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Article *in* Future Generation Computer Systems · October 2015

DOI: 10.1016/j.future.2015.09.021

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PII: S0167-739X(15)00301-5
DOI: http://dx.doi.org/10.1016/j.future.2015.09.021
Reference: FUTURE 2851

To appear in: *Future Generation Computer Systems*

Received date: 22 November 2014
Revised date: 15 September 2015
Accepted date: 17 September 2015

Highlights (for review)

Vision and motivations for the integration of Cloud Computing and Internet of Things (IoT).
Applications stemming from the integration of Cloud Computing and IoT.
Hot research topics and challenges in the integrated scenario of Cloud Computing and IoT.
Open issues and future directions for research in this scenario.

Integration of Cloud Computing and Internet of Things: a Survey

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Abstract

Cloud computing and Internet of Things (IoT) are two very different technologies that are both already part of our life. Their adoption and use is expected to be more and more pervasive, making them important components of the Future Internet. A novel paradigm where Cloud and IoT are merged together is foreseen as disruptive and as an enabler of a large number of application scenarios.

In this paper, we focus our attention on the integration of Cloud and IoT, which is what we call the *CloudIoT* paradigm. Many works in literature have surveyed Cloud and IoT separately and, more precisely, their main properties, features, underlying technologies, and open issues. However, to the best of our knowledge, these works lack a detailed analysis of the new CloudIoT paradigm, which involves completely new applications, challenges, and research issues. To bridge this gap, in this paper we provide a literature survey on the integration of Cloud and IoT. Starting by analyzing the basics of both IoT and Cloud Computing, we discuss their complementarity, detailing what is currently driving to their integration. Thanks to the adoption of the CloudIoT paradigm a number of applications are gaining momentum: we provide an up-to-date picture of CloudIoT applications in literature, with a focus on their specific research challenges. These challenges are then analyzed in details to show where the main body of research is currently heading. We also discuss what is already available in terms of platforms – both proprietary and open source – and projects implementing the CloudIoT paradigm. Finally, we identify open issues and future directions in this field, which we expect to play a leading role in the landscape of the Future Internet.

Preprint submitted to Journal of Future Generation Computer Systems September 14, 2015

Keywords: Cloud Computing, Internet of Things, Ubiquitous Networks, Cloud of Things, Pervasive Applications, Smart City, Smart Applications.

1. INTRODUCTION AND MOTIVATION

The Internet of Things (IoT) paradigm is based on intelligent and self configuring nodes (things) interconnected in a dynamic and global network infrastructure. It represents one of the most disruptive technologies, enabling ubiquitous and pervasive computing scenarios. IoT is generally characterized by real world small things, widely distributed, with limited storage and processing capacity, which involve concerns regarding reliability, performance, security, and privacy. On the other hand, Cloud computing has virtually unlimited capabilities in terms of storage and processing power, is a much more mature technology, and has most of the IoT issues at least partially solved. Thus, a novel IT paradigm in which Cloud and IoT are two complementary technologies merged together is expected to disrupt both current and Future Internet [132, 25]. We call this new paradigm ***CloudIoT.***

Reviewing the rich and articulate state of the art in this field, we found that both topics gained popularity in the last few years (Fig. 1a), and the number of papers dealing with Cloud and IoT separately shows an increasing trend since 2008 (Fig. 1b)[1]. In this paper we review the literature focusing on the integration of Cloud and IoT, a really promising topic for both research and industry, witnessed by the more recent and rapidly increasing trend dealing with Cloud and IoT together (Fig. 1c).

Inspired by well known indications in literature [74], we adopt the research methodology schematically depicted in Fig. 2. By analyzing a large number of papers mainly published between 2008 and 2014 in selected venues, *(A)* we derive a temporal characterization of the literature – aiming at showing in a qualitative way the temporal behavior of the research and the common interest about the CloudIoT paradigm (see Fig. 1) – and build the basis for the following steps. The characterization of the literature is reported in this section and is supported by Fig. 1. *(B)* We introduce a short background on both Cloud and IoT to provide the readers with the necessary basics and to tackle the integration of Cloud and IoT (Sec. 2). *(C)* We present a detailed

[1]Data have been obtained from Google Trends (`https://www.google.com/trends/`) and Scholar (`https://scholar.google.com/`) web facilities.

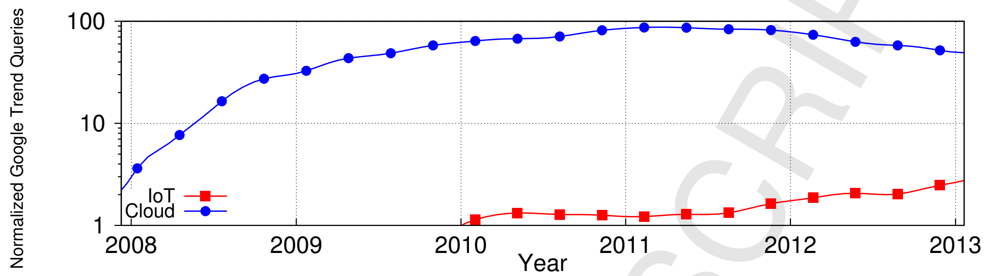
discussion on the CloudIoT paradigm, highlighting the complementarity of its components and the main driver to their integration (Sec. 3). *(D)* We detail the new application scenarios stemming from the adoption of the CloudIoT paradigm (Sec. 4). *(E)* We focus on research challenges (Sec. 5) arising from the adoption of the CloudIoT paradigm and of interest for the new applications of Sec. 4. *(F)* We describe the main platforms (both proprietary and open source) and research projects in the field of CloudIoT (Sec. 6). *(G)* Thanks to the previous six steps, we derive the open issues and future directions in the field of CloudIoT (Sec. 7). Finally, we close the paper with conclusion remarks (Sec. 8). Note that in our analysis the terms research challenge and open issue are used with different meanings. We considered as challenges (Sec. 5) the research problems generated by the integration of the two worlds currently receiving attention by the research community. Those aspects usually are or are claimed to be partially solved or solved with respect to specific contexts and applications. The main issues related to the integration that still require research efforts are instead referred to as open issues. These issues are resumed in Sec. 7, where we also point out some future research directions. It is worth noting that the differentiation between challenges and open issues has been deduced from the surveyed literature.

2. BACKGROUND AND BASIC CONCEPTS

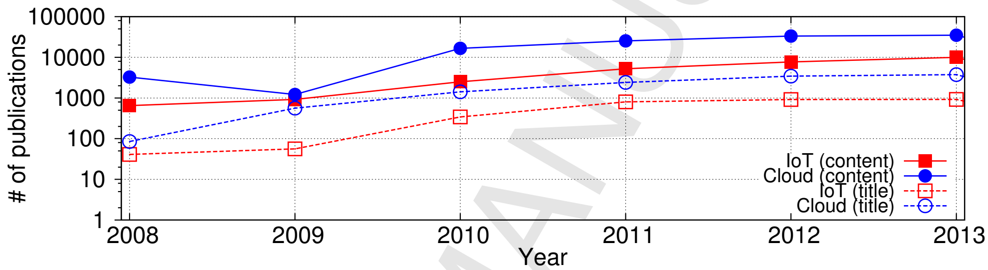
In this section we recall the basics of IoT and Cloud and overview the characteristics essential for their integration.

2.1. Internet of Things

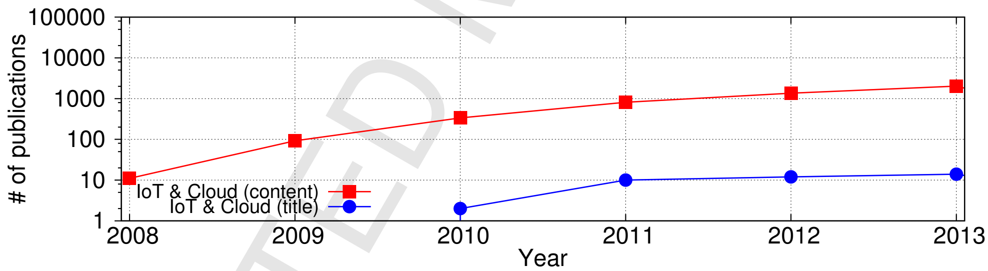
The next wave in the era of computing is predicted to be outside the realm of traditional desktop [53]. In line with this observation, a novel paradigm called Internet of Things rapidly gained ground in the last few years. IoT refers to "a world-wide network of interconnected objects uniquely addressable, based on standard communication protocols" [12, 14] whose point of convergence is the Internet. The basic idea behind it is the pervasive presence around people of things, able to measure, infer, understand, and even modify the environment. IoT is fueled by the recent advances of a variety of devices and communication technologies, but things included in IoT are not only complex devices such as mobile phones, but they also comprise everyday objects such as food, clothing, furniture, paper, landmarks, monuments,



(a) According to Google research trends.



(b) By content and title for Cloud and IoT separately.



(c) By content and title for Cloud and IoT together.

Figure 1: Interest and research trends about Cloud and IoT.

works of art, etc. [42, 60]. These objects, acting as sensors or actuators, are able to interact with each other in order to reach a common goal.

The key feature in IoT is, without doubt, its impact on every-day life of potential users [12]. IoT has remarkable effects both in work and home scenarios, where it can play a leading role in the next future (assisted living, domotics, e-health, smart transportation, etc.). Important consequences are also expected for business (e.g. logistic, industrial automation, transportation of goods, security, etc.). According to these considerations, in 2008 IoT has been reported by US National Intelligence Council as one of the six tech-

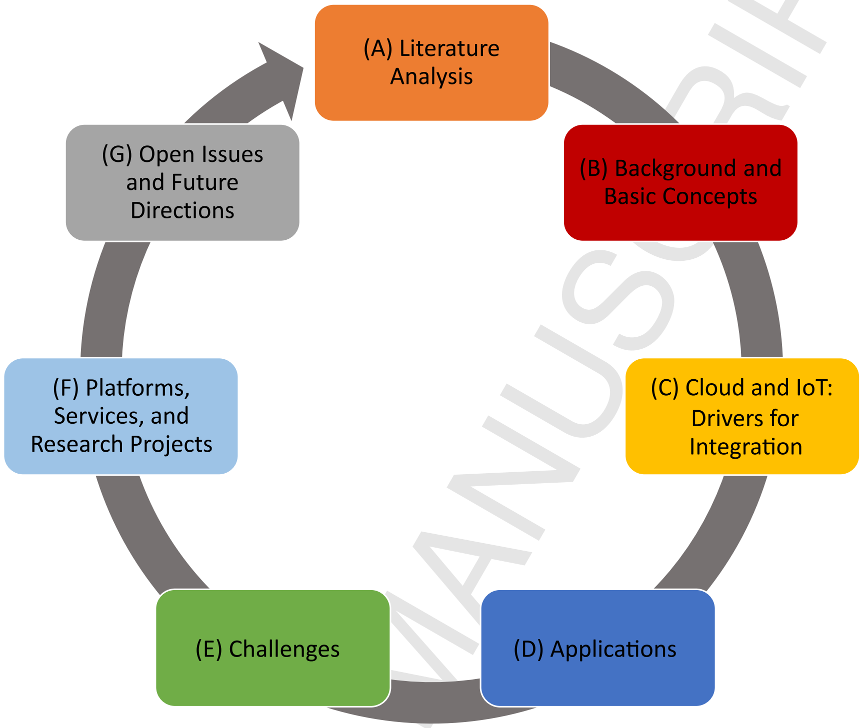


Figure 2: The research methodology adopted in this work.

nologies with potential impact on US interests towards 2025 [60]. Indeed, in 2011 the number of interconnected devices overtook the number of people [53]. In 2012, the number of interconnected devices was estimated to be 9 billion, and it was expected to reach the value of 24 billions by 2020. Such numbers suggest that IoT will be one of the main sources of big data [37].

In the following we describe a few important aspects related to IoT.

RFID. In IoT scenario, a key role is played by Radio-Frequency IDentification (RFID) systems, composed of one or more readers and several tags. These technologies help in automatic identification of anything they are attached to, and allow objects to be assigned unique digital identities, to be integrated into a network, and to be associated with digital information and services [42]. In a typical usage scenario, readers trigger the tag transmission by generating an appropriate signal, querying for possible presence of objects uniquely identified by tags. RFID tags are usually passive (they do not need on-board power supply), but there are also tags powered from

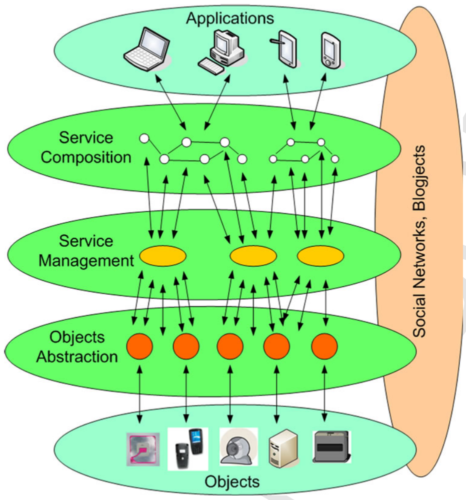


Figure 3: IoT paradigm: an overall view (source: [42]).

batteries [12, 124].

(Wireless) Sensor Networks. Another key component in IoT environments is represented by sensor networks. For example, they can cooperate with RFID systems to better track the status of things, getting information about position, movement, temperature, etc. Sensor networks are typically composed of a potentially high number of sensing nodes, communicating in a wireless multi-hop fashion. Special nodes (sinks) are usually employed to gather results. Wireless sensor networks (WSNs) may provide various useful data and are being utilized in several areas like healthcare, government and environmental services (natural disaster relief), defense (military target tracking and surveillance), hazardous environment exploration, seismic sensing, etc. [7]. However, sensor networks have to face many issues regarding their communications (short communication range, security and privacy, reliability, mobility, etc.) and resources (power considerations, storage capacity, processing capabilities, bandwidth availability, etc.). Besides, WSN has its own resource and design constraints (that are application- and environment- specific) and that heavily depend on the size of the monitoring environment [7]. The scientific community deeply addressed several issues related to sensor networks at different layers (e.g., energy efficiency, reliability, robustness, scalability, etc.) [12].

Addressing. Thanks to wireless technologies such as RFID and Wi-Fi, IoT paradigm is transforming the Internet into a fully integrated Future Internet [124]. While Internet evolution led to an unprecedented interconnection of people, current trend is leading to the interconnection of objects, to create a smart environment [53]. In this context, the ability to uniquely identify things is critical for the success of IoT since this allows to uniquely address a huge number of devices and control them through the Internet. Uniqueness, reliability, persistence, and scalability represent critical features related to the creation of a unique addressing schema [53]. Unique identification issues may be addressed by IPv4 to an extent (usually a group of cohabiting sensor devices can be identified geographically, but not individually). IPv6, with its Internet Mobility attributes, can mitigate some of the device identification problems and is expected to play an important role in this field.

Middleware. Due to the heterogeneity of the participating objects, to their limited storage and processing capabilities and to the huge variety of applications involved, a key role is played by the middleware between the things and the application layer, whose main goal is the abstraction of the functionalities and communication capabilities of the devices. The middleware can be divided in a set of layers (see Fig. 3): Object Abstraction, Service Management, Service Composition, and Application [42].

2.2. Cloud

The essential aspects of Cloud computing have been reported in the definition provided by the National Institute of Standard and Technologies (NIST) [92]: "Cloud computing is a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources (e.g., networks, servers, storage, applications, and services) that can be rapidly provisioned and released with minimal management effort or service provider interaction." Even though the main idea behind Cloud computing was not new, the term started to gain popularity after that Google's CEO Eric Shmidt used it in 2006 [130], and over the last few years the appearance of Cloud computing has hugely impacted IT industry. The availability of virtually unlimited storage [113] and processing capabilities at low cost enabled the realization of a new computing model, in which virtualized resources can be leased in an on-demand fashion, being provided as general utilities. Large companies (like Amazon, Google, Facebook, etc.) widely adopted this paradigm for delivering services over the Internet, gaining both economical and technical benefits.

Cloud Computing is a disruptive technology with profound implications for the delivery of Internet services as well as for the IT sector as a whole.

However, several technical and business-related issues are still unsolved. Specific issues have been identified for each service models, which are mainly related to security (e.g., data security and integrity, network security), privacy (e.g., data confidentiality), and service-level agreements, which could scare away part of potential users [114]. Moreover, the lack of standard APIs prevents customers to easily extract code and data from a site to run on another. More in general, outsourcing infrastructure to a Cloud provider, public Cloud customers are necessarily exposed to price increases, reliability problems or even to providers going out of business [10]. Fig. 4 summarizes the main aspects of Cloud: the main characteristics which make it a successful model, its layered architecture, and the standard service models. In the following, we describe a few important aspects of Cloud.

Layered Architecture and Service Models. The architecture of Cloud can be split into four layers: datacenter (hardware), infrastructure, platform, and application [130]. Each of them can be seen as a service for the layer above and as a consumer for the layer below. In practice, Cloud services can be grouped in three main categories: Software as a Service (SaaS), Platform as a Service (PaaS), and Infrastructure as a Service (IaaS). SaaS refers to the provisioning of applications running on Cloud environments. Applications are typically accessible through a thin client or a web browser. PaaS refers to platform-layer resources (e.g., operating system support, software development frameworks, etc.). IaaS refers to providing processing, storage, and network resources, allowing the consumer to control the operating system, storage and applications. It has raised the greatest interest so far [40].

Types of Clouds. Different types of Clouds have been identified in the literature [92, 130], as reported in the following: *(i)* Private Cloud provisioned for exclusive use by a single organization, typically owned, managed, and operated by the organization itself; *(ii)* Community Cloud – provisioned for exclusive use by a specific community of consumers that have shared concerns; *(iii)* Public Cloud – provisioned for open use by the general public; *(iv)* Hybrid Cloud – composition of two or more distinct Cloud infrastructures (private, community, or public); *(v)* Virtual Private Cloud – alternative aimed at addressing issues related to public and private Clouds, taking advantage of virtual private network (VPN) technologies for allowing business owners to setup required network settings (e.g. security, topology, etc.).

Considering the different issues related to enterprise applications and Cloud environments (e.g. lowering cost, increasing reliability, etc.), each type

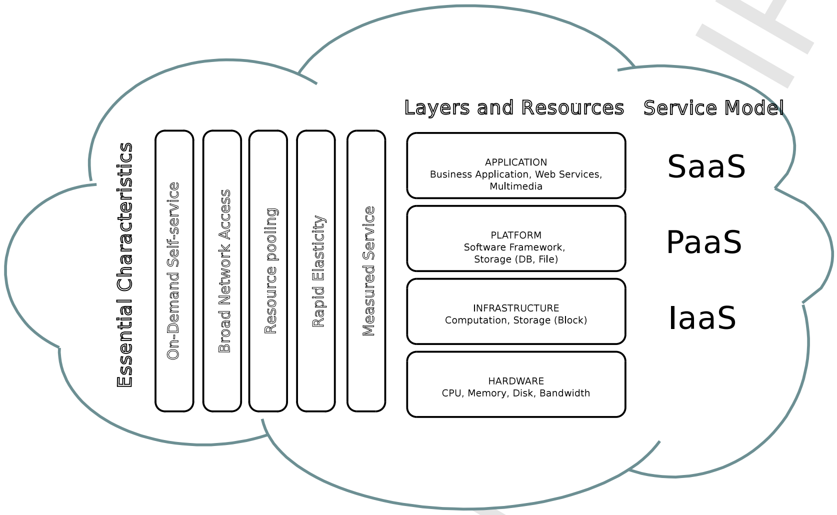


Figure 4: Cloud paradigm: an overall view.

of Cloud has his own benefits and drawbacks. Thus selecting a proper Cloud model depends on the specific business scenario.

Economical advantages. Cloud computing model is attractive since it frees the business owner from the need to invest in the infrastructure (CAPEX), renting resources according to needs and only paying for the usage. Moreover, it allows to decrease operating costs (OPEX), as service providers do not have to provision capacities according to peak load (in fact, resources are released when service demand is low). Finally, the outsourcing of the service infrastructure to the Clouds shifts the business risk towards the infrastructure provider, generally better equipped to manage it.

Technical advantages. In addition to such economical advantages, Cloud computing guarantees a number of technical benefits, including: energy efficiency, optimization of hardware and software resource utilization, elasticity, performance isolation, and flexibility.

3. CLOUD AND IOT: DRIVERS FOR INTEGRATION

The two worlds of Cloud and IoT have seen a rapid and independent evolution. These worlds are very different from each other and, even better, their characteristics are often complementary, as Tab. 1 shows. Such complementarity is the main reason why many researchers have proposed

Table 1: Complementary aspects of Cloud and IoT.

	IoT	Cloud
Displacement	pervasive	centralized
Reachability	limited	ubiquitous
Components	real world things	virtual resources
Computational capabilities	limited	virtually unlimited
Storage	limited or none	virtually unlimited
Role of the Internet	point of convergence	means for delivering services
Big data	source	means to manage

and are proposing their integration, generally to obtain benefits in specific application scenarios [8, 4, 51].

In general, IoT can benefit from the virtually unlimited capabilities and resources of Cloud to compensate its technological constraints (e.g., storage, processing, communication). To cite a few examples, Cloud can offer an effective solution for IoT service management and composition as well as for implementing applications and services that exploit the things or the data produced by them [83]. On the other hand, Cloud can benefit from IoT by extending its scope to deal with real world things in a more distributed and dynamic manner, and for delivering new services in a large number of real life scenarios. In many cases, Cloud can provide the intermediate layer between the things and the applications, hiding all the complexity and functionalities necessary to implement the latter. This will impact future application development, where information gathering, processing, and transmission will generate new challenges, especially in a multi-cloud environment [41].

In this section we discuss the main CloudIoT *drivers*, i.e., the motivations driving toward the integration of Cloud and IoT. Most of the papers in literature are actually seeing Cloud as the missing piece in the integrated scenario, i.e. they believe that Cloud fills some gaps of IoT (e.g. the limited storage). A few others, instead, see IoT filling gaps of Cloud (mainly the limited *scope*). In this paper we consider both as CloudIoT drivers and we start our discussion from the first ones.

Most of these drivers fall in three categories that are *communication*, *storage*, and *computation*, while a few others are more basic and have implications in all such categories, i.e. they are transversal. In the following, we start discussing such transversal drivers, and then detail the ones related to communication, storage, and processing.

Being IoT characterized by a very high heterogeneity of devices, technologies, and protocols, it lacks different important properties such as scalability, interoperability, flexibility, reliability, efficiency, availability, and security. Since Cloud has proved to provide them [47, 34, 115], we identify them as some of the main transversal CloudIoT drivers. Two other transversal drivers are the ease of use and the reduced cost obtained by both users and providers of applications and services [34]. Indeed, Cloud facilitates the flow between IoT data collection and data processing, and enables rapid setup and integration of new things, while maintaining low costs for deployment and for complex data processing [110]. As a consequence, analyses of unprecedented complexity [34, 101] are possible, and data-driven decision making and prediction algorithms can be employed at low cost, providing means for increasing revenues and reduced risks [129].

Communication. Data and application sharing are two important CloudIoT drivers falling in the communication category. Thanks to the CloudIoT paradigm, personalized ubiquitous applications can be delivered through the IoT, while automation can be applied to both data collection and distribution at low cost. Cloud offers an effective and cheap solution to connect, track, and manage any thing from anywhere at any time by using customized portals and built-in apps [110]. The availability of high speed networks enables effective monitoring and control of remote things [110, 47, 101], their coordination [47, 101, 115], their communications [47], and real-time access to the produced data [110].

It is worth mentioning that although Cloud can significantly improve and simplify IoT communication, it can still represent a bottleneck in some scenarios: indeed, over the last 20 years data storage density and processor power increased of a factor of 10^{18} and 10^{15} respectively, while broadband capacity increased only of 10^4 [68]. As a consequence, practical limitations can arise when trying to transfer huge amounts of data from the edge of the Internet onto Cloud.

Storage. IoT involves by definition a large amount of information sources (i.e., the things), which produce a huge amount of non-structured or semi-structured data [41], which also have the three characteristics typical of Big Data [134]: volume (i.e., data size), variety (i.e., data types), and velocity (i.e., data generation frequency). Large-scale and long-lived storage, possible thanks to the virtually unlimited, low-cost, and on-demand storage capacity provided by Cloud, represents an important CloudIoT driver. Cloud is the most convenient and cost effective solution to deal with data produced by IoT [110] and, in this respect, it generates new opportunities for data aggregation [47], integration [129], and sharing with third parties [129]. Once into Cloud, data can be treated as homogeneous through well-defined APIs [47], can be protected by applying top-level security [34], and can be directly accessed and visualized from any place [110].

Computation. IoT devices have limited processing and energy resources that do not allow complex, on-site data processing. Collected data is usually transmitted to more powerful nodes where aggregation and processing is possible, but scalability is challenging to achieve without a proper infrastructure. Cloud offers virtually unlimited processing capabilities and an on-demand usage model. This represents another important CloudIoT driver: IoT processing needs can be properly satisfied for performing real-time data analysis (on-the-fly) [110, 34], for implementing scalable, real-time, collaborative, sensor-centric applications [47], for managing complex events [110], and for supporting task offloading for energy saving [125].

Scope. As the things add capabilities, and more people and new types of information are connected, users spread across the world quickly enter the *Internet of Everything* (IoE) [43, 2], a network of networks where billions of connections create unprecedented opportunities as well as new risks. The adoption of the CloudIoT paradigm enables new smart services and applications based on the extension of Cloud through the things [110, 115] which enable the cloud to deal with a number of new, real-life scenarios, giving birth to the *Things as a Service* paradigm [27, 94, 36]. This is another important driver for CloudIoT. The literature shows how a number of new paradigms emerging from the integration of Cloud and IoT and related to this particular driver. They are summarized in Tab. 2. Since no standard has been clearly defined, there is no sharp distinction among the proposed acronyms, which in some cases appear to collide. Vehicular Cloud is another important new paradigm emerging in this area [57].

In conclusion, several motivations are driving the integration of Cloud and IoT. Some of them are actually related with specific application scenarios. Section 4 analyzes these application scenarios in details, revealing the main challenges associated with each of them.

Table 2: New Paradigms enabled by CloudIoT: everything as a Service.

XaaS (Acronym)	**X** (Expansion)	**Description**
	Things as a service [27, 94, 36]	aggregating and abstracting heterogeneous resources according to tailored thing-like semantics
SaaS [110, 129, 34] or S^2aaS [104, 72, 71]	Sensing as a service	providing ubiquitous access to sensor data
SAaaS [110]	Sensing and Actuation as a service	enabling automatic control logics implemented in the Cloud
SEaaS [110, 34]	Sensor Event as a service	dispatching messaging services triggered by sensor events
SenaaS [129]	Sensor as a service	enabling ubiquitous management of remote sensors
DBaaS [129]	DataBase as a service	enabling ubiquitous database management
DaaS [129]	Data as a service	providing ubiquitous access to any kind of data
EaaS [129]	Ethernet as a service	providing ubiquitous layer-2 connectivity to remote devices
IPMaaS [129]	Identity and Policy Management as a service	enabling ubiquitous access to policy and identity management functionalities
VSaaS [108]	Video Surveillance as a service	providing ubiquitous access to recorded video and implementing complex analyses in the Cloud

4. APPLICATIONS

CloudIoT gave birth to a new set of smart services and applications, that can strongly impact everyday life (Fig. 5). Many of the applications described in the following (may) benefit from Machine-to-Machine communications (M2M) when the things need to exchange information among themselves and not only send them towards the cloud [93]. This represents one of the open issues in this field, as discussed in Sec. 7. In this section we describe the wide set of applications that are made possible or significantly improved thanks to the CloudIoT paradigm. For each application we point out the challenges, which we discuss in detail in Sec. 5.

Healthcare. The adoption of the CloudIoT paradigm in the healthcare field can bring several opportunities to medical IT, and experts believe that it can significantly improve healthcare services and contribute to its continuous and systematic innovation [77]. Indeed, CloudIoT employed in this scenario is

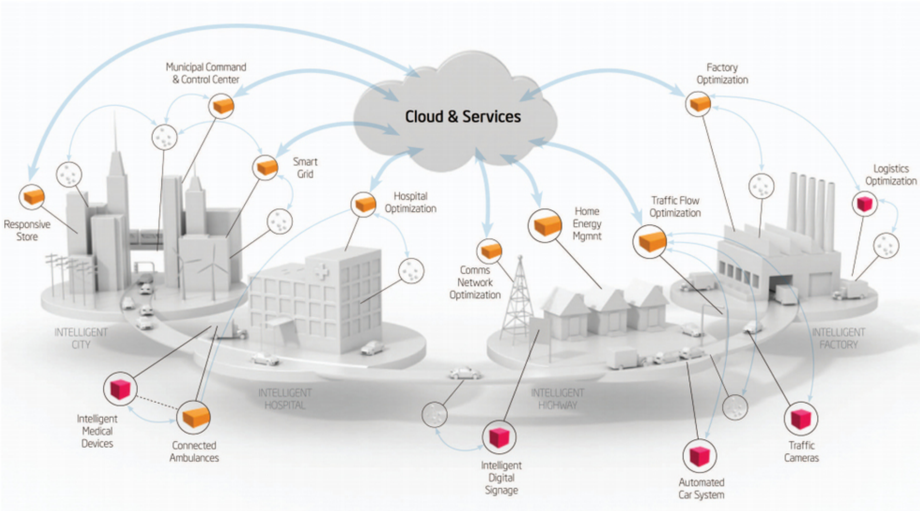


Figure 5: Services made possible thanks to the CloudIoT paradigm.
Source: `http://siliconangle.com/`

able to simplify healthcare processes and allows to enhance the quality of the medical services by enabling the cooperation among the different entities involved. Ambient assisted living (AAL), in particular, aims at easing the daily lives of people with disabilities and chronic medical conditions.

Through the application of CloudIoT in this field it is possible to supply many innovative services, such as: collecting patients' vital data via a network of sensors connected to medical devices, delivering the data to a medical center's Cloud for storage and processing, properly managing information provided by sensors, or guaranteeing ubiquitous access to, or sharing of, medical data as Electronic Healthcare Records (EHR) [48, 88, 77].

CloudIoT enables cost effective and high-quality, ubiquitous medical services [77, 48]. Pervasive healthcare applications generate a vast amount of sensor data that have to be managed properly for further analysis and processing [39]. The adoption of Cloud represents a promising solution for managing healthcare sensor data efficiently [39] and allows to abstract technical details, eliminating the need for expertise in, or control over, the technology infrastructure [6, 88]. Moreover, it leads to the easy automation of the process of collecting and delivering data at a reduced cost [77]. It further makes mobile devices suited for health information delivery, access, and communication, also on the go [97]. Cloud allows to face common challenges of this application scenario such as: security, privacy, and reliability, by enhancing medical data security and service availability and redundancy [77, 6]. Thanks to the efficient management of sensor data it is possible to provide assisted-living services in real-time [44]. Moreover, Cloud adoption enables the execution (in the Cloud) of secure multimedia-based health services, overcoming the issue of running heavy multimedia and security algorithms on devices with limited computational capacity and small batteries [97], and it provides a flexible storage and processing infrastructure to perform both online and offline analyses of data streams generated in healthcare Body Sensor Networks (BSNs)[2]. Thanks to the use of the CloudIoT paradigm BSNs can be deployed in a community of people and can generate large amounts of contextual data that are stored, processed, and analyzed in a scalable fashion [45].

In the healthcare domain, common challenges are related to the lack of trust in data security and privacy by users (exposure to hacker attacks, violation of medical data confidentiality, data lock-in and loss of governance, privilege abuse), performance unpredictability (resource exhaustion, data transfer bottlenecks, impact on real-time services, streaming QoS), legal issues (contract law, intellectual property rights, data jurisdiction) and are still object of investigation [77, 38, 97]. The lack of specific research related to the adoption of these technologies in the context of mission critical systems, of deepened reliability analyses and the limited number of case studies are often defined as the major obstacles [77, 44, 45].

Smart Cities and Communities. CloudIoT leads to the generation of services that interact with the surrounding environment, thus creating new opportunities for contextualization and geo-awareness. Sustainable development of urban areas is a challenge of key importance and requires new, efficient, and user-friendly technologies and services. The challenge is to harness the collaborative power of ICT networks (networks of people, of knowledge, of sensors) to create collective and individual awareness about the multiple sustainability threats which our society is facing nowadays at social, environmental, and political levels. The resulting collective intelli-

[2]BSNs have been recently introduced for the remote monitoring of human activities in the healthcare domains but also in other application domains such as emergency management, fitness, and behavior surveillance.

gence will lead to better informed decision-making processes and empower citizens, through participation and interaction, to adopt more sustainable individual and collective behaviours and lifestyles [58]. CloudIoT can provide a common middleware for future-oriented smart-city services [13, 115, 28], acquiring information from different heterogeneous sensing infrastructures, accessing all kinds of geo-location and IoT technologies (e.g., 3D representations through RFID sensors and geo-tagging), and exposing information in a uniform way (e.g., through a dynamically annotated map). Frameworks typically consist of a sensor platform (with APIs for sensing and actuating) and a Cloud platform which offers scalable and long-lived storage and processing resources for the automatic management and control of real-world sensing devices in a large-scale deployment. Crowdsourced and reputation-based frameworks also exist: authors of [72, 71] propose a framework implementing the Sensing as a Service paradigm in the context of smart cities and aimed at public safety. Authors of [9, 107] present an ecosystem for mobile crowdsensing applications which relies on the Cloud-based publish/subscribe middleware to acquire sensor data from mobile devices in a context-aware and energy-efficient manner. Authors of [121] focus on the burden on application developers and final users created by the need to deal with-large scale environments. Since IoT scenario is highly fragmented, sensor virtualization can be employed to reduce the gap between existing heterogeneous technologies and their potential users, allowing them to interact with sensors at different layers [106].

A number of recently proposed solutions suggest to use Cloud architectures to enable the discovery, the connection, and the integration of sensors and actuators, thus creating platforms able to provision and support ubiquitous connectivity and real-time applications for smart cities [94, 105]. For instance, authors of [76] discuss a concept towards developing a smart city using an intelligent, energy efficient, public illumination system, which would also offer ubiquitous communication. Moreover, Cloud-based platforms help to make it easier for third parties to develop and provide IoT plugins enabling any device to be connected to the Cloud [13]. This type of advanced service model hides the complexity and the heterogeneity of the underlying infrastructure, while at the same time meeting complex requirements for Cloud, such as high reactivity and timeliness, scalability, security, easy-configurability, and flexibility [13, 115, 135].

Common challenges are related to security, reliability, scale, heterogeneity and timeliness. Indeed, enabling the necessary resources, storage and computing capabilities for large amounts of heterogeneous and personalized data (coming from distributed sources) in a transparent and secure manner and the development and the deployment of various middleware platforms in a such fragmented scenario (in which different IoT ecosystems are not able to communicate between them) are not trivial tasks [115]. The involvement of multiple physical sensors in the scope of service delivery creates additional challenges associated with real-time interactions, which imposes a need for studying extensions over real-time operating systems for embedded devices, as well as how they could be supported in the scope of a Cloud environment [115]. Moreover, the resulting system has to provide a rapid setup of deployed sensors and an easy integration of new sensors in the sensing environment [94].

The blending of IoT resources into the Cloud introduces new resource management requirements, which are associated with the need to optimize not only processing, storage and I/O resources, but also sensor reading cycles, multi-sensor queries and shared access to expensive location-dependent IoT resources [115]. Significant research on sensing, actuation, and IoT is directed towards the efficient semantic annotation of sensor data [94]. Finally, while cities share common concerns – such as the need to effectively share information within and between cities and the desire for enhanced cross-border protocols – they lack a common infrastructure and methodology for collaborating, generating operational and regional fragmentation that currently prevent innovative synergies [13, 115].

Smart Home and Smart Metering. Home networks have been identified as the environment where users mainly act: CloudIoT has large application in home environments, where the joint adoption of heterogeneous embedded devices and Cloud enables the automation of common in-house activities. Indeed, the merging of computing with physical things, enables the transformation of everyday objects into information appliances which – interconnected through the Internet – can expose services through a web interface. Several smart-home applications proposed in literature involve (wireless) sensor networks and realize the connection of intelligent appliances to the Internet in order to remotely monitor their behavior (e.g., to monitor devices' power usage to improve power usage habits [26]) or remotely control them (e.g., to manage lighting, heating, and air conditioning [54]). In particular, smart lighting recently attracted growing attention from the research community [127, 91]; lighting is responsible for 19% of global use of electrical energy, and accounts for about 6% of the total emissions of greenhouse gases [23]: smart lighting control systems proved to save the energy consumed for lighting up to 45% [91]. In this scenario, the Cloud is the best candidate for building flexible applications with only a few lines of code, making home automation a trivial task [70], and providing necessary resources for tasks beyond the scope of local networks [95].

Cloud can enable direct interaction of the user to sensors/actuators (i.e. to support event-based systems) and can satisfy some crucial requirements such as internal network interconnection (i.e. any digital appliance in smart home should be able to interconnect with any other), intelligent remote control (i.e. appliances and services in the smart home should be intelligently manageable at any time by any device from anywhere), and automation (i.e. interconnected appliances within the home should implement their functions via linking to services provided by smart-home oriented Cloud) [126]. Cloud-based solutions allow to set-up an ubiquitous space where any device can be individually accessed in a standardized way [70] and to guarantee concurrent, multi-user support through the Web. To properly face the potentially high number of devices and the volume of their communication with the Cloud, administration and control of devices could be leveraged by deploying more powerful computing devices, acting as mediators among IoT devices and Cloud components, for implementing complex functionalities on top of them, mitigating the frequency of communications with the Cloud.

Several challenges must be resolved when implementing applications in this context, which are mainly related to the lack of standards and reliability. Home devices should be web-enabled, and the interaction with them should be uniform [54], (i.e. a standard web-based interface should be defined for service description and communication). Moreover, appliance recognition routines are needed to enable appliances' easy discovery. Reliability concerns also exist related to not always reachable devices, device failure, and variable QoS [70].

Video Surveillance. CloudIoT in the context of intelligent video surveillance leads to easily and efficiently store, manage, and process video contents originating from video sensors (i.e. IP cameras) and to automatically extract knowledge from scenes. It has become a tool of the greatest importance for several security-related applications. Proposed solutions are able to deliver video streams to multiple user devices through the Internet, by distributing the processing tasks over the physical server resources on-demand, in a load-balanced and fault-tolerant fashion [49].

As an alternative to in-house, self-contained management systems, complex video analytics require Cloud-based solutions (VSaaS [108]) to properly satisfy the requirements of video storage (e.g., stored media is centrally secured, fault-tolerant, on-demand, scalable, and accessible at high-speed) and video processing (e.g., computer vision algorithms and pattern recognition module execution).

Commonly considered challenges for this kind of applications are mainly related to the impossibility of using any camera connection and control due to the limited diffusion of the enabling technology and tools (need of buying new cameras)[108]. Available devices are characterized by high heterogeneity due to the lack of properly defined standards and service schemes [108, 49].

Automotive and Smart Mobility. As an emerging technology, IoT is expected to offer promising solutions to transform transportation systems and automobile services (i.e. Intelligent Transportation Systems, ITS). The integration of Cloud with IoT technologies (such as WSNs and RFID) represents a promising opportunity [57]. Indeed, a new generation of vehicular datamining Cloud service can be developed and deployed to bring many business benefits, such as increasing road safety, reducing road congestion, managing traffic and parking, performing warranty analysis and recommending car maintenance or fixing [57].

Numerous vehicles possess powerful sensing, networking, communication, and data processing capabilities, and can exchange information with each other (Vehicle to Vehicle, V2V) or exchange information with the roadside infrastructure such as camera and street lights (Vehicle to Infratructure, V2I) over various protocols, including HTTP, SMTP, TCP/IP, WAP, and Next Generation Telematics Protocol (NGTP) [55]. In this context, Ethernet and IP-based routing (being less expensive and more flexible than related technologies) are claimed to be very important technologies for future communication networks in electric vehicles, enabling the link between the vehicle electronics and the Internet. Indeed they integrate vehicles into a typical IoT, and meet the demand for powerful communication with Cloud-based services [55].

The literature proposes several examples of multi-layered, Cloud-based vehicular data platforms that merge Cloud computing and IoT technologies to tackle the main current challenges [57]. These platforms aim at providing real-time, cheap, secure, and on-demand services to customers, through different types of Clouds, which also include temporary vehicular Clouds (i.e. formed by the vehicles representing the Cloud datacenters [18]) designed to expand the conventional Clouds in order to increase on-demand the whole Cloud computing, processing, and storage capabilities, by using under-utilized facilities of vehicles.

Several challenges have been identified in literature related to this application scenario. The huge number of vehicles and their dynamically changing number make system scalability difficult to achieve [57]. Vehicles moving at various speeds frequently cause intermittent communication impacting performance, reliability, and QoS [18]. The lack of an established infrastructure makes it difficult to implement effective authentication and authorization mechanisms [18], with impacts on security and privacy provision [90]. The lack of global standards, experimental studies, and proper benchmarks on realistic ITS-Clouds affects interoperability [57].

Smart Energy and Smart Grid. IoT and Cloud can be effectively merged to provide intelligent management of energy distribution and consumption in both local- and wide-area heterogeneous environments.

The IoT nodes typically involved in this kind of processes have sensing, processing, and networking capabilities, but limited resources. Hence, computing tasks can be properly demanded to the Cloud, where more complex and comprehensive decisions can be made. Cloud adoption leads to increase the reliability by providing self-healing mechanisms and enables mutual operation and participation of the users, to achieve distributed generation, electricity quality, and demand response [128]. Cloud computing makes possible to analyze and process vast amounts of data and information coming from different sources distributed along wide area networks, for the purpose of implementation of intelligent control to objects.

Several challenges should be adequately addressed to realize the full potential of such application. Large scale distributed sources raise issues about heterogeneity, data size and collection rate, latency dynamics, and cost of security enforcement [128]. Security and privacy concerns inherent in an information-rich smart grid evironment may be further exacerbated by deployment on Cloud and introduce challenges such as: the integration of data having diverse ownership, the aggregation of public and private data, or a longer and wider exposure to attacks [111]. Legal issues can derive from the distribution of data archival over different jurisdictions [111]. Finally, consumers should gain more confidence in sharing data to help improving and optimizing services offered [111].

Smart Logistics. The adoption of CloudIoT in logistics promotes a new service mode that is radically changing business paradigms [85]. It enables new interesting scenarios and allows the easy and automated management of flows of goods between the point of origin and the point of consumption, in order to meet specific requirements expressed in terms of time, cost or means of transport. Moreover, thanks to geo-tagging technologies, it enables to automatically track goods while in transit.

CloudIoT is proposed to help conventional logistics systems in evolving into advanced systems, capable of dealing automatically with complexity and changes. Ideed, logistics resources are heterogeneous (e.g., geographical distribution, morphological diversity, and self-governing zone). These make resource sharing and management more complex. Hence, computer aided software tools supporting the adoption of IoT can experience a bottleneck in dealing with complexity, dynamics, and uncertainties in their applications in modern enterprises. The adoption of Cloud computing can help in overcoming the bottlenecks enabling complex decision-making systems where automated algorithms can be enforced to retrieve information for assembly planning [119]. By adopting a scalable and modularized architecture, Cloud helps to make the system robust, reliable, flexible, and easily expandable.

In this context, important challenges are related to resource heterogeneity, and solutions are investigated in terms of logistics virtualization and service selection [85]. The former is critical for resource sharing and dynamic allocation and provides flexibility in the use of resources. The latter allows service requesters and providers to agree on the attributes that govern the interaction and provides the selection of an appropriate web service that meets certain functional and non-functional criteria.

Environmental Monitoring. The combined use of Cloud and IoT can contribute to the deployment of a high speed information system between the entity in charge of monitoring wide-area environments and the sensors/actuators properly deployed in the area. Some applications can be related to the continuous and long-term monitoring of water level (for lakes, streams, sewages), gas concentration in air (e.g., in laboratories, deposits), soil humidity and other characteristics, inclination for static structures (e.g., bridges, dams), position changes (e.g., land slides), lighting conditions (e.g., to detect intrusions in dark places), infrared radiation for fire or animal detection [78]. Other potential applications of this kind are: agriculture information transmission and intelligent detection, intelligent cultivation control, food safety tracking, precision irrigation, forest identification, and tree tracking [110].

A Cloud-based data access is able to bridge the latency-energy requirements of low power communication segments and the ubiquitous and fast access to data for end users (either humans or IoT applications) [78]. Moreover it allows to manage and process complex events, generated by the real-time data streamed by sensors.

The main challenges in this field pertain to the potential massive-scale of the infrastructures. Specifically, environmental dynamism makes it difficult to provide computational resources that are sufficient to deal with changing environmental conditions. Moreover, challenges are also related to security, as threats can be found in information leak due to potential breaches caused by infected clients or communication channel vulnerabilities.

Finally, research is still needed on the implementation and promotion of proper communication protocols (such as IPv6 for individually addressing the things), the setting of various IoT standards for promoting interoperability and for scaling the cost of IoT facilities, and the assessment of risks and uncertainties.

In this section we have carefully surveyed and described a number of applications arising from the adoption of the CloudIoT paradigm and for each of them we have pinpointed the related challenges. In Sec. 5 we provide a detailed discussion of these challenges.

5. CHALLENGES

We have discussed how integrating Cloud and IoT provides several benefits and fosters the birth or improvement of a number of interesting applications. At the same time, we have seen that the complex CloudIoT scenario imposes several challenges for each application that is currently receiving attention by the research community [41]. This section is devoted to the analysis of such challenges. In the following we first deal with the typical challenges raised by the application scenarios reported above. We then focus on other important recurring challenging topics strictly related to CloudIoT.

Security and Privacy. When critical IoT applications move towards the Cloud, concerns arise due to the lack of, e.g., trust in the service provider,

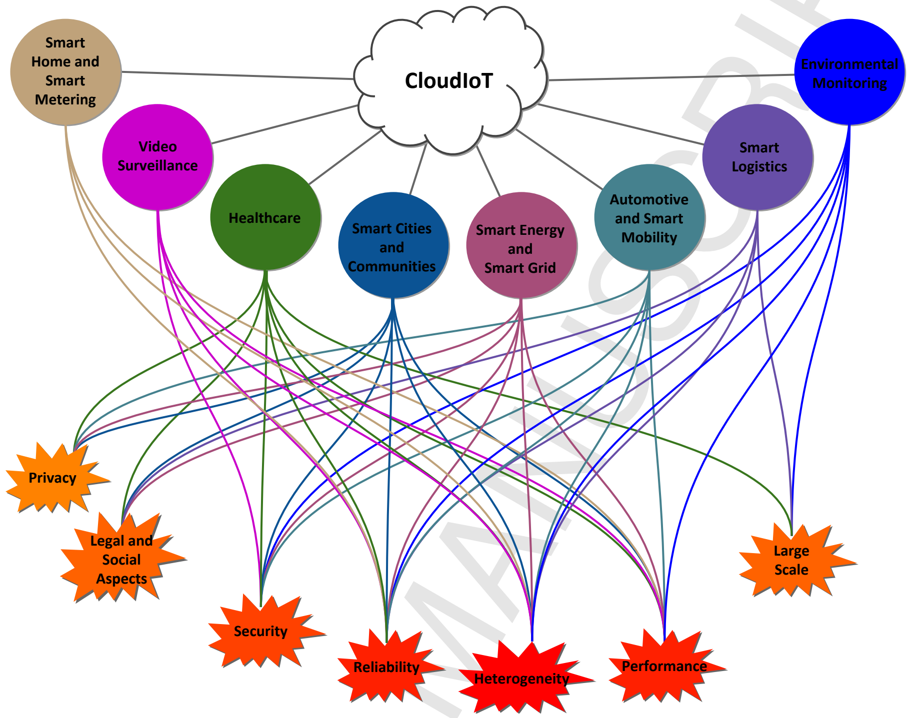


Figure 6: Application scenarios driven by the CloudIoT paradigm and related challenges.

knowledge about service level agreements (SLAs), and knowledge about the physical location of data. Accordingly, new challenges require specific attention [16, 111, 114]. Such a distributed system is exposed to several possible attacks (e.g., session riding, SQL injection, cross site scripting, and side-channel) and important vulnerabilities (e.g., session hijacking and virtual machine escape). Multi-tenancy can also compromise security and lead to sensitive information leakage. Moreover, public key cryptography cannot be applied at all layers due to the computing power constraints imposed by the things. These are examples of topics that are currently under investigation in order to tackle the big challenge of security and privacy in CloudIoT.

Heterogeneity. A big challenge in CloudIoT is related to the wide heterogeneity of devices, operating systems, platforms, and services available and possibly used for new or improved applications.

Cloud platforms heterogeneity is also a non-negligible concern. Cloud services typically come with proprietary interfaces, causing resource integration and mash-up to be properly customized based on the specific providers. This issue can be exacerbated when users adopt multi-cloud approaches, i.e. when services depend on multiple providers in order to improve application performance and resilience or vendor lock-in [52]. These aspects are only partially solved by cloud brokering, voluntarily implemented by cloud providers (in form of federation) or by third parties.

IoT services and applications have typically been conceived as isolated vertical solutions, in which all system components are tightly coupled to the specific application context. For each possible application/service, providers have to survey target scenarios, analyze requirements, select hardware and software environments, integrate heterogeneous subsystems, develop, provide computing infrastructure, and provide service maintenance. On the other hand, also thanks to Cloud service delivery models, CloudIoT should ease IoT service delivery [84]. However, although PaaS-like models would represent a generic solution for facilitating the deployment of IoT applications, their implementation requires tackling the big challenge of heterogeneity. For instance, the interaction with (management of) huge amounts of highly heterogeneous things (and the related data produced) has to be properly addressed into the Cloud at different levels. This challenge involves several aspects, where solutions are being investigated in terms of unifying platforms and middleware (described in detail in Section 6), interoperable programming interfaces [70], means for copying with data diversity [111], etc.

Performance. Often CloudIoT applications introduce specific performance and QoS requirements at several levels (i.e. for communication, computation, and storage aspects) and in some particular scenarios meeting requirements may not be easily achievable. In particular, obtaining stable acceptable network performance to reach the Cloud is a main challenge, considering that broadband increase did not follow storage and computation evolution [68, 110]. In fact, in several scenarios (e.g., when mobility is required) provisioning of data and services needs to be performed with high reactivity [57, 94]. Since timeliness may be heavily impacted by unpredictability issues real-time applications are mainly susceptible to performance challenges [115, 110]. Usability and user experience also can be affected by poor QoS (e.g., when multimedia streaming is needed)[77].

Reliability. When CloudIoT is adopted for mission-critical applications, reliability concerns typically arise e.g., in the context of smart mobility, vehicles are often on the move and the vehicular networking and communication is often intermittent or unreliable. When applications are deployed in resource-constrained environments a number of challenges related to device failure or not always reachable devices exists [57].

From the one hand, Cloud capabilities help to overcome some of these challenges (e.g., Cloud enhances the reliability of the devices by allowing to offload heavy tasks and thus to increase devices' battery duration or offering the possibility of building a modularized architecture) [128, 119]; on the other hand, it introduces uncertainties related to data center virtualization or resource exhaustion [110, 77]. The lack of reliability analyses and of the development of specific case studies exacerbate the challenge.

Large Scale. CloudIoT allows to design novel applications aimed at integrating and analyzing information coming from real-world (embedded) devices [105, 78, 19, 94, 110, 121]. Some of the depicted scenarios implicitly require the interaction with a very large number of these devices, usually distributed across wide-area environments. The large scale of the resulting systems makes typical challenges harder to overcome (e.g., requirements about storage capacity and computational capability for further processing become arduous to be satisfied when facing long-lived data collected at high-rate). Moreover the distribution of the IoT devices makes monitoring tasks harder since they have to face latency dynamics and connectivity issues.

Legal and Social Aspects. These are two important challenges, partly related. Legal aspects are extremely important and actual in the current research for specific application scenarios. Think, for example, to a CloudIoT service based on user-provided data. In this case, on the one hand, the service provider has to conform to different international laws. And, on the other hand, users have to be provided with incentives in order to contribute to data collection. In more general terms, Social aspects are of interest for research and are currently considered an interesting challenge because, often, the investment into omnipresent Internet-capable devices is not reasonable in every scenario. It is more convenient to give the opportunity to users to participate in submitting data that represent a thing [11]. The authors of [32] have identified a set of issues to be addressed by any system which incorporates humans as a source of sensor data, in order to remain trusted by its users (such as integrating the qualitative observations generated by humans with the machine-generated quantitative observations, or the need to characterize and manage data quality, reliability, reputation, and trustworthiness). Users could also be empowered with new building blocks and tools:

accelerators, frameworks, and toolkits that enable the participation of users in IoT as done in the Internet through Wikis and Blogs [33]. Such tools and techniques should enable researchers and design professionals to learn about user work, giving users an active role in technology design. To achieve this, these tools should allow users to easily experiment various design possibilities in a cost-effective way. Related to this challenge, researchers are trying to provide adequate tools for implementing a cooperative prototyping approach, where users and designers explore together applications and their relations.

Besides the challenges reported above, other important aspects are currently of large interest for the research community. They partly intersect with the challenges reported above, but they require a separate discussion as they involve a large body of research on their own.

Big Data. With an estimated number of 50 billion devices that will be networked by 2020, specific attention must be paid to transportation, storage, access, and processing of the huge amount of data they will produce. Thanks to the recent development in technologies, IoT will be one of the main sources of big data, and Cloud will enable to store it for long time and to perform complex analyses on it. The ubiquity of mobile devices and sensor pervasiveness, indeed call for scalable computing platforms (every day 2.5 quintillion bytes of data are created) [37]. Handling this data conveniently is a critical challenge, as the overall application performance is highly dependent on the properties of the data management service [37]. For instance, cloud-based methods for Big Data summarization based on the extraction of semantic feature are actually under investigation [69]. Hence, following the NoSQL movement, both proprietary and open source solutions adopt alternative database technologies for big data [31]: time-series, key-value, document store, wide column stores, and graph databases. Unfortunately, no perfect data management solution exists for the Cloud to manage big data [129]. Moreover, data integrity is an important factor, not only for its impact on the qualities of service, but also for security and privacy related aspects expecially on outsourced data[87].

Sensor Networks. Sensor networks have been defined as the major enabler of IoT [129] and as one of the five technologies that will shape the world, offering the ability to measure, infer, and understand environmental indicators, from delicate ecologies and natural resources to urban environments [53]. Recent technological advances have made efficient, low-cost, and low-power miniaturized devices available for use in large-scale, remote sensing applications [5]. Moreover, smartphones, even though limited by power consumption and reliability, come with a variety of sensors (GPS, accelerometer, digital compass, microphone, and camera), enabling a wide range of mobile applications in different domains of IoT. In this context, the timely processing of huge and streaming sensor data, subject to energy and network constraints and uncertainties, has been identified as the main challenge [131]. Cloud provides new opportunities in aggregating sensor data and exploiting the aggregates for larger coverage and relevancy, but at the same time affects privacy and security [131]. Furthermore, being lack of mobility a typical aspect of common IoT devices, the mobility of sensors introduced by smartphones as well as wearable electronics represents a new challenge [103].

Monitoring. As largely documented in the literature, monitoring is an essential activity in Cloud environments for capacity planning, for managing resources, SLAs, performance and security, and for troubleshooting [3]. As a consequence, CloudIoT inherits the same monitoring requirements from Cloud, but the related challenges are further affected by volume, variety, and velocity characteristics of IoT.

Fog Computing. Fog computing is an extension of classic Cloud computing to the edge of the network (as fog is a cloud close to the ground). It has been designed to support IoT applications characterized by latency constraints and requirement for mobility and geo-distribution [20, 133, 1]. Even though computing, storage, and networking are resources of both the Cloud and the Fog, the latter has specific characteristics: edge location and location awareness implying low latency; geographical distribution and a very large number of nodes in contrast to centralized Cloud; support for mobility (through wireless access) and real-time interaction (instead of batch processes); support for interplay with the Cloud. Authors of [89] proposed an analysis showing how building Fog computing projects is challenging. Indeed, the adoption of Fog-based approaches requires various specific algorithms and methodologies dealing with reliability of the networks of smart devices, and operating under specific conditions that ask for fault tolerant techniques.

6. PLATFORMS, SERVICES, AND RESEARCH PROJECTS

In this section we describe open source and proprietary platforms for implementing the new vision and paradigms of Sec. 3 and the new CloudIoT applications of Sec. 4. Also, we survey research projects focused on the

Table 3: Challenges pertaining CloudIoT applications.

Applications	Privacy	Legal and Social Aspects	Large Scale	Security	Reliability	Performance	Heterogeneity
Smart Home and Smart Metering					✓	✓	✓
Video Surveillance				✓	✓	✓	✓
Healthcare	✓	✓	✓	✓	✓	✓	✓
Smart Cities and Communities	✓	✓		✓	✓	✓	✓
Smart Energy and Smart Grid	✓	✓		✓	✓	✓	✓
Automotive and Smart Mobility				✓	✓	✓	✓
Smart Logistics		✓	✓		✓		✓
Environmental Monitoring			✓	✓	✓	✓	✓

(Challenges: Privacy, Legal and Social Aspects, Large Scale, Security, Reliability, Performance, Heterogeneity)

CloudIoT paradigm, which we believe are an example of the research efforts funded in this important area.

6.1. Platforms

The design of CloudIoT platforms can lead to develop intelligent infrastructures, enabling smart applications to benefit from cloud-based frameworks [81]. These platforms would enable the new paradigms reported in Tab. 2 and discussed in Sec. 3. Based on such platforms, end-users would be able to leverage intelligent providers' sensing and actuating infrastructures, rather than having to deploy sensing infrastructures by themselves – which proved to be a time-consuming and tedious task that dramatically slows innovation [65]. The resulting virtualization of sensing resources should also provide a mean to customize the virtual sensing infrastructure in order to adapt to the different applications.

While the literature reports efforts in defining a generic high-level architecture to deal with the integration of Cloud and IoT [36, 67] – e.g., Software defined IoT (SDIoT) – there are several open source and proprietary platforms available for Cloud and IoT integration. Most of them are aimed at solving one of the main issues in this field that is related to the heterogeneity of things and Clouds. These platforms try to bridge this gap implementing a middleware towards the things and another towards the Cloud, and they typically provide an API towards the applications. Other platforms are instead bound to specific hardware devices or Clouds. Tab. 4 reports the main characteristics of these platforms and services. In the following we review both types of platforms, starting with the ones belonging to the former group.

IoTCloud [100] is an open source project aimed at integrating the things (smart phones, tablets, robots, web pages, etc.) with backends for managing sensors and their messages and for providing an API to applications interested in these data. The platform has been showcased with video sensors (i.e., IP cameras) on the FutureGrid Cloud testbed [46]. The software is available online through the code sharing platform github. OpenIoT [98] is another open source effort fostered by a research project financed by the EU. The project aims at providing a middleware to configure and deploy algorithms for collection and filtering messages by things, while at the same time generating and processing events for interested applications. The authors of [81] discuss the infrastructural functional modules and the design principles of the middleware for enabling the dynamic, self-organizing formulation of optimized IoT applications in cloud environments. Among the main focuses of OpenIoT are the mobility aspects of IoT for energy-efficient orchestration of data collection and transmission to the Cloud. The project web site [98] contains different videos showing possible applications in several scenarios. Also this software is available online through github. There are also projects specifically aimed at creating toolkits for the interaction of IoT and Cloud. For example, IoT Toolkit (run by a Silicon Valley based organization called OSIOT) [64] aims at developing a toolkit that allows to glue the several protocols available for the things, for the Cloud, and for the applications.

As for the proprietary solutions (e.g. platforms typically bound to specific things or Clouds), Postscapes publishes a catalog of projects, events, interviews, and company/job listings within the industry [61]. Interesting examples include open source projects run by private companies. For example, the open source project of NimBits [96] provides a set of software to be installed on private or public Clouds (mainly Google App Engine) to create a PaaS that collects data from things and triggers computations or alerts when specific conditions are verified. The company provides also a Cloud service for running this software that is free of charge but has some usage limitations. On the other side, there are companies that provide things ready to be integrated in Clouds. For example, openPicus [62] is an Italian company which builds things (e.g. small sensors equipped with WiFi or GPRS connectivity) using an open hardware approach. The idea is to build very cheap products that have full TCP/IP stack implemented and HTTP server on-board, which allows to interact with them using simple RESTful APIs.

Finally, there are also several services (es. Xively [122], Open.Sen.se [99], ThingSpeak [118], CloudPlugs [29], Carriots [22]) that allow to collect data from things and to store these data on the Cloud offered by the service provider. These services typically provide an API and different example applications to use the data collected by the things, which range from specific, proprietary things to open, and widely distributed ones (e.g. Arduino). This is the most common market trend is this area, allowing service providers to offer free subscriptions and make business out of data provided by the users. Starting from these services, companies have created toolkits for their integration in CloudIoT frameworks. For example, NetLab [63] is a toolkit for interaction among physical and digital objects (e.g. controlling video movies through arduino). NetLab has created two widgets called CouldIn and Cloud-Out that allow to interact with several CloudIoT services. In particular, they allow to periodically send data from things to these services or to periodically retrieve data from these services. Compliant services include Xively (formerly COSM and Pachube), Open.Sen.se, and ThingSpeak. Hardware producers have also started to launch Cloud services where clients can upload their data. For example, at Synapse they created a component of their operating system (SNAP) that allow to send data to private and public Cloud and to manage the related tasks (operation, administration, maintenance, and provisioning) [116]. Recently Intel has also launched an initiative [59] that provides a software library for Galileo/Edison platforms (compatible with arduino) and a private Cloud where data can be stored by things based on Galileo/Edison platforms and accessed by applications though a public API. The sources of software as well as the designs of the hardware are released to the public (i.e. open source and open hardware).

6.2. Research Projects

ClouT [28], which stands for "Cloud of things", is a research project run by industrial and research partners as well as city administrations from Europe and Japan. The partners aim at developing infrastructure, services, tools and applications for municipalities and their stakeholders (citizens, service developers, etc.) to create, deploy, and manage user-centric applications based on IoT and Cloud integration. Target applications include enhanced public transportation, increased citizen participation through mobile devices

Table 4: Platforms, services and research projects.

	Proprietary things	Open things	Private cloud	Public cloud	Free	Open source	Application API	Last update	Ready to use
IoTCloud	✓	✓	n/a	n/a	✓	✓	✓	Oct. 14	✓
OpenIoT	✓	✓	✓	✓	✓	✓	✓	Oct. 14	✓
IoT Toolkit	✓	✓	n/a	n/a	✓	✓	n/a	Dec. 13	
NimBits	✓	✓	✓	partly	✓	✓	n/a	Nov. 14	✓
openPicus	✓		n/a	n/a	n/a	n/a	✓	n/a	n/a
Xively	✓	✓	✓		✓		✓	n/a	✓
Open.Sen.se	✓	✓	✓		✓		✓	n/a	✓
ThingSpeak	✓	✓	✓		✓		✓	n/a	✓
CloudPlugs	✓	✓	✓		✓		✓	n/a	✓
Carriots	✓	✓	✓		✓		✓	n/a	✓
NetLab	✓	✓	✓		✓	✓	n/a	Oct. 14	✓
Intel IoT Analytics	✓	✓	✓		✓	✓	✓	Nov. 14	✓
Synapse IoT Cloud	✓		✓	✓			✓	Nov. 14	✓
ClouT	✓	✓	✓	✓	n/a	n/a	✓	n/a	

(e.g. to photograph and record situations of interest to city administrators), safety management, city event monitoring, and emergency management.

IoT6 is a European research project on the future Internet of Things. It aims at exploiting IPv6 and related standards (e.g., 6LoWPAN, CORE, COAP) to overcome current shortcomings (e.g. in terms of fragmentation) in the area of IoT research and development. Its main objectives are to research, design, and develop a highly scalable IPv6-based service-oriented architecture to achieve interoperability, mobility, Cloud computing integration, and intelligence distribution among heterogeneous things, applications, and services.

The OpenIoT project, cited before for its open source platform, aims at creating an open source middleware for getting information from heterogeneous things, hiding the differences among these objects. The project explores efficient ways to use and manage Cloud environments for things and resources (such as sensors, actuators, and smart devices) and offering utility-based (i.e., pay-as-you-go) IoT services. Authors of [106] present a federation of Future Internet of Things IoT-LAB (FIT IoT-LAB) integrated with OpenIoT, providing a very large scale infrastructure facility suitable for testing small wireless sensor devices and heterogeneous communicating objects.

Several projects target research issues related to IoT and do not explicitly mention issues related to their integration with the Cloud. However, we report them here because they often mention data collection and elaboration platforms that are very likely being Clouds (right now or in the next years). These project include Smart Santander [112], The Cooperative ITS Corridor from Rotterdam to Vienna [30], and WISEBED [120].

7. OPEN ISSUES AND FUTURE DIRECTIONS

Thanks to the analyses we have done in Sec. 3, in Sec. 4, and in Sec. 5, here we resume the main issues related to CloudIoT still requiring research efforts and point out some future directions [7, 82].

7.1. Open Issues

Standardization. The lack of standards is actually considered as a big issue towards CloudIoT by a large number of researchers. Currently most things are connected to the Cloud through web-based interfaces, which are able to reduce the complexity for developing such applications [109]. However, they are not specifically designed for efficient machine-to-machine communications and introduce overhead in terms of network load, delay, and data processing. Moreover, interoperability is still an issue, because both the Cloud and the Things implement non-standard heterogeneous interfaces [35]. Even though the scientific community has provided multiple contributions to the deployment and standardization of IoT and Cloud paradigms, a clear necessity of standard protocols, architectures and APIs is being demanded in order to facilitate the interconnection among heterogeneous smart objects and the creation of enhanced services, which realize the CloudIoT paradigm [115].

Power and Energy Efficiency. Recent CloudIoT applications involve frequent data transmission from the things to the Cloud, which, in turn, may rely on smartphones as gateway [83]. Such process quickly drains battery capacity on both the things and the gateway limiting the continuous operation to 24 hours or less. The literature shows that, in the field strictly related to the integration of Cloud and IoT, obtaining energy efficiency in both data processing and transmission is an important open issue. However, significant research effort has already been spent for what concerns the Cloud and IoT separately. For handling such issue, several directions have been proposed: more efficient data transmission and compression technologies [38];

data caching mechanisms for reusing collected data in time-tolerant applications [123]; middleware to handle adverse situations and to compress data in case of continuous and long-duration monitoring of data [75]. These open issues have therefore implications also in terms of communication technologies, which are described later on in this section.

Big Data. In a previous section we have described big data as an important research topic, tightly coupled with CloudIoT and with several related challenges. Even if several contributions have been provided, we consider big data as an important open issue, where research is still strongly necessary. CloudIoT involves the management and processing of huge amounts of data and events coming from different locations and heterogeneous source types, where most applications require complex operations to be performed in real-time [56, 117]. On the one hand, this means properly synchronizing events coming from remote sources and reconstructing and correlating their semantics in order to infer the situation meaningful for the specific application. On the other hand, it means to process in real time huge amounts of multimedia data and to derive in time the information necessary to trigger relevant services and assist the user in his current location.

Security and Privacy. As for the previous case, we consider security and privacy to be both a research challenge that is receiving a lot of attention as well as an open issue where more effort is still required. While many users are already concerned about privacy and security in Cloud-based applications, since CloudIoT brings data coming from the real world into the Cloud and enables triggering actions into the real world, such concerns are much more relevant. As for privacy, providing properly designed authorization roles and policies while transparently guaranteeing that only authorized individuals have access to sensitive data is still a challenge, especially when data integrity must be ensured in response to authorized changes [80]. Regarding security, it remains challenging to cope with different threats from hackers [73]: malware can be injected into physical sensors to produce tampered data; raw or processed data can be stolen/tampered on the Cloud; compromised gateways can cause security breaches to the CloudIoT system; the communication channels are vulnerable to side-channel information leak.

Intelligence. The centralization into the Cloud of real-time data coming from heterogeneous things enables enhanced decision-making capabilities by using sophisticated information selection and fusion mechanisms. Although research efforts have been spent in this field [102], maximizing the intelligence in this context is still an open challenge.

Integration Methodology. While CloudIoT solutions have been already built around specific applications, little effort has been spent to derive a common methodology to integrate Cloud and IoT systems. Since sets of applications have common requirements, several standardized workflows could be defined. Moreover, a generic and flexible platform could be the starting point for implementing such workflows more easily.

Pricing and Billing. Different entities involved in CloudIoT systems have their own customer and service management, and methods of payments and pricing. Moreover, the cost for deploying things is decreasing, while the cost to keep them connected to the Cloud increases exponentially. Hence, setting the price for integrated services, distributing it among the different entities, and managing the payment process are still open issues in the CloudIoT integrated scenario.

Network Communications. CloudIoT involves several heterogeneous network technologies, where many applications require continuity in the transmission of data and overall consumption of bandwidth increases dramatically. On the one hand, the efficiency of the access management for enabling continuity and for optimizing the bandwidth usage is still an open issue [50]. On the other hand, current bandwidth limitation cannot support the increasing trend [123], and additional research work is necessary to improve the allocation methods at huge scales. Moreover, many CloudIoT applications (e.g., healthcare) require fault-tolerant and reliable continuous transfer of data from the things to the Cloud. For instance, a patient wearing body sensors may be out of coverage area from the gateway (e.g., a smartphone). Thus, scenarios intrinsically prone to connection failures require specific support in order to avoid accumulation of errors [17].

Novel solutions for network communications are of paramount importance in both human-centric and M2M contexts. The proliferation of mobile devices, and the increasing usage of Cloud computing, along with the increasing demand for multimedia services, are changing the life style of users and creating new opportunities to providers and clients. Indeed, multimedia data will account for up to 90% of all the Internet traffic in a few years, and most of the content will be created and accessed by mobile things (e.g., smartphones or tablets) carried by humans or placed in vehicles [24]. The integration of human-centric multimedia networking into Internet Cloud computing environments allows mobile users to have new multimedia experiences not previously available. For instance, the Cloud can be configured to perform a set of important tasks and services for mobile multimedia users and networks, ranging from assessing the video quality level and load balancing to multimedia transcoding and redundancy/error correction schemes. This novel mobile multimedia era imposes new challenges for networks, contents, terminals, and humans, and must overcome problems associated, for instance, with high congestion, low scalability, fast battery consumption, and poor user experience. CloudIoT involves M2M communications among many heterogeneous devices with different protocols [16], which depend on the specific application scenario. M2M communication can be seen as an advanced form of sensor networks, where the ultimate goal is to provide comprehensive connections among all smart devices. However, the communication framework from sensor networks faces difficulties in satisfying the requirements of recent scenarios such as ITS, where each smart device can play more than one of the possible roles: sensor, decision maker, and action executor [86]. M2M largely benefited from the advances in wireless communication technologies, such as wearable and implantable biosensors, along with recent developments in the embedded computing, intelligent systems, and Cloud computing areas [93]. In the literature, a few realizations of M2M communications have also been proposed, leveraging for example, Bluetooth (IEEE 802.15.1), Zigbee (IEEE 802.15.4), or WiFi (IEEE 802.11b and p) technologies. However, there is still no consensus on the network architecture of a general scenario for M2M communications. Managing the things in a uniform fashion in a heterogeneous scenario, while providing required performance still represents an open issue [21, 15]. The majority of applications do not involve mobility: in stationary scenarios, IoT often adopts IEEE 802.15.4/6LoWPAN solutions [103]. On the other hand, scenarios such as vehicular networks mostly adopt IEEE 802.11p. However, being WiFi and Bluetooth the most widely used radio technologies for wireless networks, their adoption for IoT applications is increasing: they represent a cheaper solution, most mobile devices already support them (e.g., smart phones), and both standards are becoming more and more low power. In some other cases, when power constraints are less critical, GPRS is still used for Internet connectivity, but it results in a very costly solution (e.g., multiple SIM cards are necessary) [103]. Recently, serious attention was attracted by the standardization progress of LTE-Advanced, and the impacts of introducing M2M communications into LTE-Advanced are now under considerable study in 3GPP [86]. We believe that research on network communications for CloudIoT is still needed in order to provide effective and efficient solutions.

SLA Enforcement. CloudIoT users require things-generated data to be transferred and processed according to application dependent constraints, which can be strict in case of critical scenarios. Guaranteeing a certain QoS level about Cloud resources might not be always possible for a single provider, thus relying on multiple Cloud providers might be necessary to avoid SLA violations. However, dynamically selecting the best combination of Cloud providers still represents an open issue because of costs, time and heterogeneity of QoS management support [79].

Storage. Storage solutions have been frequently considered in this paper. For example, we have already considered them as a driver for the integration of Cloud and IoT. However, the literature considers this as a still open issue as current solutions may not provide the necessary support for future applications. For example, the storage of data transferred from the things to the Cloud involves some engineering issues still requiring research efforts. While data has to be properly timestamped to enable server-side reconstruction and processing, transfers require proper timing in order to avoid excessive burstiness of network and processing load [17]. One possible direction to address such issues involves the introduction of predictive storage and caching [66].

Scalability and Flexibility. CloudIoT requires efficient mechanisms to match collected data and events to appropriate applications and services. Providing flexible subscription schemas and events management while guaranteeing scalability with respect to things and users is still considered an open issue [79].

7.2. Future Directions

In order to enable the full potential of CloudIoT, additional research effort is expected in several directions:

- Properly identifying, naming, and addressing things will be necessary to support both the huge number of things and their mobility. While IPv6 could be the proper solution, its large-scale adoption is still an ongoing process and additional research is necessary to both speed up this slow process in specific scenarios (e.g. access networks) and to cope with new mobility and scalability requirements.

- Solutions for detecting environmental changes based on IoT data will enable the delivery of enhanced context-based services, helping to provide the best service depending on the situation. Such opportunity will incentivate the research of more effective algorithms for delivering personalized contents and ads.

- Large scale support for multi-networking (e.g., multihoming, multipath, multicast), connection handover and roaming will be mandatory for improving network reliability and guaranteeing continuous connectivity, QoS, redundancy, and fault tolerance. In this context solutions based on Software Defined Networking are also envisaged.

- Many applications of CloudIoT would benefit from efficient and flexible mechanisms for creating logically isolated network partitions over globally distributed network infrastructures, which could be another important driver for research in network virtualization and software-defined networking fields.

- Converging towards a common open service platform environment for providing APIs to develop third-party CloudIoT-based applications will enable new business opportunities and drive research efforts in the direction of defining standard protocols, libraries, languages, and methodologies for CloudIoT.

8. CONCLUSION

The integration of Cloud Computing and Internet of Things represents the next big leap ahead in the Future Internet. The new applications arising from this integration – we called CloudIoT– open up new exciting directions for business and research.

In this paper, we surveyed the literature in order to identify the complementary aspects of Cloud and IoT and the main drivers for integrating them into a unique environment. Since the adoption of the CloudIoT paradigm enabled several new applications, we derived the main research challenges of interest for each of them. We further analyzed such challenges in order to identify current research directions. Finally, we surveyed available platforms and projects by comparing their main aspects and identified open issues and future research directions in this field.

Thanks to the CloudIoT paradigm everyday life and activities will be potentially improved for everyone: smart cities will enable more efficient public services and promote new business opportunities, ubiquitous healthcare applications will improve the quality of life for many patients, etc. These new application scenarios pose important research challenges such as the heterogeneity of involved devices and technologies; the required performance, reliability, scalability and security; privacy preservation; legal and social aspects. The open issues of CloudIoT paradigm pertain mainly power and energy efficiency, SLA enforcement, pricing and billing, security and privacy. The envisioned future directions include the identification of the definitive solution for naming and addressing things, the large scale support for multi-networking, and the convergence toward a common open service platform environment.

ACKNOWLEDGEMENTS

This work is partially funded by the MIUR projects: PLATINO ($PON01\_01007$), SMART HEALTH ($PON04a2\_C$), S2-MOVE ($PON04a3\_00058$), SIRIO ($PON01\_02425$), and art. 11 DM 593/2000 for NM2 SRL.

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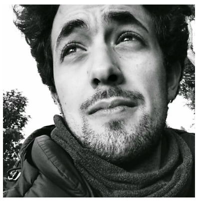

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