties around 3 main functions, depending upon the user-application that edge is expected to support: storing (in the sense of saving data that was submitted by things, other edges, and/or clouds), processing (in the sense of acting on data), and relaying (in the sense of transferring data to other parties). In Figure 2 , an edge is meant for supporting the (permanent *versus* temporary for later relaying) storage of data about the cyber-physical surroundings; an edge is meant for supporting the (batch *versus* continuous) processing of data including those that are stored; and an edge is meant for supporting the (continuous *versus* intermittent) relay of data to other parties. These data either are available in storage, result from processing, or are both.

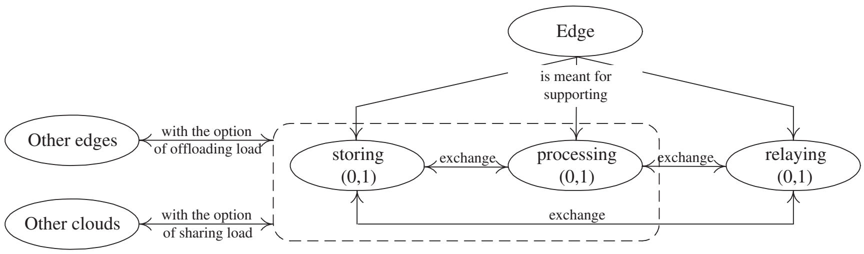

FIGURE 2 Duties associated with edge

Like things, edges' duties of storing, processing, and relaying form 4 independent lifecycles as per the following details:

1. Storing→Processing→Relaying: stored data are passed on to processing; and the data that result from this processing are relayed to other parties. We note that the opposite could happen through Relaying→Processing→Storing when the edge receives external data from things, other edges, and/or other clouds.

2. Storing→Processing: stored data are passed on to processing; and the data that result from this processing are finals. We note that the opposite could happen through Processing→Storing.

3. Storing→Relaying: stored data are relayed to other parties. We note that the opposite could happen through Relaying→Storing.

4. Processing→Relaying: data that result from processing are relayed to other parties. We note that the opposite could happen through Relaying→Processing.

The above-mentioned lifecycles could be expanded to accommodate edges' limited storage and/or processing resources (dashed rectangle in Figure 2). Indeed, an edge has the options of offloading some load to other edges, in the vicinity for example, or sharing some load with other clouds (11). We note that other edges and/or clouds could involve the edge in their respective offloading and sharing loads. The below 2 lifecycles are examples of this expansion (where *i*/*e* means *i*nternal/*e*xternal):

1. *i*-Storing→*i*-Relaying→*e*-Storing: in addition to its internal storage capabilities, an edge relays some data to another edge so that it uses its external storage's capabilities.

2. *i*-Storing→*i*-Processing→*i*-Relaying→*e*-Storing: in addition to its internal storage capabilities, an edge relays data resulting from internal processing to another edge so that it uses its external storage's capabilities.

Cloud's duties/lifecycles are like edge's duties/lifecycles in terms of storing, processing, and relaying (Figure 3). However, the main difference resides in how their respective lifecycles are expanded to accommodate first, the limited storage and/or processing resources (applicable to both edge and cloud) and second, the abundance of these resources (applicable to cloud, only; dashed rectangle in Figure 3). On the one hand, edge offloads/shares any extra load (Figure 2). On the other hand, cloud scales out with the help of other clouds to meet extra load or scales in up or down to manage any extra or less load, respectively. Like edge, the cloud could support other clouds when they scale out.

4 | COLLABORATIVE SCENARIOS

Today's IoT user-applications cannot be dependent on a single technology (either SQL or noSQL) nor a single operation model (either centralized or decentralized). Indeed, these applications' stakeholders are expected to engage in collaborative scenarios requiring the combination of their

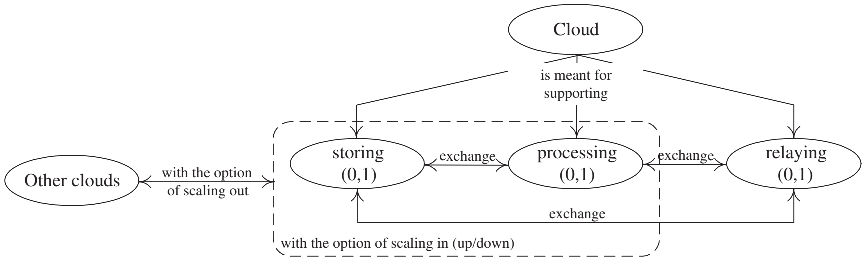

FIGURE 3 Duties associated with cloud

respective duties. For instance, an IoT application consists of capturing traffic data using things (road sensors), sending these data to an edge-based regional traffic center for initial processing (e.g., filtering), and then sending the resulting data to the cloud-based country traffic center for final integration and storage. We identify 5 collaborative scenarios (*T*/*E*/*C* means *T*hing/*E*dge/*C*loud):

1. Thing to Edge: the involved duties per stakeholder lead to the following representative cases:
    - *T*-Sensing→*T*-Communicating→*E*-Storage: data that a thing senses are communicated by the thing to the edge for storage.
    - *T*-Actuating→*T*-Communicating→*E*-Storage. data that a thing actuates are communicated by the thing to the edge for storage.
    - Etc.
2. Thing to Cloud: the involved duties per stakeholder lead to the following representative cases:
    - *T*-Sensing→*T*-Communicating→*C*-Storage: data that a thing senses are communicated by the thing to the cloud for storage. The edge is bypassed.
    - *T*-Actuating→*T*-Communicating→*C*-Storage. data that a thing actuates are communicated by the thing to the cloud for storage. The edge is bypassed.
    - Etc.
3. Thing to Edge and Cloud (concurrently,|): the involved duties per stakeholder lead to the following representative cases:
    - *T*-Sensing→*T*-Communicating→*E*-Storage|*C*-Storage: data that a thing senses are communicated by the thing to both the edge and the cloud for storage.
    - *T*-Actuating→*T*-Communicating→*E*-Processing|*C*-Storage: data that a thing senses are communicated by the thing to the edge for processing and to the cloud for storage.
    - Etc.
4. Thing to Edge then to Cloud: the involved duties per stakeholder lead to the following representative cases:
    - *T*-Sensing→*T*-Communicating→*E*-Storage→*C*-Storage: data that a thing senses are communicated by the thing to the edge for initial storage and then to the cloud for final storage (e.g., integration).
    - *T*-Sensing→*T*-Communicating→*E*-Processing→*C*-Processing→*C*-Storage: data that a thing senses are communicated by the thing to the edge for initial processing and then to the cloud for final processing (e.g., integration) and storage.
    - Etc.
5. Thing to Cloud then to Edge: the involved duties per stakeholder lead to the following representative cases:
    - *T*-Sensing→*T*-Communicating→*C*-Storage→*E*-Storage: data that a thing senses are communicated by the thing to the cloud for initial storage and then (some of these data) to the edge for final storage.
    - *T*-Sensing→*T*-Communicating→*C*-Processing→*E*-Processing→*E*-Storage: data that a thing senses are communicated by the thing to the cloud for initial processing and then (some of the resulting data) to the edge for final processing and storage.
    - Etc.

Based on the above-mentioned collaborative scenarios, it is noticeable that there is not a particular response to the question of who serves the Internet of Things better: cloud, only; edge, only; or both together. The requirements on IoT applications will dictate the relevant model to adopt. Requirements could be low latency, data sensitivity, data volume, data freshness, user mobility, transfer frequency, etc.

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