On the Integration of Cloud Computing and Internet of Things

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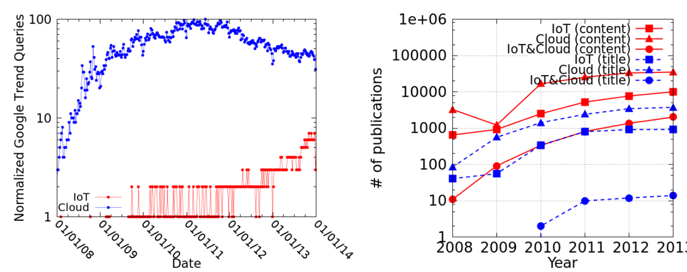
***Abstract*—Cloud computing and Internet of Things (IoT), two very different technologies, are both already part of our life. Their massive adoption and use is expected to increase further, making them important components of the Future Internet. A novel paradigm where Cloud and IoT are merged together is foreseen as disruptive and an enabler of a large number of application scenarios. In this paper we focus our attention on the integration of Cloud and IoT, which we call the *CloudIoT* paradigm. Many works in literature have surveyed Cloud and IoT separately: their main properties, features, underlying technologies, and open issues. However, to the best of our knowledge, these works lack a detailed analysis of the CloudIoT paradigm. To bridge this gap, in this paper we review the literature about the integration of Cloud and IoT. We start analyzing and discussing the need for integrating them, the challenges deriving from such integration, and how these issues have been tackled in literature. We then describe application scenarios that have been presented in literature, as well as platforms – both commercial and open source – and projects implementing the CloudIoT paradigm. Finally, we identify open issues, main challenges and future directions in this promising field.**

I. 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 and small things with limited storage and processing capacity, and consequential issues 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 [59], [23]. We call this new paradigm CloudIoT. This paper reviews the literature about the integration of Cloud and IoT a really promising topic for both research and industry. We have reviewed the rich and articulate state of the art in this field by considering a large number of papers proposing an integrated usage of Cloud and IoT, and published between 2008 and 2013 in different, selected venues. As shown in Fig. 1, 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]. On the other hand, a more recent and rapidly increasing trend deals with Cloud and IoT together. Following the indications reported in [40], we adopt the research methodology schematically depicted in Fig. 2. We first provide 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. Second, we provide a detailed discussion on the CloudIoT paradigm, highlighting the complementarity and the need for their integration. Third, we detail the new application scenarios stemming from the adoption of the CloudIoT paradigm. Fourth, jointly analyzing the CloudIoT paradigm and the application scenarios, we derive the hot topics and related issues for research. Fifth, we describe the main platforms (both commercial and open source) and research projects in the field of CloudIoT. Finally, thanks to the previous seven steps, we derive the open issues and future directions in the field of CloudIoT.



(a) Interest from Google research trends. (b) Interest by content and title.

Fig. 1: Research and interest trends about Cloud and IoT.

II. CLOUD AND IOT: THE NEED FOR THEIR INTEGRATION

The two worlds of Cloud and IoT have seen an independent evolution. However, several mutual advantages deriving from their integration have been identified in literature and are foreseen in the future. On the one hand, IoT can benefit from the virtually unlimited capabilities and resources of Cloud to compensate its technological constraints (e.g., storage, processing, energy). Specifically, the Cloud can offer an effective solution to implement IoT service management and composition as well as applications that exploit the things or the data produced by them. On the other hand, the 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. The complementary characteristics of Cloud and IoT arising from the different proposals in literature and inspiring the CloudIoT

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

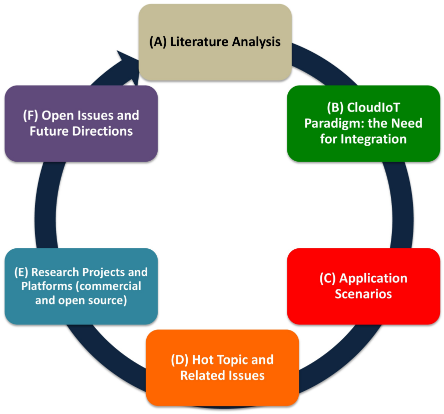


Fig. 2: The research methodology adopted in this work.

paradigm are reported in Tab. I. Essentially, the Cloud acts as intermediate layer between the things and the applications, where it hides all the complexity and the functionalities necessary to implement the latter. This framework will impact future application development, where information gathering, processing, and transmission will produce new challenges to be addressed, also in a multi-cloud environment [30]. In the following, we summarize the issues solved and the advantages obtained when adopting the CloudIoT paradigm.

Storage resources. 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 [30] having the three characteristics typical of Big Data [60]: volume (i.e., data size), variety (i.e., data types), and velocity (i.e., data generation frequency). Hence it implies collecting, accessing, processing, visualizing, archiving, sharing, and searching large amounts of data [50]. Offering virtually unlimited, low-cost, and on-demand storage capacity, Cloud is the most convenient and cost effective solution to deal with data produced by IoT [50]. This integration realizes a new convergence scenario [47], where new opportunities arise for data aggregation [32], integration [56], and sharing with third parties [56]. Once into the Cloud, data can be treated in a homogeneous manner through standard APIs [32], can be protected by applying top-level security [27], and directly accessed and visualized from any place [50].

Computational resources. IoT devices have limited processing resources that do not allow on-site data processing. Data collected is usually transmitted to more powerful nodes where aggregation and processing is possible, but scalability is challenging to achieve without a proper infrastructure. The unlimited processing capabilities of Cloud and its on-demand model allow IoT processing needs to be properly satisfied and enable analyses of unprecedented complexity [27], [47]. Data-driven decision making and prediction algorithms would be possible at low cost and would provide increasing revenues and reduced risks [56]. Other perspectives would be to perform real-time processing (on-the-fly) [50], [27], to implement scalable, real-time, collaborative, sensor-centric applications [32], to manage complex events [50], and to implement task offloading for energy saving [53].

Communication resources. One of the requirements of IoT is to make IP-enabled devices communicate through dedicated hardware, and the support for such communication can be very expensive. Cloud offers an effective and cheap solution to connect, track, and manage any thing from anywhere at any time using customized portals and built-in apps [50]. Thanks to the availability of high speed networks, it enables the monitoring and control of remote things [50], [32], [47], their coordination [32], [47], [52], their communications [32], and the real-time access to the produced data [50].

TABLE I: Complementarity and Integration of Cloud and IoT.

IoT	Cloud
pervasive (things placed everywhere)	ubiquitous (resources usable from everywhere)
real world things	virtual resources
limited computational capabilities	virtually unlimited computational capabilities
limited storage or no storage capabilities	virtually unlimited storage capabilities
Internet as a point of convergence	Internet for service delivery
big data source	means to manage big data

New capabilities. IoT is characterized by a very high heterogeneity of devices, technologies, and protocols. Therefore, scalability, interoperability, reliability, efficiency, availability, and security can be very difficult to obtain. The integration with the Cloud solves most of these problems [32], [27], [52], also providing additional features such as ease-of-access, ease-of-use, and reduced deployment costs [27].

New paradigms. The adoption of the CloudIoT paradigm enables new scenarios for smart services and applications based on the extension of Cloud through the things [50], [52]:

- SaaS (Sensing as a Service) [50], [56], [27], providing ubiquitous access to sensor data;
- SAaaS (Sensing and Actuation as a Service) [50], enabling automatic control logics implemented in the Cloud;
- SEaaS (Sensor Event as a Service) [50], [27], dispatching messaging services triggered by sensor events;
- SenaaS (Sensor as a Service) [56], enabling ubiquitous management of remote sensors;
- DBaaS (DataBase as a Service) [56], enabling ubiquitous database management;
- DaaS (Data as a Service) [56], providing ubiquitous access to any kind of data;
- EaaS (Ethernet as a Service) [56], providing ubiquitous layer-2 connectivity to remote devices;
- IPMaaS (Identity and Policy Management as a Service) [56], enabling ubiquitous access to policy and identity management functionalities;
- VSaaS (Video Surveillance as a Service) [49], providing ubiquitous access to recorded video and implementing complex analyses in the Cloud.

III. APPLICATIONS

In this section we describe a wide set of applications that are made possible or significantly improved thanks to the

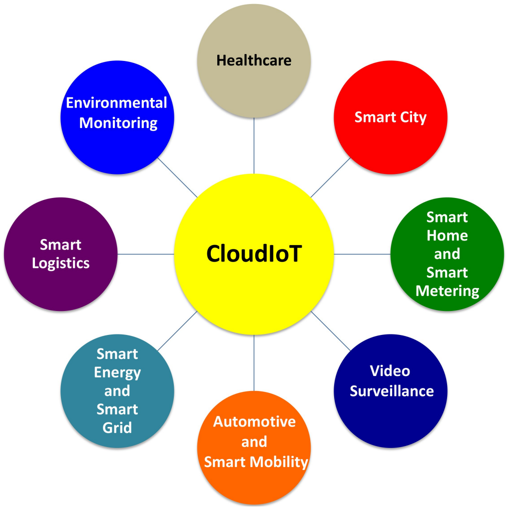


Fig. 3: Application scenarios driven by the CloudIoT paradigm.

CloudIoT paradigm. For each application we point out the challenges, which we discuss in detail in Sec. IV.

Healthcare. IoT and multimedia technologies have made their entrance in the healthcare field thanks to ambient-assisted living and telemedicine [57]. Smart devices, mobile Internet, and Cloud services contribute to the continuous and systematic innovation of Healthcare and enable cost effective, efficient, timely, and high-quality ubiquitous medical services [41], [33]. Pervasive healthcare applications generate a vast amount of sensor data that have to be managed properly for further analysis and processing [29]. The adoption of Cloud in this scenario leads to the abstraction of technical details, eliminating the need for expertise in, or control over, the technology infrastructure [15], [43], and it represents a promising solution for managing healthcare sensor data efficiently [29]. It further makes mobile devices suited for health information delivery, access and communication, also on the go [46], enhancing medical data security, availability, and redundancy [41], [15]. Moreover, it enables the execution (in the Cloud) of secure multimedia-based health services, overcoming the issue of running heavy multimedia & security algorithms on devices with limited computational capacity and small batteries [46]. In this field, common issues related to management, technology, security, and law have been investigated: interoperability, system security, streaming Quality of Service (QoS), and dynamically increasing storage are commonly considered obstacles [41].

Smart City. IoT can provide a common middleware for future-oriented Smart-City services [17], [52], 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. A number of recently proposed solutions suggest to use Cloud architectures to enable the discovery, connection, and integration of sensors and actuators, thus creating platforms able to provision and support ubiquitous connectivity and real-time applications for smart cities [45]. Frameworks can consist of a sensor platform (with APIs for sensing and actuating) and a Cloud platform for the automatic management, analysis, and control of big data from large-scale, real world devices [52]. This type of advanced service model hides the complexity of the underlying Cloud infrastructure, whilst at the same time meeting complex public sector requirements for Cloud, such as security, heterogeneity, interoperability, scalability, extensibility, high reactivity, and configurability [17], [52]. 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 [17]. 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 [17], which may result from the application of a holistic approach [52]. Common issues are related to security, resilience, and real-time interactions [52].

Smart Home and Smart Metering. IoT has large application in home environments, where heterogeneous embedded devices enable the automation of common in-house activities. 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 [39]. In order to let a variety of independent single-family smart homes access reusable services over the Internet, the resulting solution should satisfy three crucial requirements [54]: internal network interconnection (i.e., every 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 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). Several smart-home applications proposed in literature involve (wireless) sensor networks and implement smart metering solutions to provide recognition of appliances [24], intelligent management of energy consumption [24], lighting, heating, and air conditioning [36]. Several issues must be resolved to materialize this vision [36]. Home devices should be web-enabled, their discovery and service description should be standardized, and the interaction with them should be uniform. 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 volume and the frequency of communications with the Cloud.

Video Surveillance. Intelligent video surveillance has become a tool of the greatest importance for several security-related applications. As an alternative to in-house, self-contained management systems, complex video analytics require Cloud-based solutions (VSaaS [49]) to properly satisfy the requirements of storage (e.g., stored media is centrally secured, fault-tolerant, on-demand, scalable, and accessible at high-speed) and processing (e.g., video processing, computer vision algorithms and pattern recognition modules to extract knowledge from scenes). Proposed solutions [34] intelligently store and manage video content originating from (IP and analog) cameras, and efficiently deliver it 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.

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 technologies with WSNs, RFID, satellite networks, and other intelligent transportation technologies represents a promising opportunity to tackle the main current challenges [38]. A new generation of IoT-based vehicular data Clouds can be developed and deployed to bring many business benefits, such as increasing road safety, reducing road congestion, managing traffic, and recommending car maintenance or fixing [38]. The literature proposes several examples of multi-layered, Cloud-based vehicular data platforms that merge Cloud computing and IoT technologies. 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 [20]). Vehicular Clouds are 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. Thanks to these platforms, innovative, vehicular, data Cloud services can be deployed (e.g., intelligent parking Cloud service, or vehicular data-mining Cloud service) [38]. More in general, 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, integrating the vehicle into a typical IoT, and meeting the demand for powerful communication with Cloud-based services [37]. Several issues have been identified in literature affecting this application scenario [38], [20]. The huge number of vehicles and their dynamically changing number make system scalability difficult to achieve. Vehicles moving at various speeds frequently cause intermittent communication impacting performance, reliability, and QoS. The lack of an established infrastructure makes it difficult to implement effective authentication and authorization mechanisms, with impacts on security and privacy provision [44]. The lack of global standards and experimental studies on realistic ITS-Clouds affect interoperability.

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. In the first case, for instance, lighting could be provided where and when strictly necessary by exploiting the information collected by different types of nodes [36]. Such nodes have sensing, processing, and networking capabilities, but limited resources. Hence, computing tasks should be properly distributed among them or demanded to the Cloud, where more complex and comprehensive decisions can be made. In the second case, the problem on energy alternative and compatible use can be solved by integrating system data in the Cloud, while providing self-healing, mutual operation and participation of the users, optimal electricity quality, distributed generation, and demand response [55]. The integration of Cloud platforms in this IoT scenario increases the concerns about security and privacy issues for Smart Grid software deployment for utilities. These concerns should be adequately addressed to realize the full potential of such application: consumers should gain more confidence in sharing data to help improving and optimizing services offered [51].

IV. HOT TOPICS AND RELATED CHALLENGES

Migrating IoT application specific data into the Cloud offers great convenience, such as reduction of cost and complexity related to direct hardware management. Accordingly, the complex scenario of CloudIoT includes many aspects related to several heterogeneous topics, each of them imposing challenges when requiring specific capabilities to be satisfied. For instance, the following capabilities are required to guarantee trusted and efficient services: security, privacy, reliability, availability, portability, and semantic interoperability [19], [30]. When critical IoT applications move towards the Cloud, new concerns arise due to the lack of some essential properties: trust in the service provider, knowledge about service level agreements (SLAs), and knowledge about the physical location of the data storage. Accordingly, new challenges require specific attention [19]: the distributed nature of the system exposes several significant attacks (e.g., session riding, SQL injection, cross site scripting, and side-channel) and vulnerabilities (e.g., session hijacking and virtual machine escape); multi-tenancy could compromise security and may lead to sensitive information leakage; public key cryptography cannot be applied at all layers due to the computing power constraints imposed by the things. As summarized in Table II, in the following we report how providing certain capabilities has proved challenging in the recent literature when addressing several main topics pertaining to CloudIoT.

Service delivery. IoT services are typically provided as isolated vertical solutions, in which all system components are tightly coupled to the specific application context. For each deployed application service, providers have to survey target application environments, analyze its requirements, select hardware devices, integrate heterogeneous subsystems, develop applications, provide computing infrastructure, and provide service maintenance. On the other hand, leveraging Cloud service delivery models, CloudIoT can enable efficient, scalable, and easily-extensible IoT service delivery [42]. Although PaaS-like models would represent a generic solution for facilitating the deployment of most IoT applications, their adoption moves some IoT challenges into the Cloud world. For instance, the interaction with (management of) huge amounts of highly heterogeneous things (produced data) has to be properly addressed into the Cloud at different levels.

Networking and Communication Protocols. CloudIoT involves machine-to-machine (M2M) communications among many heterogeneous devices with different protocols [19], which depend on the specific application scenario. Dealing with this heterogeneity to manage the things in a uniform fashion while providing required performance [22], [18] is challenging. The majority of application areas does not involve mobility: in stationary scenarios, IoT often adopts IEEE 802.15.4/6LoWPAN solutions [48]. On the other hand, other scenarios such as vehicular networks mostly adopt IEEE 802.11p specifications. However, being WiFi and Bluetooth the most widely used radio technologies for personal 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 used for Internet connectivity, but it results in a very costly solution (e.g., multiple SIM cards are necessary) [48].

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) [28]. Handling this data conveniently is a critical challenge, as the overall application performance is highly dependent on the properties of the data management service [28]. Hence, following the NoSQL movement, both commercial and open source solutions adopt alternative database technologies for big data [25]: 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 [56].

Sensor Networks. Sensor networks have been defined as the major enabler of IoT [56] 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 [35]. Recent technological advances have made efficient, low-cost, and low-power miniaturized devices available for use in large-scale, remote sensing applications [14]. 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 [58]. 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 [58]. 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 [48].

User Participation. The investment into omnipresent Internet-capable devices is not reasonable in every scenario. Therefore, it would be convenient to give the opportunity to users to participate in submitting data that represent a thing [16]. Users could also be empowered with new building blocks and tools: accelerators, frameworks, and toolkits will enable the participation of users in IoT as done in the Internet through Wikis and Blogs [26]. Such tools and techniques should enable researchers and design professionals to learn about users 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. In this scenario, one challenge is to provide adequate prototyping tools for implementing a cooperative prototyping approach, where users and designers explore together applications and their relations.

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 [13]. 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.

V. PLATFORMS, SERVICES, AND RESEARCH PROJECTS

In this section we describe open source and commercial platforms for CloudIoT and three research projects focused on this topic, which we believe are an example of the research efforts funded in this important area.

A. *Platforms*

There are several open source and commercial platforms 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. III 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 [1] 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 [31]. The software is available online through github. OpenIoT [2] 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. Among the main focuses of OpenIoT are the mobility aspects of IoT for energy-efficient orchestration of data collecting and transmission to the Cloud. The project web site [2] 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) [3] aims at developing a toolkit that allows to glue the several protocols available both for the things, for the Cloud, and for the applications.

As for the commercial 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 [4]. Interesting examples include open source projects run by private companies. For example, the open source project of NimBits [5] 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 [6] is an Italian company which builds things (e.g.

TABLE II: Topics and challenges pertaining CloudIoT.

	Efficiency	Scalability	Extensibility	Reliability	Security	Privacy	Interoperability	Availability	Mobility	Pervasiveness	Energy saving	Uniformity	Maintainability	Cost effectiveness	Large scale
Service delivery	✓	✓	✓									✓	✓	✓	✓
Monitoring	✓	✓	✓	✓	✓	✓									
Big Data	✓	✓				✓	✓	✓	✓			✓		✓	✓
Sensor Networks	✓			✓			✓		✓	✓	✓	✓		✓	✓
User Participation						✓		✓	✓	✓	✓			✓	✓
Networking and Communication Protocols	✓								✓		✓	✓			

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 [7], Open.Sen.se [8], ThingSpeak [9]) 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. Starting from these services, companies have created toolkits for their integration in CloudIoT frameworks. For example, NetLab [10] 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 CloudOut 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.

TABLE III: 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	✓	✓	✓	May13	✓
OpenIoT	✓	✓	✓	✓	✓	✓	✓	Apr14	✓
IoT Toolkit	✓	✓	n/a	n/a	✓	✓	n/a	Dec 13	
NimBits	✓	✓	✓	partly	✓	✓	n/a	Mar 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	✓
NetLab	✓	✓	✓		✓	✓	n/a	Dec 13	✓

B. *Research Projects*

ClouT [11], 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 (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.

VI. OPEN ISSUES AND FUTURE DIRECTIONS

Thanks to the analyses we have done in Sec. II, in Sec. III, and in Sec. IV, here we resume the main issues related to CloudIoT still requiring research efforts and point out some future directions.

The need for Standards. Even though the scientific community gave 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 [52]. In particular Mobile-to-Mobile (M2M) is a leading paradigm, but there is a very little standardization for it. Hence the several existing solutions use standard Internet, cellular, and Web technologies. Moreover, the state of the art lacks domain specific environments for rapid development and efficient CloudIoT service delivery. Indeed, most architectures proposed at the initial stage of IoT either have come from the WSN perspective or are based on Cloud at the center.

Energy Efficient Sensing. WSN typically consists of low-cost, low-power, and energy-constrained sensors. Each operation, calculation, and inter-communication consumes the node energy. Also when specific sensors are replaced by smart devices, energy saving is a major issue and energy efficient management is more than desirable. Several techniques can be adopted to achieve energy saving: for instance, compressive sensing enables reduced signal measurements without impacting accurate reconstruction of the signal and utilizes synchronous communication to reduce the transmitting power of each sensor. On the other side, CloudIoT, involving Cloud paradigm is not affected by energy issues. Indeed, it is possible to lease on-demand computing and storage resources through Cloud in an optimal manner from the energetic point of view. In addition, local computations can be shifted to the Cloud, in order to save computational resources and device energy.

New Protocols. MAC and routing protocols are critical for the system to work efficiently. Even though several protocols have been proposed for various domains (with TDMA, CSMA, and FDMA schemes), none of them has been accepted as a standard, and with the growing number of things, further research is required. Energy is the main consideration for routing protocols. Although the literature reports existing routing protocols can work with minor modifications in IoT scenarios (considering that the number of hops in multi-hop scenario is limited and that a backbone is typically available) [35], IETF ROLL workgroup (which deals with routing over low-power lossy networks) claims that existing routing protocols such as OSPF, IS-IS, AODV, and OLSR have been found to not satisfy Low Power and Lossy Networks (LLNs) specific routing requirements in their current form (e.g. optimization for energy saving, typical point-to-multipoint traffic patterns, restricted frame-sizes, limits in trading efficiency for generality). Hence RPL (ripple) protocol draft has been proposed [12].

Participative Sensing. The problem of missing samples is critical in people-centric sensing. Indeed, relying on users volunteering data is a severe limitation to the ability to produce meaningful data. Moreover data ownership and privacy issues must be addressed and appropriate participation incentives must be identified to achieve genuine end-user engagement [35].

Complex Data Mining. Current technologies are not able to completely solve all issues related to the complexity of big data. The percentage of data an organization can analyse is on the decline: due to the high number of big data producers and the high frequency of data generation, the gap between data available to organizations and data they can process is getting wider. Approximate results are typically orders of magnitude faster compared to traditional query execution [56]. Research efforts are required to meet the challenge of big data. New technologies and query optimizations are required to analyze large volumes of data faster with efficient resource and power consumption [56]. Big data consists of high-valued data mixed with dirty and erroneous data. Extracting useful information at different spatial and temporal resolutions is a challenging problem in artificial intelligence research. While state-of-art methods use shallow learning, an emerging focus is deep learning, which aims at learning multiple levels of abstraction, which can be used to interpret given data. Heterogeneous spatio-temporal (geo-related and sparsely distributed) data coming from IoT elaborations are not always ready for direct consumption using visualization platforms. New visualization schemes have to be developed (e.g. 3D, GIS), in order to create attractive and easy to understand visualizations [35].

Cloud Capabilities. Security, which concerns every networked environment, is a major issue for CloudIoT. Indeed both its IoT side (i.e., RFID, WSN) and its Cloud side are vulnerable to a number of attacks. In IoT context, encryption can ensure data confidentiality, integrity, and authenticity. However it cannot address insider attacks (e.g. during WSN reprogramming) and it is difficult to implement on computation-constrained devices. RFID is the most vulnerable component, since no higher level of intelligence can be enabled on it. Also, security aspects related to Cloud require attention since Cloud handles the economics, along with data and tools. Moreover, Cloud platforms need to be enhanced to support the rapid creation of applications, by providing domain specific programming tools and environments and seamless execution of applications, harnessing capabilities of multiple dynamic and heterogeneous resources, to meet QoS requirements of diverse users. Cloud scheduling algorithms need to manage task duplication for failure management, in order to deliver services in a reliable manner. Moreover, they should be able to deal with QoS parameters.

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 [21]. 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.

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