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On the interplay of Internet of Things and Cloud Computing: A systematic mapping study

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ABSTRACT

The Internet of Things (IoT) is a novel paradigm relying on the interaction of smart objects (things) among each other and with physical and/or virtual resources through the Internet. Despite the recent advances that have made IoT a reality, there are several challenges to be addressed towards exploiting its full potential and promoting tangible benefits to society, environment, economy, and individual citizens. Recently, Cloud Computing has been advocated as a promising approach to tackle some of the existing challenges in IoT while leveraging its adoption and bringing new opportunities. With the combination of IoT and Cloud Computing, the cloud becomes an intermediate layer between smart objects and applications that make use of data and resources provided by these objects. On the one hand, IoT can benefit from the almost unlimited resources of Cloud Computing to implement management and composition of services related to smart objects and their provided data. On the other hand, the cloud can benefit from IoT by broadening its operation scope to deal with real-world objects. In spite of this synergy, the literature still lacks of a broad, comprehensive overview on what has been investigated on the integration of IoT and Cloud Computing and what are the open issues to be addressed in future research and development. The goal of this work is to fill this gap by systematically collecting and analyzing studies available in the literature aiming to: (i) obtain a comprehensive understanding on the integration of IoT and Cloud Computing paradigms; (ii) provide an overview of the current state of research on this topic; and (iii) identify important gaps in the existing approaches as well as promising research directions. To achieve this goal, a systematic mapping study was performed covering papers recently published in journals, conferences, and workshops, available at five relevant electronic databases. As a result, 35 studies were selected presenting strategies and solutions on how to integrate IoT and Cloud Computing as well scenarios, research challenges, and opportunities in this context. Besides confirming the increasing interest on the integration of IoT and Cloud Computing, this paper reports the main outcomes of the performed systematic mapping by both presenting an overview of the state of the art on the investigated topic and shedding light on important challenges and potential directions to future research.

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1. Introduction

The *Internet of Things* (IoT) has rapidly evolved in the last years as an umbrella term envisioning that every single object on Earth (the so-called *things*) can be identified, controlled, and monitored through the Internet. These heterogeneous smart objects are typically endowed with sensing and/or actuation capabilities, thus being able to capture physical phenomena and translate them into data streams (thereby providing information about the environment where they are inserted into), as well as to affect the physical realm as a response to various stimuli. Furthermore, they can seamlessly collaborate with other physical and/or virtual resources also available in the Internet to provide value-added information and functionalities for end-users and applications with minimum human intervention.

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The dissemination of the IoT paradigm can produce a significant impact of the daily lives of human beings with the emergence of new applications and systems in several real-world domains. From the point of view of a user, IoT will play a leading role in application scenarios such as domotics, smart homes, healthcare, and enhanced learning. From the perspective of business users, the most apparent effects will be similarly visible in fields such as logistics, industry, energy, agriculture, and retail. Ultimately, IoT can foster the development of wide-scope applications in the contexts of smart cities, environmental monitoring, etc. [1–3].

Despite the advances in terms of information and communication technologies (ICTs) for making IoT a reality, this paradigm has a variety of open issues that require further research and development efforts, as discussed in several recent studies [1,4–6]. One of these challenges refers to the huge amount of physical devices interacting over the network. Indeed, previsions point out that billions of connected things will be in use by 2020 and hence IoT infrastructures need to be scalable enough to handle such a numerous amount of heterogeneous devices within the environment. An immediate consequence is the volume of data provided by these devices and transmitted through the network, which will also increase as well surely reaching an unprecedented level. In this context, challenges arise in terms of collecting, analyzing, managing, and storing such a large, non-structured, diverse volume of data.

Recently, the *Cloud Computing* paradigm has been advocated as a promising solution to meet some of the requirements of IoT. Cloud Computing can be defined as a model that allows accessing a set of shared and configurable computing resources (e.g., networks, servers, storage facilities, applications) offered as services [7]. These resources can be rapidly provisioned and released with minimum management effort or interaction with the service provider and are offered on-demand, so that users pay only the amount of the effective use of a resource, i.e., in a pay-per-use model. In addition, Cloud Computing promises reduced upfront investment, high availability, fault-tolerance, virtually infinite scalability, etc., characteristics that have notably attracted the attention from both academia and industry [8]. These features are appealing to IoT as they will allow any device to be a simple terminal without the need of possessing large computational resources since cloud services can be transparently, pervasively accessed via Internet. Envisioning the potential benefits brought by Cloud Computing to IoT, major cloud vendors such as Amazon and Google have recently started offering cloud services aiming to support IoT devices and applications in terms of computing capabilities, data analytics, resource elasticity, and scalability [9,10].

The alignment of IoT and Cloud Computing can take place through two different ways, namely (i) *bringing the cloud to the things* and (ii) *bringing the things to the cloud*. *Bringing the cloud to the things* refers to take advantage of the main features offered by cloud services to compensate technological constraints of IoT in terms of storage, processing, and energy, as well as to enhance the capabilities of IoT infrastructures and applications. As an example, most of the things in IoT are devices with low processing power and storage due to their limited energetic capabilities, a contrast to the several complex processing tasks that need to be performed. To overcome this limitation, such devices could play the role of simple data providers and send data to be processed and stored directly on the cloud, i.e., externally to the device itself. On the other side of the spectrum, *bringing the things to the cloud* stands for leveraging IoT-based capabilities and offering them as pay-per-use services on the cloud, leading to what has been sometimes referred to as *Cloud of Things* (CoT) [11]. This relies on the notion of Everything as a Service (XaaS or *aaS), a flexible, customizable model that envisions offering not only computing resources, but also anything that can be consumed as utility cloud services [12]. An example of this approach is the concept of *Sensing as a Service*, a model to virtualize, share, and reuse sensing devices and their respective data to be ubiquitously consumed from the cloud [13,14]. In this perspective, the cloud becomes an intermediate layer between the smart things and users/applications, thus hiding the inherent complexity of the former aiming to foster the development of the latter [15].

Q2

Given the increasing interest and the clear synergy on the integration of IoT and Cloud Computing, a comprehensive overview of the state of the art on this topic is quite relevant. Such an overview can enable both researchers and practitioners to critically reflect on the current state of the art and to identify important challenges requiring attention in future research and development. Nevertheless, to the best of our knowledge, there is currently no systematic study providing a broad panorama about what has been investigated so far and what are the open issues in this context. In the literature, a few studies have previously strived to summarize the existing work and some possible challenges on the integration of IoT and Cloud Computing [15–17]. However, they offer only a partial panorama of this relationship and they were performed in an ad-hoc way, thus not following a systematic, well-defined procedure. Furthermore, despite the combination of IoT and Cloud Computing can overcome some of the open issues to be individually solved in both sides, new, additional challenges arise from such a relationship and/or the existing ones can become more critical [16,18]. Therefore, the sought overview can play an important role in terms of providing a comprehensive agenda for future research towards tackling these challenges.

Aiming at addressing these issues, we have performed a *systematic mapping study* (or shortly *systematic mapping*) on the integration of the IoT and Cloud Computing paradigms. A systematic mapping is a form of secondary study performed to obtain a comprehensive overview of a given research topic, identify research gaps, and collect evidences to commission future research. In addition, it allows primary studies in a domain to be plotted at a high level of granularity, thus answering broad research questions regarding the current state of the research on a topic [19]. A systematic mapping follows a rigorous, methodological procedure that seeks to minimize bias while allowing other researchers to reproduce the same process when exploring the same research topic. To achieve this purpose, a well-defined protocol is established with research questions and explicit criteria to evaluate and select the primary studies. This protocol must be strictly followed throughout the whole process in order to provide scientific value to the obtained findings.

The goal of this systematic mapping is threefold: (i) to obtain a comprehensive understanding on the integration of the IoT and Cloud Computing paradigms; (ii) to provide an overview of the current state of research on this topic; and (iii) to identify important gaps in the existing approaches as well as promising research directions. To achieve this goal, studies published in recent journals, conferences, and workshops available at five relevant electronic databases were collected and analyzed. As a result, 35 primary studies presenting strategies and solutions on how to integrate IoT and Cloud Computing as well scenarios, research challenges, and opportunities in this context were selected. This paper reports the main outcomes of the performed systematic mapping by both (i) presenting an overview of the state of the art on the integration of IoT and Cloud Computing and (ii) shedding light on important current challenges and potential directions to future research.

The remainder of this paper is structured as follows. Section 2 presents the systematic mapping methodology, research questions, search strategy, selection criteria, and data extraction method. Section 3 details how the study was conducted to select relevant primary studies from the literature. Section 4 provides a synthesis of the extracted data as well as answers to the research questions. Section 5 elicits some challenges that can drive further

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Table 1
Research questions and respective goals.

Research question	Goal
RQ1: What are the main topics investigated on the integration of the IoT and Cloud Computing paradigms?	To obtain a comprehensive understanding on the integration IoT and Cloud Computing and to identify what has been investigated in this context
RQ2: What are the strategies for integrating IoT and Cloud Computing?	To understand how and to which extent IoT and Cloud Computing have been effectively integrated
RQ3: What are the existing architectures supporting the construction and execution of cloud-based IoT systems?	To characterize the architectures and infrastructures comprising the integration of IoT and Cloud Computing

Table 2
Electronic databases used in the automated search process.

Database	URL
IEEEXplore	http://ieeexplore.ieee.org
ACM digital library	http://dl.acm.org
ScienceDirect.com	http://www.sciencedirect.com
Scopus	http://www.scopus.com
Web of science	http://www.webofknowledge.com

research in this context. Section 6 enumerates threats to the validity of this systematic mapping. Finally, Section 7 contains some concluding remarks.

2. Research methodology

A *systematic mapping* is an evidence-based secondary study recently advocated as a useful mean to synthesize existing work from the literature by using a systematic, well-defined procedure. This type of study offers multiple benefits. First, systematic mappings are able to provide a comprehensive overview of the state of the art (or state of the practice) on the investigated research topic [20]. Second, they can identify relevant gaps in the literature and collect evidences to commission further research, thus avoiding effort duplication [21]. In this perspective, systematic mappings allow analyzing all available studies in a given domain at a high level thereby answering broad research questions regarding the current state of the art of the literature [19].

A systematic mapping typically comprises three basic steps, as depicted in Fig. 1. The *planning* step yields a protocol defining the research questions to be answered, the search strategy to be adopted, the criteria to be used for selecting primary studies, and the methods for extracting and synthesizing data. In the *conduction* (or *execution*) step, primary studies are identified, selected, and evaluated according to the previously established protocol. Finally, the *reporting* (or *analysis*) step aggregates information extracted from the relevant primary studies considering the research questions and outlines conclusions from them.

2.1. Research questions

Aiming at finding primary studies to understand and summarize evidences about the synergic relationship between IoT and Cloud Computing, we have proposed the research questions (RQs) outlined in Table 1.

2.2. Search strategy

In order to retrieve primary studies, we have used an automated search process performed over five electronic databases (see Table 2), which are among the most popular ones in Computer Science and Engineering and are able to ensure a high coverage of potentially relevant studies [22,23]. In addition, we have taken into account other important criteria, such as: (i) coverage of the electronic database; (ii) content update, i.e., if the publications are regularly updated; (iii) availability of the full text of the primary study; (iv) easiness of building the search through fields and commands available at the electronic database; (v) quality of the results, which is related to the accuracy of the results obtained by the automated search procedure; and (vi) versatility to export results [24].

Based on the defined research questions, two main keywords were initially identified, namely *Internet of Things* and *Cloud Computing*. In addition, possible variations such as synonyms and singular/plural forms were considering, thus resulting in the following search string:

`((internet of things OR iot OR web of things OR wot OR machine to machine OR m2m OR machine-to-machine) AND cloud computing) OR (cloud of things OR cloud-of-things)`

in which the main keywords were connected by using the `AND` logical operator. In turn, the possible variations and synonyms were connected by using the `OR` logical operator.

2.3. Selection criteria

Selection criteria were used to evaluate each retrieved primary study according to the defined research questions. The main goal was to include studies that are potentially relevant to answer the research questions and to exclude the ones that do not contribute to answer them.

We have considered the following two inclusion criteria:

IC1: The study presents and/or discusses scenarios, research challenges, and opportunities on the integration of the IoT and Cloud Computing paradigms.
IC2: The study presents a strategy on how to integrate IoT and Cloud Computing (at either the architectural, platform or programming level, for example).

We have also established the following seven exclusion criteria:

EC1: The study is not directly related to IoT.
EC2: The study is not directly related to Cloud Computing.
EC3: The study does not address the integration of the IoT and Cloud Computing paradigms.
EC4: The study is a previous version of a more complete study about the same research.
EC5: The study does not have an abstract or the full text is not available.
EC6: The study is a table of contents, foreword, tutorial, editorial, keynote talk, or summary of conference/workshop.
EC7: The study is not written in English, which is the most common language in scientific papers.

In this systematic mapping, a given primary study is considered as relevant if it does not meet any of the aforementioned exclusion criteria and it meets at least one inclusion criterion.

3. Selection process

This systematic mapping was undertaken from March to June 2015 and involved four researchers. The primary studies were searched, selected, and evaluated according to the established protocol, resulting in a set of possibly relevant studies. During the search process, the generic search string has undergone minor changes in order to make it compatible with the specificities of each electronic database engine. Afterwards, the automated search procedure was performed over the selected electronic databases by searching for all studies that have matched the adapted search

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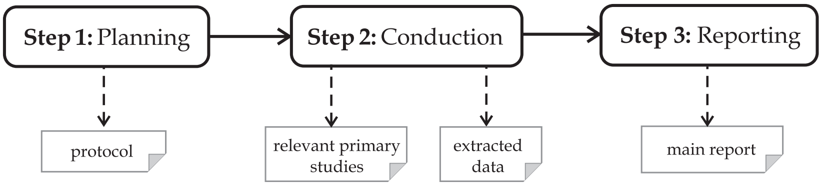

Fig. 1. Process for reviewing literature in systematic mappings [19].

string. The automated search was limited only to title, abstract, and keyword fields.

The selection of the studies was divided in two main phases. The preliminary selection encompassed reading title, abstract, and keywords of the studies retrieved from the electronic databases, whereas the final selection encompassed the full reading of the filtered studies. In order to minimize the effect of any bias or misinterpretation, four researchers have individually performed the selection activities. After retrieving the studies from the electronic databases, studies indexed by more than one database were removed and then the researchers have performed the first selection to filter studies based on the selection criteria (see Section 2.3) against the information available in title, abstract, and keywords. Next, an agreement meeting was held in order to compare the results and solve existing conflicts, thus resulting in a consensual preliminary selection. Afterwards, the full text of the filtered studies was read and the selection criteria were applied in order to compose the final set of relevant studies. A new agreement meeting was carried out again in order to compare results and solve conflicts.

Fig. 2 depicts the steps for selecting the relevant primary studies. After removing studies retrieved by two or more electronic databases, 842 studies were evaluated based on their title, abstract, and keywords against the selection criteria, resulting in a set of 105 potentially relevant studies. The full text of the filtered studies was read and the selection criteria were applied again. As a result, 35 primary studies were selected as relevant to this systematic mapping (see Appendix A).

4. Results

In this section, we summarize the results of the performed systematic mapping considering the research questions and the extracted/synthesized data. We first present a brief overview of the selected primary studies (Section 4.1) and then the answers to each research question based on the analysis of such studies (Sections 4.2–4.4).

4.1. Overview of selected primary studies

Distribution along the years. As both IoT and Cloud Computing represent relatively new research fields, it is interesting to observe when studies on the convergence of these paradigms were published. In particular, this useful to identify when such areas have begun to converge and when the research on this convergence has gained momentum. Fig. 3 shows the evolution of the selected primary studies along the years. It is possible to observe that almost all studies were published in the last three years (no study was published before 2012), thus confirming that the integration of IoT and Cloud Computing has been target of a very recent interest from the scientific community. We have not plotted data regarding year 2015 due to its incompleteness: as the automated search procedure was performed in March 2015, only one study had been published so far. Furthermore, it is possible to notice the clear increasing trend on the number of publications along the years, denoting that more relevant publications on this topic may be expected for the next years.

Table 3
Distribution of application domains targeted by the selected studies.

Application domains	Studies
Healthcare	S11, S12, S15, S20
Smart cities	S13, S20
Ambient Assisted Living (AAL)	S8
Smart homes	S29
Mobile applications	S10, S27
Intelligent business services	S33
Supply chain management	S34

Publication venues. We have also observed the venues where the selected primary studies were published. As shown in Fig. 4, 29 studies (83%) were published in conferences and workshops, a possible indicative that they are at an early development stage and/or not fully validated. In addition, the selected studies were published in 29 different venues (see Appendix B), thus indicating that there is still no leading conference/journal addressing the integration of IoT and Cloud Computing possibly due to the novelty of this topic in the scientific community. Another consequence of the lack of such a leading venue is that some studies were published in venues addressing either IoT or Cloud Computing or even correlated topics of interest.

Validation/evaluation methods. After examining the 29 studies that present a concrete approach on the integration of IoT and Cloud Computing, we have noticed that a quarter of these studies did not present any method for validating or evaluating their proposal (see Fig. 5). In addition, more than half of these studies are limited to either present an example illustrating a possible scenario in which the proposed approach could be applied (4 of 29 studies, i.e., 13.79%) or show a simple proof of concept (prototype) aimed to demonstrate the implementation and/or application of the approach (12 of 29 studies, i.e., 41.38%). Therefore, it is possible to clearly conclude that stronger methods are required to validate/evaluate the proposed approaches aiming at providing solid evidences about their efficiency, effectiveness, and feasibility.

Application domains. As shown in Table 3, 12 studies (34.28%) present proposals targeting seven specific application domains, which represent typical scenarios that can benefit from the adoption of IoT and can also potentially benefit from the integration of this paradigm with Cloud Computing. In general, these studies take advantage of cloud services to: (i) provide scalability upon a myriad of heterogeneous physical devices; (ii) increase and decrease the use of infrastructure resources (e.g., CPU, storage, application services, etc.) according to the demands of applications, thus taking advantage of the elasticity of cloud; and (iii) allow ubiquitous access to data available on the cloud. Additionally, the cloud is used as a promising solution for challenges faced by some specific application domains. For example, healthcare and smart city applications are typically characterized by large amounts of data produced by heterogeneous sensors and that need to undergo

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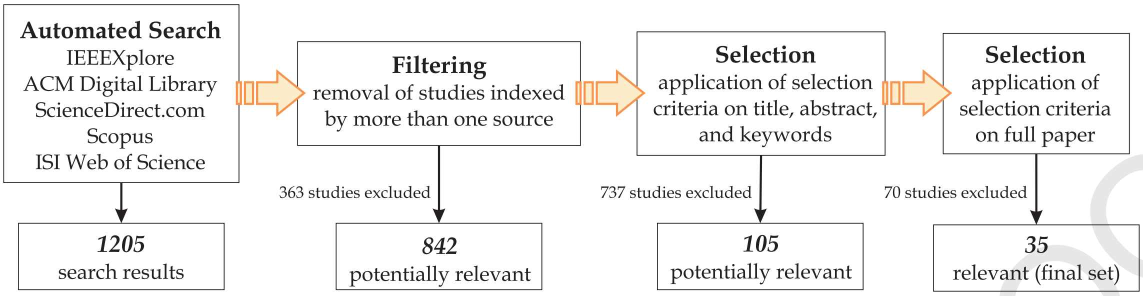

Fig. 2. Steps for selecting the relevant primary studies.

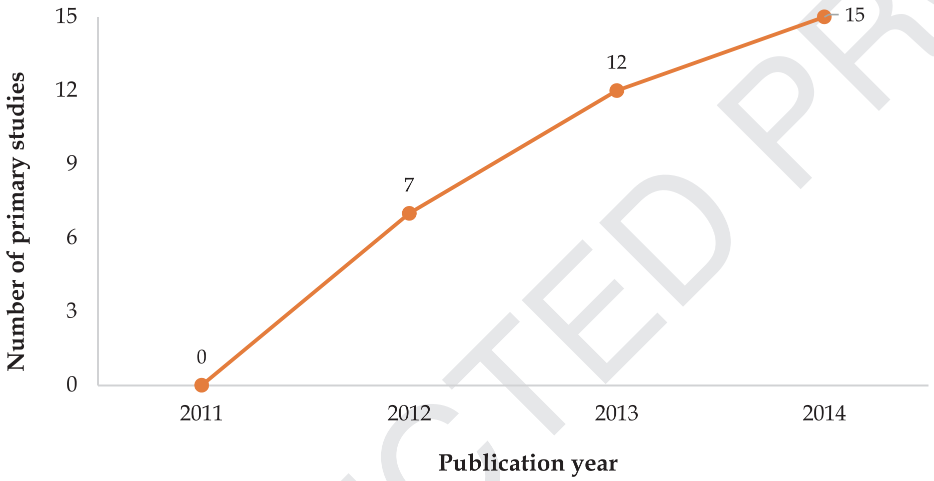

Fig. 3. Evolution of the selected primary studies along the years.

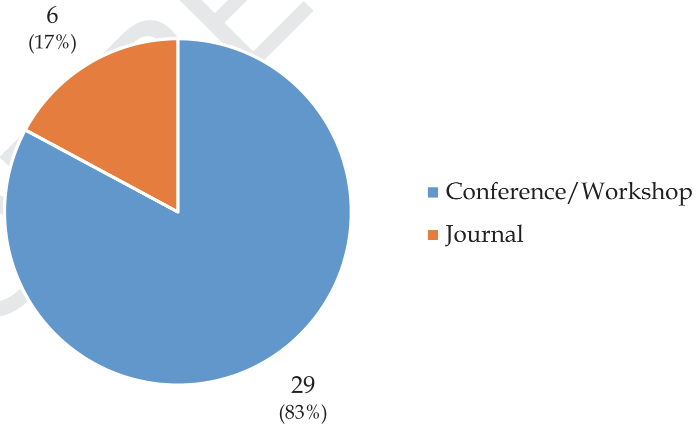

Fig. 4. Venue types in which the selected primary studies were published.

complex processing and analysis tasks. Healthcare applications have important requirements to be fulfilled, such as high availability and the need of performing tasks at real-time, under penalty of threats to life, health, and safety of human beings. Smart city applications rely on ICTs for collecting data from several urban sensors to be used in management, education, transportation, and public safety services in a city in order to provide value-added services to the citizens and government entities. Therefore, processing such a volume of data and providing efficient means of sharing them are relevant concerns that can exploit both cloud and IoT capabilities. Moreover, the adoption of Cloud Computing can play a significant role in these and other scenarios towards meeting the aforementioned requirements and being a distributed stratum for management, analysis, dissemination, and control of data from IoT devices.

4.2. RQ1 – main investigated topics

Aiming to obtain a comprehensive understanding on the integration of IoT and Cloud Computing and to identify what has been investigated in this context, we have analyzed the primary goals of each study. 29 of the 35 selected studies propose concrete solutions that can be broadly classified into four categories, namely: (i) *architecture*, which refers to a high-level structure targeting the integration of IoT and Cloud Computing and defining components, their respective roles, and how they should interact for concretizing such an integration; (ii) *platform*, i.e., a hardware and/or software infrastructure providing APIs to support the development and execution of applications, as well as the integration, management, and real-time monitoring of IoT devices; (iii) *framework*, i.e., a software infrastructure providing reusable components to foster the

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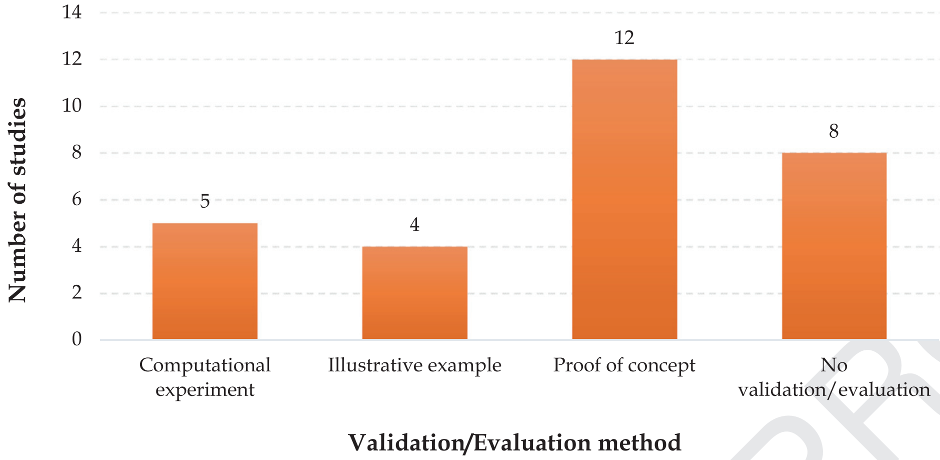

Fig. 5. Methods for validating/evaluating proposed approaches.

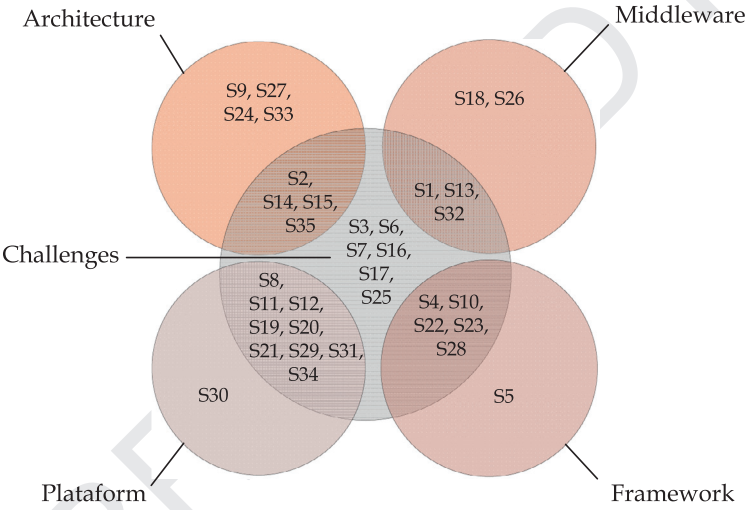

Fig. 6. Main topics addressed in the selected primary studies.

development of applications; and (iv) *middleware* providing both generic and domain-specific services to applications and/or end-users while abstracting away underlying IoT devices and cloud resources. In addition, it is worth observing that 27 of 35 selected studies present and/or discuss challenges related to the integration of IoT and Cloud Computing. Fig. 6 depicts a separation of the studies according to these topics, each one briefly described in the following.

Architectures. Eight studies have proposed high-level architectures for the integration between IoT and Cloud Computing, in particular focusing on sharing data and providing monitoring and actuation capabilities by using the cloud infrastructure. In spite of the existing differences among these architectures and their respective purposes, they present some common elements such as: (i) sensors responsible for gathering information from people and the environment (e.g., health data, location, luminosity, etc.) to be made available on the cloud; (ii) software components running over the cloud to perform tasks such as processing and making information obtained from IoT devices; and (iii) components within a network layer through which data are transmitted to the software components on the cloud. In general, the components of the proposed architectures are organized into layers according to their features, e.g., (i) sensors, RFID tags, and other devices responsible for capturing and providing information about the physical world; (ii) network devices responsible for mediating the communication between sensors and the cloud; and (iii) software components responsible for consuming information provided by sensors. The communication between devices and these software components that consume information takes place either through drivers tailored to each device or via smart gateways mediating such a communication. In both cases, we found the use of the REST (*REpresentational State Transfer*) architectural style [25,26] as the predominant choice for transmitting data to the cloud. As an example, the communication between devices and the cloud platform in study S2 is performed through a smart gateway responsible for receiving data from devices, temporarily storing them to perform preprocessing tasks on such data, and finally transmitting the received data to the cloud. In study S33, drivers installed in a gateway allow devices to communicate with it, which in turn forwards information received from devices to the cloud via REST. Additionally, the proposed architectures were designed to benefit from high performance, availability, and data storage capabilities offered by cloud platforms in order to support a large number of devices and users. In study S15, which targets the healthcare domain, vital signs, motion, and contextual information are collected from wearable sensors and sent via Bluetooth to mobile devices (e.g., smartphones), which play the role of a gateway and forward such data via Internet to a server on the cloud. Before sending data to be stored and analyzed on the cloud, these mobile devices can perform tasks such as data preprocessing, prioritization of data according to their criticality, temporary storage, and aggregation.

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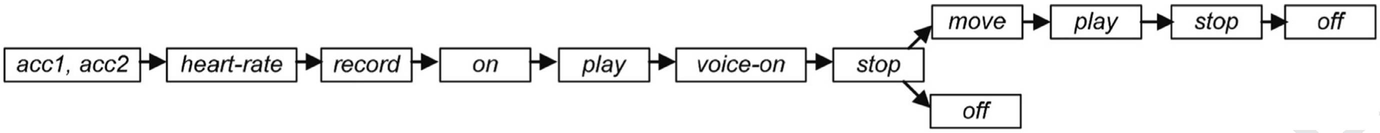

Fig. 7. Example of device orchestration performed in the platform proposed by study S8.

Platforms. As shown in Fig. 6, 10 studies have proposed platforms targeting the integration of the IoT and Cloud Computing paradigms. In particular, the main purpose of these platforms is to allow integrating, managing, and monitoring IoT devices at real-time through browsers or mobile devices. In these platforms, the amount of cloud resources required to support the integrated devices is provided on-demand. They also aim to support the development of applications using IoT devices by providing APIs for data storage, data retrieval and analysis, and deployment and execution of applications. In addition, there are other relevant features offered by some platforms in the selected studies, such as support for the orchestration of devices (study S8) and sharing of virtualized IoT devices (study S34). In study S8, device orchestration is performed with the assistance of a dashboard through which users can specify a profile describing a sequence of high-level tasks that must be performed by the integrated devices to realize a given activity. Afterwards, a gateway realizes the orchestration of the devices according to the previously defined tasks against the capabilities of each device (known a priori by the gateway). Fig. 7 shows an example of an orchestration designed to monitor a patient with cardiac problems. This orchestration is composed of actions performed by the devices used in the environment, namely two accelerometers, a heart rate sensor, a video camera, a voice transmission device, and a media player.

Frameworks. Six of the selected studies have proposed frameworks that offer APIs and reusable features to support the development of applications benefiting from the convergence of IoT and Cloud Computing. Some of the offered facilities are: (i) high-level interfaces to access heterogeneous devices; (ii) communication between smart-objects via REST and WebSockets [27]; and (iii) device virtualization to encapsulate and access IoT resources and capabilities by using a uniform API. An example of these frameworks supporting the development of applications based on both IoT and cloud is PatRICIA, proposed in study S23. PatRICIA provides a programming model defining high-level constructs and operators to enable developers to implement applications without being concerned about the complexity of low-level device services and raw sensor data streams. Some examples of the operators available at the PatRICIA framework are: (i) *send*, for communicating with devices; (ii) *notify*, for subscribing to and receiving information about events; (iii) *poll*, for synchronization; and (iv) *delimit*, which refers to tasks to be performed under satisfaction of certain conditions. In turn, study S10 aims to provide a set of development kits (SDKs) for developing context-aware mobile applications that make use of smart objects (that communicate among each other by using WebSockets) while taking advantage of scalability provided by the cloud.

Middleware. Five studies have proposed using a middleware layer to allow integrating IoT and Cloud Computing. In general, they address important concerns such as: (i) abstractions to virtualize devices, i.e., representing (groups of) sensors as virtual entities that expose their capabilities at a high-level and abstract away details related to protocol and data formats, thus facilitating their use by applications; (ii) abstractions aimed to uniquely identify devices; (iii) communication based on the publish-subscribe model [28] in which applications register interest in some information and are immediately notified when such an information is updated, thereby allowing to monitor information obtained by sensors at real-time, for example; (iv) standardized interfaces to enable applications to access resources such as information, sensors, and cloud platforms towards minimizing interoperability issues; (v) security mechanisms to ensure information integrity and privacy; (vi) services for controlling and managing devices; and (vii) discovery services aimed to identify new IoT devices. The proposals reported in two studies (S1 and S13) have been designed targeting the domain of smart cities, in particular to create an ecosystem that allows developing smart applications based on both IoT and Cloud Computing with capabilities for device discovery, efficient data processing, access to information provided by the integrated devices, etc. In study S13, a middleware called ClouT provides services such as device discovery, (meta)data storage and retrieval, and analysis and extraction of data stored on the cloud for identifying events that occur in the city. In turn, the middleware presented in study S1 provides sensor discovery capabilities and allows large data processing in the cloud infrastructure as well as real-time delivery of notifications to mobile devices through the use of a publish/subscribe communication mechanism. In addition, devices and their respective capabilities are semantically described by using ontologies, thus supporting for semantic reasoning and querying for mobile devices.

Challenges on the integration of IoT and Cloud Computing. Finally, we have observed that the majority of the selected studies devotes some attention to present and/or discuss challenges related to the integration of IoT and Cloud Computing besides presenting solutions to some of them. As previously mentioned, the combination of these paradigms can overcome some of the open issues individually observed in each side, e.g., resource limitations of IoT devices remedied by the use of cloud services. However, other challenges persist and become more critical despite such an integration, in particular interoperability (i.e., standardization of data and protocols) and security in terms of data integrity and confidentiality. With a smaller frequency, other challenges were also found, such as the need of processing large volumes of data coming from IoT devices (studies S7 and S23), the lack of standardization of data from IoT devices, virtualization of IoT devices on the cloud (studies S9 and S13), device orchestration (study S8), and energy efficiency (studies S3 and S20). Furthermore, it is worth mentioning the existence of six studies (S3, S6, S7, S16, S17 and S25) whose main goal is to elicit and discuss relevant challenges in this context. We provide a more detailed discussion about these and other challenges on the integration of IoT and Cloud Computing in Section 5.

4.3. RQ2 – strategies for integrating IoT and Cloud Computing

We have identified three broad categories in which the selected studies can be classified with respect to integration strategies for IoT and Cloud Computing, namely (i) *minimal integration*, (ii) *partial integration*, and (iii) *full integration*. This classification was made based on an assessment of how both paradigms were integrated to each other in 29 of 35 selected studies, which are the ones presenting concrete solutions (i.e., architectures, frameworks, platforms or middleware). In the minimal integration category, both paradigms are used in their original purpose with almost no real integration between them. In the partial integration category, both paradigms are used in conjunction to provide at least one novel service layer that would not exist otherwise. Finally, the solutions

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Table 4
Categories of integration strategies found in the selected primary studies.

Integration strategy	Selected studies
Minimal integration	S2, S4, S8, S11, S12, S14, S15, S19, S20, S21, S23, S27, S31
Partial integration	S1, S5, S9, S10, S18, S22, S24, S26, S28, S29, S30, S32, S34
Full integration	S13, S33, S35

in the full integration category provide a completely new perspective in which all service layers result from the use of both paradigms. Table 4 shows a categorization of the selected studies into these groups, each one detailed in the following.

The *minimal integration* strategy is characterized by the existence of an IoT middleware or platform deployed in a cloud environment (either in the IaaS – *Infrastructure as a Service* layer or in the PaaS – *Platform as a Service* layer) to make use of cloud services. Such a platform is usually related to the provision of visualization, computation, analytics, and storage of data collected from smart objects in a scalable way, capabilities achieved thanks to the adoption of the Cloud Computing paradigm in this context. As shown in Table 4, this category is represented by seven primary studies. For instance, the solution proposed in study S11 encompasses (i) collecting data from healthcare sensors, (ii) using a smart gateway to send these data to a Web platform deployed on a cloud infrastructure, and (iii) visualizing the collected data in such a platform. Similarly, study S14 presents an IoT Web portal that collects data from several types of sensors through an Internet gateway. Collected data are stored using a scalable cloud storage and the Web portal (also deployed in the cloud infrastructure) provides visualization and analytics services based on the underlying cloud infrastructure.

The *partial integration* strategy is characterized by a higher integration level in comparison to the minimal integration strategy. In this case, not only the IoT middleware or platform is deployed in a cloud environment, but the platform also provides new service models based on abstractions of smart objects. Therefore, service models such as SOaaS – *Smart Object as a Service* and SaaS – *Sensing as a Service* are provided to abstract away the heterogeneity of devices and virtualize their capabilities. These novel service models allow smart objects to be concurrently controlled by several users and/or applications (i.e., in a multi-tenant approach), including their actuation capabilities. For instance, study S10 proposes a framework that provides the notion of SOaaS, which envisions encapsulating and exposing smart objects as services. This approach allows smart objects to be accessed, actuate, and dynamically reconfigured at runtime. Similarly, study S18 presents a middleware that virtualizes physical smart things allowing isolation among multiple applications sharing them. The middleware can also allow efficient sharing and resource conflict resolution in the use of smart things.

Finally, in the highest level of integration, the *full integration* strategy stands for the emergence of new service models that extend all of the conventional Cloud Computing layers (i.e., IaaS, PaaS, and SaaS) to encompass services provided by physical objects. This means that physical devices are able to expose their functionalities as standardized cloud services. As first-class entities in the cloud, devices can also be used in conjunction with traditional cloud resources provided by third parties. For example, the developer of an environmental monitoring application can compose sensing capabilities of the so-called cloud of things along with computational and storage capabilities of traditional cloud. Based on the full integration strategy, study S13 proposes new service models in the context of smart cities. The first one is called CIaaS – *City Infrastructure as a Service*, which expands the traditional IaaS layer to offer virtualized resources by means of standard interfaces and allows seamlessly accessing any device, data, and computing capabilities. The second layer is called CPaaS – *City Platform as a Service*, which expands the traditional PaaS layer to foster the development of applications as well as to provide a set of specialized middleware services, such as data processing for analysis and extraction of data stored in the cloud, service composition for aggregating data/services offered by deployed applications, and resource access for storing and retrieving (meta)data from the smart city. Finally, the uppermost level is called CSaaS – *City Software as a Service*, an expansion of the traditional SaaS layer represented by applications developed/deployed by using services provided at the CIaaS and CPaaS layers. Similarly, the framework proposed in study S33 is composed of three layers. The lowermost layer (called *WoT Infrastructure*) is built upon the traditional IaaS layer and provides a basic IoT infrastructure (comprising embedded devices and Web gateways) to bridge different types of sensors, actuators, and other devices, which are exposed as Web resources. In turn, the middle layer (*Service and Business Operation*) expands the traditional PaaS layer and provides service composition and business process management. At last, the uppermost layer (*Intelligent Services*) is an expansion of the traditional SaaS layer and it provides a collection of IoT applications and interfaces for end-users, which have a pay-per-use direct access to the provided services. Fig. 8 presents the architectures proposed in studies S13 and S33. Even though these studies use different names for their layers, both architectures have some similarities. For instance, the lowermost layer of studies S13 and S33 mainly focuses on the boundary between the physical and the digital realms, dealing with the virtualization of IoT devices. The middle layer is concerned with providing middleware services and supporting the execution of applications. The uppermost layer focuses on providing relevant applications that make use of the services made available by the lower layers.

4.4. RQ3 – architectures and infrastructures for IoT and cloud

In order to answer this research question, we have striven to characterize the architectures and infrastructures supporting the construction, deployment, and execution of IoT applications in cloud platforms. We noticed that these architectures were designed considering particular features, thus making them significantly distinct from each other and hindering the conception of a general picture of what would be an architectural solution targeting the convergence of IoT and Cloud Computing. A reason for such a difference is the lack of standardized means for supporting the design of these architectures when integrating IoT and Cloud Computing. Nevertheless, we have observed that the majority of the solutions (23 studies, i.e., 66%) has adopted traditional approaches such as smart gateways, Web services relying upon SOAP (*Simple Object Access Protocol*) [29] or REST and drivers or APIs deployed in the SaaS cloud layer. On the other hand, the studies have typically adopted the PaaS layer to support the deployment of tools and services for developing applications, as well as the IaaS layer as underlying infrastructure for hosting and executing applications.

Despite several studies use the concepts of the three traditional cloud layers (IaaS, PaaS, SaaS) as a starting point for constructing their architectures, the proposed approaches are not limited to these service models, thus creating novel concepts and/or adapting

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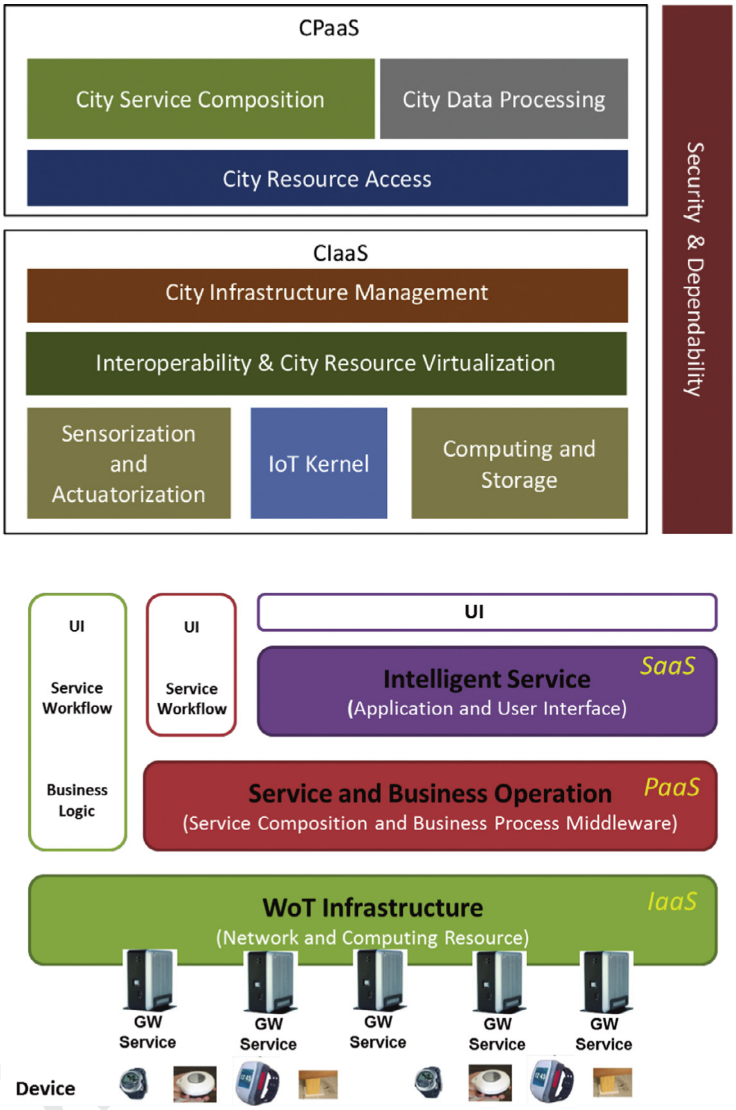

Fig. 8. Architectures of the solutions proposed in studies S13 (top) and S33 (bottom).

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Table 5
Traditional and novel cloud-based service models considered and/or proposed by the selected studies.

Service model	Description	Studies
Software as a Service (SaaS)	Applications are designed and deployed for end-users over the Web	S4, S5, S8, S9, S12, S13, S14, S28, S29, S30, S31, S32, S33, S34, S35
Platform as a Service (PaaS)	Tools and services to support the development of applications	S10, S11, S13, S14, S19, S21, S23, S29, S30, S32, S33, S34, S35
Infrastructure as a Service (IaaS)	Delivery of infrastructure (e.g., servers, storage, network, operating systems) as a service	S13, S14, S15, S22, S25, S27, S30, S33, S34, S35
Network as a Service (NaaS)	Virtualization of devices in a wireless sensor network	S26
Sensing as a Service (SaaS)	Ubiquitous access to sensor data	S1, S5
Sensing and Actuation as a Service (SAaaS)	Sensing and actuation capabilities provided as services	S9, S24
Smart Object as a Service (SOaaS)	Virtualization physical smart objects (things) for multi-tenancy support	S18

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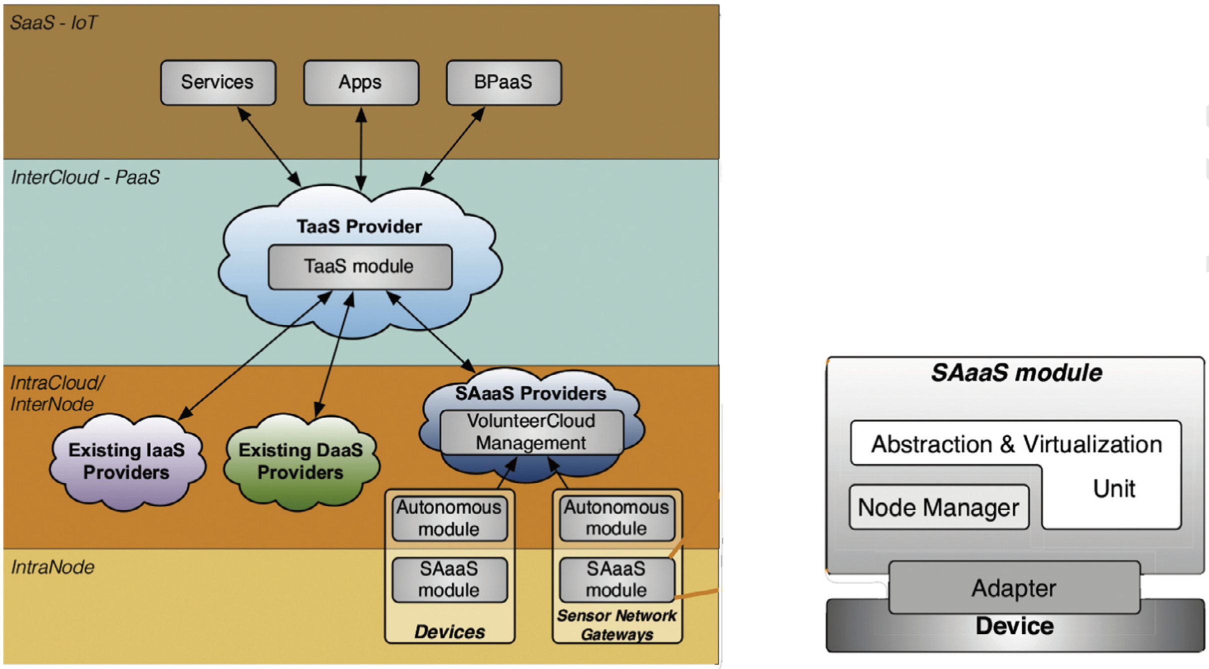

Fig. 9. Representation of the architecture presented in study S9 encompassing the SAaaS concept.

them to the IoT scenario. For instance, while the traditional SaaS model is concerned with delivering software that can be used over the Internet by using a thin client (browser), some studies have adapted this concept to IoT for creating the SaaS – *Sensing as a Service* model, characterized by accessing sensor data via Internet. Novel service models were also proposed aiming at enhancing the synergy between the IoT and Cloud Computing paradigms, as summarized in Table 5. In the following, we present an overview of these novel concepts.

Inspired on the utility model offered by cloud services, SAaaS – *Sensing and Actuation as a Service* aims at exposing wireless sensor networks (WSNs), smartphones or other devices endowed with sensors/actuators as services accessible through the Internet. To deal with this novel concept, studies S9 and S24 propose different approaches. In the former (see Fig. 9), SAaaS modules at the bottom of the architecture virtualize sensing and actuation capabilities of IoT devices, expose such resources as services at the minor granularity level, and relay sensor events to upper layers. These SAaaS modules in the proposed architecture also use adapter interfaces to directly interact with the sensors/actuators, maintain connectivity control, and translate commands and relay them to the respective underlying physical endpoints, through device-native communication protocols. In turn, the approach found in the latter (see Fig. 10) encompasses the concept of smart sensors, which are capable of performing an initial processing of the collected data besides sensing tasks. The proposed architecture is based on a virtualized and distributed infrastructure provided by a cloud IaaS environment as means of offering computational and flexible storage capacity with enhanced performance. Therefore, virtualization allows seamlessly using information produced by heterogeneous sensor networks and making it available to upper layers of the architecture, such as the ones responsible for business logics and decision-making, as well as end-user applications.

The NaaS – *Network as a Service* model is characterized by the virtualization of devices in a wireless sensor network in which hardware resources are exposed as services. Study S26 proposes Serviceware, a service-oriented middleware that allows sensor network infrastructure resources to be virtualized and exposed as services, as depicted in Fig. 11. The middleware is directly deployed into devices and it works as an encapsulating layer over the device's operating system (OS) in order to virtualize its hardware resources, which are accessed by using the API provided by the OS layer.

Finally, SOaaS – *Smart Object as a Service* is a model that envisions virtualizing physical smart objects to be used by multiple applications, i.e., in a multi-tenant way. Study S18 proposes ECO, a middleware compliant with this model (see Fig. 12). The ECO middleware is organized in three layers, namely *Device Framework Layer* (DFL), *Object Orchestration Layer* (OOL), and *Virtualization Layer* (VL). Above VL, ECO Runtime APIs hide complex operations performed at the virtualization layer and provide developers with abstractions for developing their applications atop the ECO middleware. In turn, DFL aims to provide a unified access to heterogeneous networks and capabilities of smart things. OOL provides management of uniform resource objects (UROs), which enable VL to access heterogeneous devices and services with no knowledge about the underlying protocols. Finally, VL enables multiple applications to use smart things at a higher abstraction level.

5. Challenges on the integration of IoT and Cloud Computing

As previously mentioned, despite the combination of IoT and Cloud Computing can overcome some of the open issues to be individually solved in both sides, new, additional challenges arise from such a synergistic relationship. In this section, we provide a non-exhaustive list of some challenges identified from the analyzed studies and other ones that we regard as relevant to pave the way for future research in this context.

Reference architectures for cloud-based IoT solutions. As reported in Section 4.4, the existing solutions relying upon the convergence of IoT and Cloud Computing are significantly different from each other. Such a distinction is mainly due to the lack of standardized means for supporting the design of these solutions, resulting in an increased complexity and significant effort from architects and developers. This problem becomes worse with the absence of a proper guidance for achieving both functional and non-functional requirements since the conception of these solutions up to their

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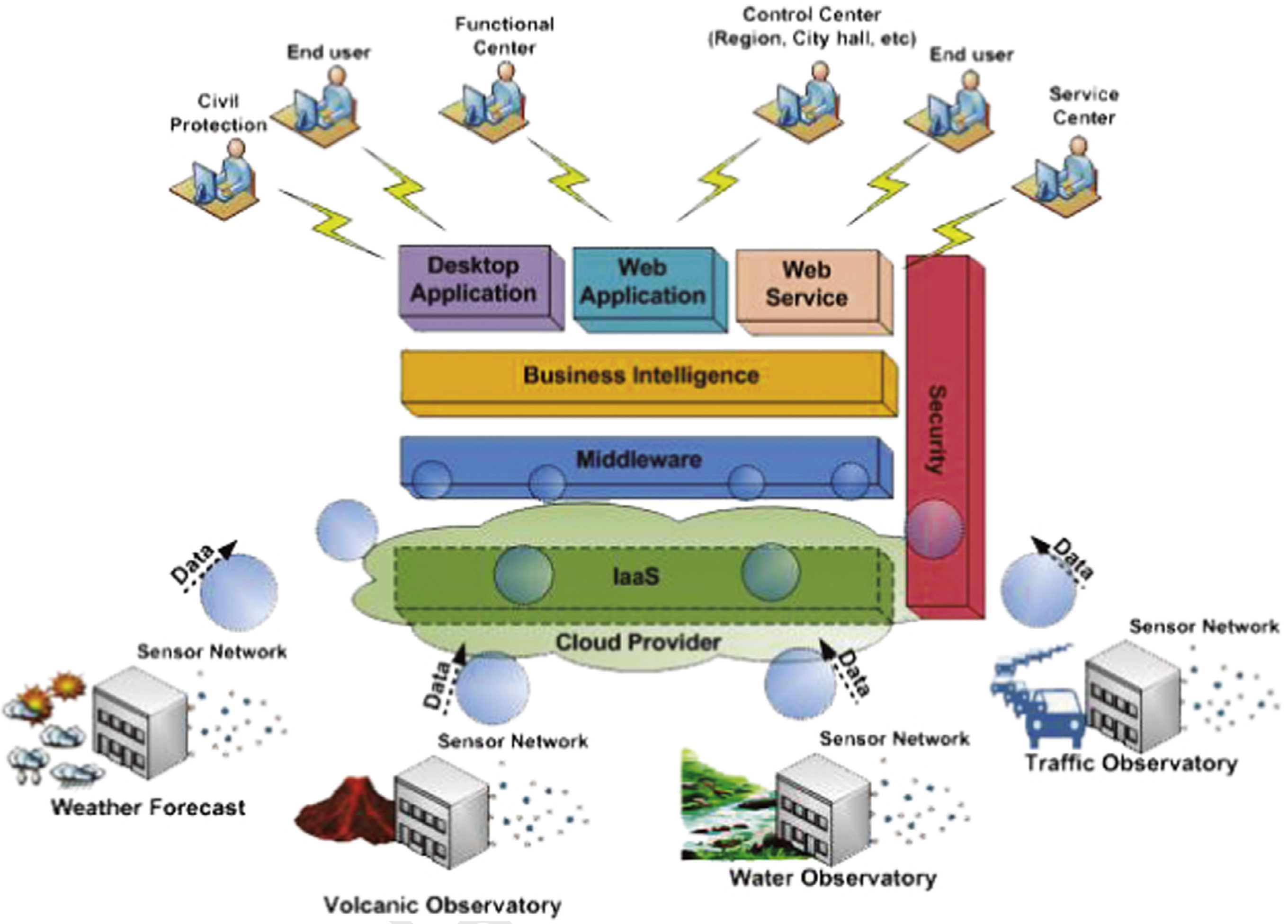

Fig. 10. Architecture presented in study S24 envisioning SAaaS.

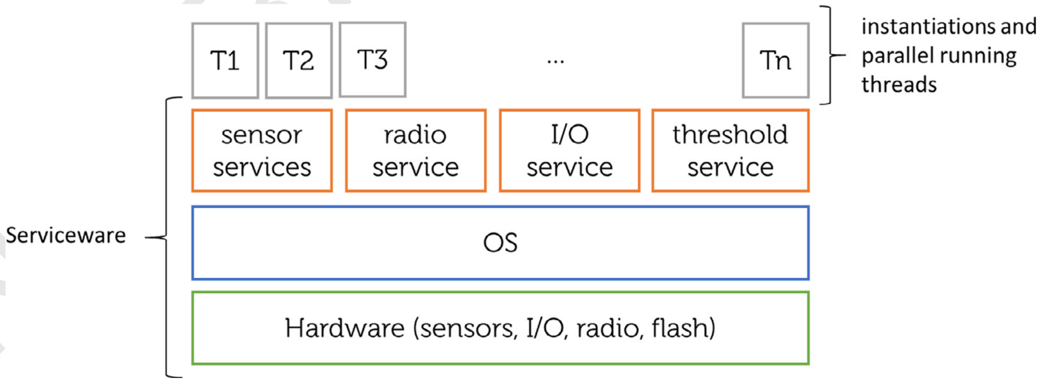

Fig. 11. Architecture of Serviceware middleware proposed in study S26.

implementation and deployment. To mitigate these issues, reference architectures could play a role in terms of defining the essential building blocks for constructing architectural solutions that take into account the integration of IoT and Cloud Computing. Reference architectures can be understood as abstract architectures encompassing knowledge and experiences in a given application domain, thus being able to facilitate and guide development, standardization, interoperability, and evolution of software systems in such a domain [30]. Therefore, directions provided by a reference architecture can be important elements to guide and facilitate the development of cloud-based IoT architectures coping with their increasing scale and complexity. Furthermore, considering that developing interoperable solutions is an important concern, such an interoperability can be achieved by constructing architectural solutions founded upon a reference architecture [31]. After analyzing the solutions proposed in the selected studies, we have noticed that the OpenIoT platform [32] seems to go in the direction of becoming a reference architecture in the integration of IoT and Cloud Computing as it provides guidelines and mechanisms to construct new architectures in this context. As an example, OpenIoT was successfully used to develop the architectural solutions proposed in studies S1 and S28 in different application domains.

Efficient use of cloud resources by IoT devices/applications. The huge amount of physical devices connected to the Internet

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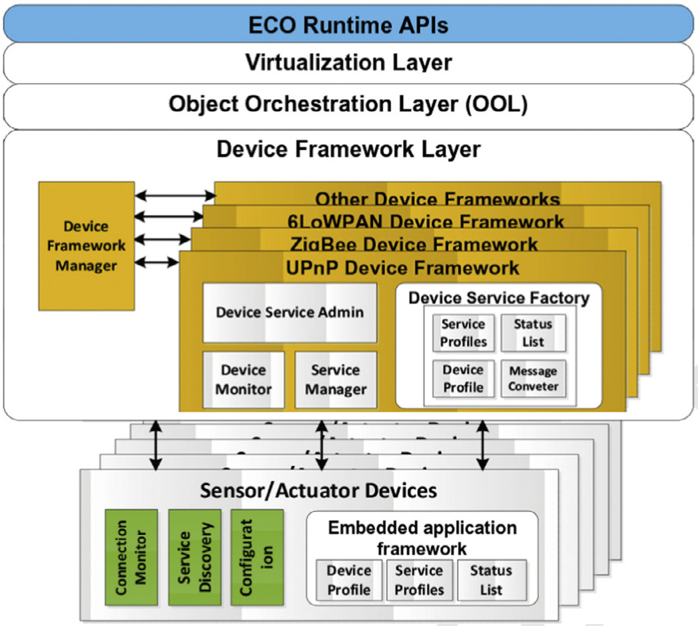

Fig. 12. Architecture of ECO middleware proposed in study S18.

generating and sending data to be processed on the cloud will consume a significant amount of network, processing, and storage resources. If all data generated by devices are sent to the cloud, massive data streams transmitted across wide area networks may cause network congestion and the communication latency may be intolerable for applications that have real-time (or quasi-real-time requirements). Even though current cloud platforms seem to be prepared to provide as many resources as required, the exhaustive use of such resources may bring expensive monetary costs. As highlighted by studies S2, S3 and S6, it is necessary to propose strategies able to minimize the amount of cloud resources to be consumed by IoT-based applications and to decide where to process data generated by devices in an efficient way. One of the strategies presented by these studies is applying the concept of *Fog Computing*, which extends Cloud Computing to the edge of the network towards providing processing, storage, and networking services between devices and cloud platforms [33,34]. Such a novel paradigm is appealing for IoT since it can reduce the consumption of cloud resources while reducing latency for applications and end-users, an essential requirement for some critical applications, such as the ones in the healthcare domain. According to the aforementioned studies, this concept could be applied by using smart gateways and local clouds, which will responsible for mediating the communication between IoT devices and cloud platforms and as well as providing preprocessing and temporary storage of information coming from the devices. Nonetheless, additional research efforts are required for realizing these solutions and hence mitigate the raised challenges. There is also a need of carefully evaluating where to store and process sensed data to meet different types of applications in order to obtain the best out of cloud resources while exploiting the capabilities (albeit limited) of the devices themselves.

Standardization of data and services. Data produced by the various IoT devices do not follow any sort of standardization, i.e., they are usually provided in different formats, units, etc. Moreover, currently there are no means for describing IoT devices and their capabilities in a standardized way, so that software agents cannot easily perform tasks such as automatic discovery and orchestration of devices, data, and services. These concerns are important to be addressed in the context of IoT and Cloud Computing as means of allowing applications to benefit from data provided by IoT devices and from the scalability and availability promoted by cloud services. As an attempt to mitigate this challenge, study S8 suggests following the recent initiatives proposed by OASIS, in particular the DPWS (*Device Profile for Web Services*) standard [35]. DPWS has been designed as a language-independent set of specifications and guidelines to describe devices and their capabilities as services, thus fostering interoperability among them. In addition, ontologies have been suggested for semantically describing devices. A relevant example is the approach used in the OpenIoT middleware [32]. OpenIoT extends the W3C's Semantic Sensor Network (SSN) ontology [36] to provide a common model to semantically describe both physical and virtual sensors while enhancing existing vocabularies for smart objects with additional concepts relevant to the integration of IoT and Cloud Computing. The main premise of adopting such an ontology is to offer an easy way to combine data streams and services from diverse IoT applications that feature incompatible semantics (e.g., measurement units, raw sensor values, etc.) as well as to support seamless discovery and monitoring of sensors, which are not restricted to physical devices, but rather represent anything that can calculate/estimate the value of a phenomenon.

Contextual information. In IoT, sensor data are not the only information to be manipulated, but also their context, i.e., any information that can be used to characterize a person, location or object considered as relevant to the environment [37]. Relevant contextual information such as measurement properties, location, state of entities, and data precision can be annotated along with the raw data obtained by the sensing devices for a posteriori retrieval and/or further processing aimed towards reacting to stimuli [38]. In spite of the fact that the insertion of contextual information adds more value and semantics to sensor data, it also increases the heterogeneity in terms of the used data formats. Indeed, the use of different data representation models poses a barrier for information exchange and retrieval. The way in which data generated by the myriad of IoT devices are extracted and accessed must be reviewed to allow the extraction and easy access to the wide range of data available to end-users and applications.

Data security and privacy. Data obtained from IoT devices can contain sensitive information that others may be interested in, not only the sensed data themselves, but also their corresponding meta-information (e.g., location). As pointed out in study S16,

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outsourcing these data to the cloud raises a number of issues related to privacy concerns mainly due to the lack of control or at least transparency over the access to data, which can be handled by third parties or misused for unintended purposes. Moreover, many devices able to share information and to be controlled via Internet may become vulnerable to several types of attacks. In this scenario, hackers or malicious users may try to remotely control devices, acquire confidential information or promote changes in the contents of messages while they are transmitted. As IoT devices often have limited processing capabilities, they usually do not have very complex security mechanisms such as data encryption, authentication, etc. Therefore, it is necessary to investigate mechanisms aiming at protecting critical and/or sensitive data from IoT devices and ensuring security when storing them on the cloud. At the same time, these actions must be lightweight and require a minimum of processing resources from IoT devices. Nonetheless, data security and privacy in the Cloud Computing context still suffers from several limitations and threats [39], thereby making the convergence of IoT and Cloud Computing more dramatic if these concerns are not properly addressed.

High heterogeneity of IoT and cloud environments. IoT and Cloud Computing are characterized by a high degree of heterogeneity, thus requiring solutions allowing interoperability among resources. On the one hand, it is necessary to handle a myriad of IoT devices from several manufacturers and with different capabilities/functionalities and network protocols, an issue that creates operational barriers to use such devices in a holistic, integrated way [40]. On the other hand, the heterogeneity and lack of standardization in Cloud Computing hampers the use of cloud services offered by multiple providers. This issue directly affects the development and deployment of applications since they become highly coupled to a single cloud provider and its services and constraints, leading to a problem known as cloud lock-in [41]. Despite middleware platforms have recently drawn attention from both academia and industry as promising solutions to integrate heterogeneous devices and provide high-level models for developing IoT applications, most of the existing proposals have not achieved a mature development state and often neglect important requirements in this context [42,43]. In turn, the literature still lacks of effective means of seamlessly using services provided by different cloud providers while considering parameters such as quality of service and cost efficiency [44]. Therefore, further research is necessary aiming at providing middleware platforms able to tackle the inherent heterogeneity of IoT and cloud environments while leveraging the development and deployment of applications that benefit from the integration of a plethora of IoT devices and can use multiple cloud services offered by different providers. In addition, it is important to provide users/developers with flexible mechanisms that allow easily shifting from a given service provider to another as well as selecting the cloud services that meet application requirements.

Elasticity concerns. In the Cloud Computing paradigm, elasticity allows dynamically increasing or decreasing the use of computational resources as response to the varying demands of users and applications. This principle aims at adjusting the amount of provisioned resources to exactly match the current needs, thus minimizing resource overprovisioning and avoiding unnecessary costs with idle or underutilized resources. Despite being one of the fundamental traits of Cloud Computing, elasticity has not yet received enough attention when integrating cloud services and IoT. As discussed in study S22, systems and solutions relying on the convergence of IoT and Cloud Computing are usually not tailored to incorporate elasticity concerns. For example, new types of resources such as data streams and devices delivered by an IoT infrastructure are not provided elastically, thereby preventing current IoT systems to fully take advantage of the benefits offered by the elastic nature of the Cloud Computing paradigm. Therefore, new approaches are required to inherently incorporate elasticity concerns in cloud-based IoT systems.

Dependability concerns. Both IoT and cloud environments are highly dynamic. IoT devices can become unavailable for diverse reasons, e.g., failure, battery depletion, lack of network connectivity, user mobility, etc. In turn, cloud environments may experience typical situations such as unavailability or quality degradation of services used by applications. For both cases, it is necessary to provide means of adapting applications at runtime with minimal or no disruption, thus ensuring a proper response to several events at runtime as well as the satisfaction of non-functional requirements such as availability and quality. Although dependability is especially important for safety-critical applications, in which failures or quality degradation may be a threat to people or lead to economic losses and physical damages, none of the selected primary studies addresses this requirement.

Support to the development of applications. Currently, there is no de facto standard to programming languages for IoT devices and no standardized programming models for building IoT-based applications. IoT elements (sensors, actuators, gateways, applications, etc.) are often developed, deployed, and separately from cloud services such as storage and data processing. For example, most cloud services can reactively monitor the load from IoT and adjust their performance behavior, but they rarely communicate back to the IoT elements to steer it. Furthermore, it is hard to control and manage both IoT and cloud services as a uniform software layer. Truong and Dudstar [18] outline three essential phases that should be considered in the life cycle of a cloud-based IoT system: (i) *development phase*, including techniques for selecting, composing, and integrating components across the system for specifying and developing possible governance and control operations; (ii) *deployment and provisioning phase*, which includes techniques for deploying several types of software components at different levels of abstraction and capabilities to configure deployments and continuous resource provisioning; and (iii) *operation phase*, which includes capabilities to monitor end-to-end metrics, perform governance processes across the system, and control coordinated elasticity processes. Transversally, it is necessary to provide environments to support development of applications based on data streams generated by devices and available through the cloud.

Models for device virtualization. One of the first steps to realize the integration of IoT and Cloud Computing is to have a model for virtualizing devices (sensors, actuators, and other physical objects) and exposing their functionalities as services that can be requested by applications on-demand. By virtualizing devices, it is possible to extend the functionality of cloud platforms to encompass physical objects. However, the traditional service provisioning model must also be extended by creating a novel model of sensing/actuation as a service as well as novel business models to encompass the provision of this new type of service. Regardless of the adopted approach, lightweight virtualization techniques are required to accommodate the limited resources of IoT devices. In addition, physical devices and networks need to expose their functionalities to third parties, preferably using open Web standards. Therefore, the use of open interfaces can allow resources to be used in conjunction with well-established cloud tools and open cloud platforms and promotes interoperability with other existing systems and IoT applications.

6. Threats to validity

The conducted systematic mapping and its results may have been affected by some threats to validity. In the following, we discuss some of these limitations.

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Incompleteness of the study search. The completeness of this systematic mapping may have been affected by missing relevant studies. In order to reduce this threat, we have used electronic databases (see Table 2) that are among the most relevant available sources in Computer Science and Engineering [22,23]. However, there are still limitations. First, some studies may have been missed due to technical limitations of the automated search engines, an issue that is out of our control. Second, the selected electronic databases do not represent an exhaustive list of publication sources, so that other databases might also be included. Third, we have not performed snowballing [45], a useful technique that consists of checking the reference lists of the read studies aiming at finding additional studies that were not retrieved in the automated search procedure. Fourth, we are aware about studies fitting the scope of our research (such as the ones focused on the integration of sensor networks and Cloud Computing), but that were not retrieved in the automated search process. This can be explained by the fact that they do not consider the terms used in the search string (e.g., IoT), which refer to a wider range of devices rather being limited to sensors. Therefore, other possibly relevant studies could have been identified and considered in this systematic mapping.

Bias on study selection. In order to make the results of this systematic mapping study reproducible, the protocol presented in Section 2 clearly established the search terms used in the automated search procedure, search sources, and criteria for selecting the primary studies. However, different researchers tend to have different understandings on these criteria, so that the results of the study selection performed by different researchers are likely to be varied. Even though the drawn conclusions may have been influenced by the researchers' opinions, we have striven to mitigate the effect of any personal bias or misinterpretation by adopting a multiple-revision strategy.

Inaccuracy of data extraction. Bias on data extraction may result in inaccuracy of the extracted data items, thus affecting the analysis of the selected studies. We have striven to reduce this bias by clearly defining the data items outlined in the data extraction spreadsheets. In addition, the data items to be extracted in this systematic mapping were discussed among the researchers and agreed upon their meaning.

Bias on data synthesis. Not all studies sufficiently and clearly describe the details of information to be extracted as data items aiming at supporting the answers to the defined research questions. Therefore, we have had to infer certain pieces of information regarding data items during data synthesis. In order to minimize the inaccuracy of such inferences, we have conducted discussions aiming at solving any disagreement and clarifying potential ambiguities.

7. Conclusion

The IoT paradigm has increasingly received attention from both academia and industry as a key enabler for the emergence of new applications and systems with a significant influence in the daily lives of human beings. Recently, we have witnessed the convergence of this paradigm with Cloud Computing largely motivated by the need of IoT infrastructures and applications to be enhanced in terms of computational resources, scalability, and performance. Furthermore, the cloud arises as a promising solution to overcome or alleviate several challenges faced by the IoT paradigm, which is essentially characterized by heterogeneous physical devices with technological constraints. In spite of this synergy, the literature still lacks of a wide, comprehensive overview on what has been investigated on the integration of IoT and Cloud Computing and the open issues in this context. To tackle this gap, we have performed a systematic mapping study aimed to provide a broad panorama of the current state of the art on this topic and identify important challenges that can give directions for future research. We have analyzed 35 primary studies retrieved from five major electronic Computer Science and Engineering publication databases in order to: (i) obtain a comprehensive understanding on the convergence of IoT and Cloud Computing; (ii) identify what has been investigated in this context; (iii) understand how and to which extent IoT and Cloud Computing have been effectively integrated; and (iv) characterize the proposed solutions comprising the integration of IoT and Cloud Computing.

Our analyses of the selected studies have resulted in several findings about the current state of the art on the convergence of the IoT and Cloud Computing paradigms. First, almost all analyzed studies were published in the last three years, thus confirming an increasing interest of the scientific community on this topic and denoting that more relevant publications may be expected for the next years. Second, despite the several initiatives investigating the integration of IoT and Cloud Computing, existing proposals are still in infancy, i.e., they are at an initial development state and/or not fully validated. Indeed, we have found a significant number of studies lacking from any method to validate/evaluate their approaches and solutions or presenting simple proofs of concept, thereby indicating the lack of solid evidences about their efficiency, effectiveness, and feasibility. Third, we mapped four main types of concrete solutions proposed in the selected studies, namely: (i) *architectures*, which refer to high-level infrastructures targeting the integration of IoT and Cloud Computing and defining components and their respective roles; (ii) *platforms*, i.e., hardware and/or software infrastructures providing APIs to support the development and execution of applications as well as the management and monitoring of IoT devices at real-time; (iii) *frameworks*, which are software infrastructures providing reusable elements to foster the development of applications; and (iv) *middleware* providing services to applications and/or end-users while abstracting away underlying heterogeneous IoT devices and cloud resources. It is important to highlight that these solutions are significantly distinct from each other mainly due to the absence of standardized means for supporting their design, hindering a general picture of what would be an architectural solution targeting the integration of IoT and Cloud Computing. Fourth, the convergence of these paradigms is still limited, i.e., they are used either in their original purpose with almost no effective integration between them or in conjunction to provide new service models aiming at enhancing the synergy between IoT and Cloud Computing.

Finally, we have outlined a non-exhaustive list of some challenges identified from the analyzed studies and other ones that we considered as relevant to pave the way for future research in this context. These challenges refer to the need of: (i) standardizing cloud-based IoT solutions, data, and services; (ii) making IoT devices/applications to use cloud resources in an efficient way; (iii) dealing with massive and real-time data; (iv) handling contextual information; (v) providing effective solutions that consider data security and privacy; (vi) abstracting away the high heterogeneity of both IoT and cloud environments; (vii) considering elasticity and dependability concerns; (viii) supporting the development and deployment of cloud-based IoT applications; and (ix) providing models for device virtualization. In summary, the panorama presented in this paper provides not only a comprehensive overview on what has been investigated and developed in the integration of IoT and Cloud Computing, but it also points directions to future research in this context. With these analyses, such an overview can contribute to a more effective development of IoT infrastructures and applications taking advantage of the benefits and capabilities offered by the Cloud Computing paradigm.

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Appendix A. Selected studies

Study ID	Reference	Citation count in Dec. 2015 (Google scholar)
S1	I. P. Zărko, K. Pripuzǐć, M. Serrano, M. Hauswirth, IoT data management methods and optimization algorithms for mobile publish/subscribe services in cloud environments, in: Proceedings of the 2014 European Conference on Networks and Communications, IEEE, USA, 2014, pp. 1–5. doi:10.1109/EuCNC.2014.6882657	4
S2	M. Aazam, E.-N. Huh, Fog computing and smart gateway based communication for cloud of things, in: Proceedings of the 2014 International Conference on Future Internet of Things and Cloud, IEEE Computer Society, Washington, DC, USA, 2014, pp. 464–470. doi:10.1109/FiCloud.2014.83	17
S3	M. Aazam, P. P. Hung, E.-N. Huh, Smart gateway based communication for cloud of things, in: Proceedings of the 9th IEEE International Conference on Intelligent Sensors, Sensor Networks and Information Processing, IEEE, USA, 2014, pp. 1–6. doi:10.1109/ISSNIP.2014.6827673	14
S4	N. Alhakbani, M. M. Hassan, M. A. Hossain, M. Alnuem, A framework of adaptive interaction support in cloud-based Internet of Things (IoT) environment, in: G. Fortino, G. D. Fatta, W. Li, S. Ochoa, A. Cuzzocrea, M. Pathan (Eds.), Proceedings of the 7th International Conference on Internet and Distributed Computing Systems, Vol. 8729 of Lecture Notes in Computer Science, Springer International Publishing, Switzerland, 2014, pp. 136–146. doi:10.1007/978-3-319-11692-1_12	3
S5	J. Barbarán, M. Díaz, B. Rubio, A virtual channel-based framework for the integration of wireless sensor networks in the cloud, in: Proceedings of the 2014 International Conference on Future Internet of Things and Cloud, IEEE Computer Society, Washington, DC, USA, 2014, pp. 334–339. doi:10.1109/FiCloud.2014.59	0
S6	F. Bonomi, R. Milito, J. Zhu, S. Addepalli, Fog computing and its role in the Internet of Things, in: Proceedings of the First Edition of the MCC Workshop on Mobile cloud computing, ACM, New York, NY, USA, 2012, pp. 13–15. doi:10.1145/2342509.2342513	252
S7	A. Botta, W. De Donato, V. Persico, A. Pescape, On the integration of Cloud Computing and Internet of Things, in: Proceedings of the 2014 International Conference on Future Internet of Things and Cloud, IEEE Computer Society, Washington, DC, USA, 2014, pp. 23–30. doi:10.1109/FiCloud.2014.14	27
S8	J. Cubo, A. Nieto, E. Pimentel, A cloud-based Internet of Things platform for ambient assisted living, Sensors 14 (8) (2014) 14070–14105. doi:10.3390/s140814070	5
S9	S. Distefano, G. Merlino, A. Puliafito, Towards the Cloud of Things: Sensing and actuation as a service, a key enabler for a new cloud paradigm, in: Proceedings of the 8th International Conference on P2P, Parallel, Grid, Cloud and Internet Computing, IEEE Computer Society, Washington, DC, USA, 2013, pp. 60–67. doi:10.1109/3PGCIC.2013.16	5
S10	C. Doukas, F. Antonelli, COMPOSE: Building smart & context-aware mobile applications utilizing IoT technologies, in: Proceedings of the 2013 Global Information Infrastructure Symposium, IEEE, USA, 2013, pp. 1–6. doi:10.1109/GIIS.2013.6684373	5
S11	C. Doukas, I. Maglogiannis, Bringing IoT and Cloud Computing towards pervasive healthcare, in: Proceedings of the 6th International Innovative Mobile and Internet Services in Ubiquitous Computing, IEEE Computer Society, Washington, DC, USA, 2012, pp. 922–926. doi:10.1109/IMIS.2012.26	32
S12	C. Doukas, T. Pliakas, P. Tsanakas, I. Maglogiannis, Distributed management of pervasive healthcare data through Cloud Computing, in: K. S. Nikita, J. C. Lin, D. I. Fotiadis, M.-T. A. Waldmeyer (Eds.), Proceedings of the Second International ICST Conference on Wireless Mobile Communication and Healthcare, Vol. 83 of Lecture Notes of the Institute for Computer Sciences, Social Informatics and Telecommunications Engineering, Springer Berlin Heidelberg, Germany, 2012, pp. 386–393. doi:10.1007/978-3-642-29734-2_53	1
S13	J. A. Galache, T. Yonezawa, L. Gurgen, D. Pavia, M. Grella, H. Maeomichi, ClouT: Leveraging Cloud Computing techniques for improving management of massive IoT data, in: Proceedings of the 7th IEEE International Conference on Service-Oriented Computing and Applications, IEEE Computer Society, Washington, DC, USA, 2014, pp. 324–327. doi:10.1109/SOCA.2014.47	1
S14	J. Gubbia, R. Buyya, S. Marusica, M. Palaniswami, Internet of Things (IoT): A vision, architectural elements, and future directions, Future Generation Computer Systems 29 (7) (2013) 1645–1660. doi:10.1016/j.future.2013.01.010	719
S15	M. M. Hassan, H. S. Albakr, H. Al-Dossari, A cloud-assisted Internet of Things framework for pervasive healthcare in smart city environment, in: Proceedings of the 1st International Workshop on Emerging Multimedia Applications and Services for Smart Cities, ACM, New York, NY, USA, 2014, pp. 9–13. doi:10.1145/2661704.2661707	1
S16	M. Henze, L. Hermerschmidt, D. Kerpen, R. Häußling, B. Rumpe, K. Wehrle, User-driven privacy enforcement for cloud-based services in the Internet of Things, in: Proceedings of the 2014 International Conference on Future Internet of Things and Cloud, IEEE Computer Society, Washington, DC, USA, 2014, pp. 191–196. doi:10.1109/FiCloud.2014.38	4
S17	S. Karnouskos, V. Somlev, Performance assessment of integration in the cloud of things via Web services, in: Proceedings of the 2013 IEEE International Conference on Industrial Technology, IEEE, USA, 2013, pp. 1988–1993. doi:10.1109/ICIT.2013.6505983	8
S18	S. H. Kim, D. Kim, Multi-tenancy support with organization management in the Cloud of Things, in: Proceedings of the 2013 IEEE International Conference on Services Computing, IEEE Computer Society, Washington, DC, USA, 2013, pp. 232–239. doi:10.1109/SCC.2013.61	2
S19	F. Li, M. Vögler, M. Claeßens, S. Dustdar, Efficient and scalable IoT service delivery on cloud, in: Proceedings of the 6th International Conference on Cloud Computing, IEEE Computer Society, Washington, DC, USA, 2013, pp. 740–747. doi:10.1109/CLOUD.2013.64	15
S20	J. Mohammed, A. Thakral, A. F. Ocneanu, C. Jones, C.-H. Lung, A. Adler, Internet of Things: Remote patient monitoring using Web services and Cloud Computing, in: Proceedings of the 2014 IEEE International Conference on Internet of Things, Green Computing and Communications, and Cyber-Physical-Social Computing, IEEE Computer Society, Washington, DC, USA, 2014, pp. 256–263. doi:10.1109/iThings.2014.45	1
S21	S. Mosser, F. Fleurey, B. Morin, F. Chauvel, A. Solberg, I. Goutier, SENSAPP as a reference platform to support cloud experiments: From the Internet of Things to the Internet of Services, in: Proceedings of the 14th International Symposium on Symbolic and Numeric Algorithms for Scientific Computing, IEEE Computer Society, Washington, DC, USA, 2012, pp. 400–406. doi:10.1109/SYNASC.2012.71	20
S22	S. Nastic, S. Sehic, D.-H. Le, H.-L. Truong, S. Dustdar, Provisioning software-defined IoT cloud systems, in: Proceedings of the 2014 International Conference on Future Internet of Things and Cloud, IEEE Computer Society, Washington, DC, USA, 2014, pp. 288–295. doi:10.1109/FiCloud.2014.52	8
S23	S. Nastic, S. Sehic, M. Vögler, H.-L. Truong, , S. Dustdar, PatRICIA – a novel programming model for IoT applications on cloud platforms, in: Proceedings of the 6th IEEE International Conference on Service-Oriented Computing and Applications, IEEE Computer Society, Washington, DC, USA, 2013, pp. 53–60. doi:10.1109/SOCA.2013.48	13

(continued on next page)

Study ID	Reference	Citation count in Dec. 2015 (Google scholar)
S24	A. Puliafito, SensorCloud: An integrated system for advanced multi-risk management, in: Proceedings of the 3rd IEEE Symposium on Network Cloud Computing and Applications, IEEE Computer Society, Washington, DC, USA, 2014, pp. 1–8. doi:10.1109/NCCA.2014.10	0
S25	P. Rao B. B., P. Saluja, N. Sharma, A. Mittal, S. V. Sharma, Cloud Computing for Internet of Things & sensing based applications, in: Proceedings of the 6th International Conference on Sensing Technology, IEEE, USA, 2012, pp. 374–380. doi:10.1109/ICSensT.2012.6461705	31
S26	S. Rea, M. S. Aslam, D. Pesch, Serviceware - a service based management approach for WSN cloud infrastructures, in: Proceedings of the 2013 IEEE International Conference on Pervasive Computing and Communications Workshops, IEEE, USA, 2013, pp. 133–138. doi:10.1109/PerComW.2013.6529470	3
S27	D. Seo, C.-S. Jeong, Y.-B. Jeon, K.-H. Lee, Cloud infrastructure for ubiquitous M2M and IoT environment mobile application, Cluster Computing 18 (2) (2015) 599–608. doi:10.1007/s10586-014-0415-7	0
S28	J. Soldatos, M. Serrano, M. Hauswirth, Convergence of utility computing with the Internet-of-Things, in: Proceedings of the 6th International Conference on Innovative Mobile and Internet Services in Ubiquitous Computing, IEEE Computer Society, Washington, DC, USA, 2012, pp. 874–879. doi:10.1109/IMIS.2012.135	33
S29	M. Soliman, T. Abiodun, T. Hamouda, J. Zhou, C.-H. Lung, Smart home: Integrating Internet of Things with Web services and Cloud Computing, in: Proceedings of the 5th IEEE International Conference on Cloud Computing Technology and Science, Vol. 2, IEEE Computer Society, Washington, DC, USA, 2013, pp. 317–320. doi:10.1109/CloudCom.2013.155	16
S30	G. Suciu, A. Vulpe, S. Halunga, O. F. G. Todoran, V. Suciu, Smart cities built on resilient Cloud Computing and secure Internet of Things, in: Proceedings of the 19th International Conference on Control Systems and Computer Science, IEEE Computer Society, Washington, DC, USA, 2013, pp. 513–518. doi:10.1109/CSCS.2013.58	28
S31	K. Velusamy, D. Venkitaramanan, S. K. Vasudevan, P. Periasamy, B. Arumugam, Internet of Things in cloud, Journal of Engineering and Applied Sciences 8 (9) (2013) 304–313	0
S32	D. Vouyioukas, A. Moralis, M. Sardis, D. Drakoulis, G. Labropoulos, S. Kyriazakos, D. Dres, EPIKOUROS – Virtualized platforms using heterogeneous sensor services in Cloud Computing environment, in: Proceedings of the 4th International Conference on Wireless Communications, Vehicular Technology, Information Theory and Aerospace and Electronic Systems, IEEE, USA, 2014, pp. 1–5. doi:10.1109/VITAE.2014.6934461	1
S33	Z. Wu, T. Itälä, T. T. C. Zhang, Y. Ji, M. Hämäläinen, Y. Liu, Gateway as a service: A Cloud Computing framework for Web of Things, in: Proceedings of the 19th International Conference on Telecommunications, IEEE, USA, 2012, pp. 1–6. doi:10.1109/ICTEL.2012.6221246	8
S34	J. Yan, S. Xin, Q. Liu, W. Xu, L. Yang, L. Fan, B. Chen, Q. Wang, Intelligent supply chain integration and management based on cloud of things, International Journal of Distributed Sensor Networks 2014. doi:10.1155/2014/624839	3
S35	J. Zhou, T. Leppanen, E. Harjula, M. Ylianttila, T. Ojala, C. Yu, H. Jin, CloudThings: A common architecture for integrating the Internet of Things with Cloud Computing, in: Proceedings of the 17th IEEE International Conference on Computer Supported Cooperative Work in Design, IEEE, USA, 2013, pp. 651–657. doi:10.1109/CSCWD.2013.6581037	32

Appendix B. Distribution of the selected primary studies over venues

Acronym	Venue name	Type	Studies
FiCloud	International Conference on Future Internet of Things and Cloud	Conference	S2, S5, S7, S16, S22
IMIS	International Conference on Innovative Mobile and Internet Services in Ubiquitous Computing	Conference	S11, S28
SOCA	IEEE International Conference on Service-Oriented Computing and Applications	Conference	S23
EMASC	International Workshop on Emerging Multimedia Applications and Services for Smart Cities	Workshop	S15
–	Sensors	Journal	S8
IDCS	International Conference on Internet and Distributed Computing Systems	Conference	S4
ICST	International Conference on Sensing Technology	Conference	S25
–	Cluster Computing	Journal	S27
CSCWD	International Conference on Computer Supported Cooperative Work in Design	Conference	S35
GIIS	Global Information Infrastructure Symposium	Conference	S10
MobiHealth	International ICST Conference on Wireless Mobile Communication and Healthcare	Conference	S12
CLOUD	IEEE International Conference on Cloud Computing	Conference	S19
VITAE	International Conference on Wireless Communications, Vehicular Technology, Information Theory and Aerospace and Electronic Systems	Conference	S32
MCC	ACM Mobile Cloud Computing Workshop	Workshop	S15
ICT	International Conference on Telecommunications	Conference	S33
–	International Journal of Distributed Sensor Networks	Journal	S34
FGCS	Future Generation Computer Systems	Journal	S14
–	Journal of Engineering and Applied Sciences	Journal	S31
iThings	IEEE International Conference on Internet of Things	Conference	S20
EuCNC	European Conference on Networks and Communications	Conference	S1
SCC	IEEE International Conference on Services Computing	Conference	S18
ICIT	IEEE International Conference on Industrial Technology	Conference	S17
SYkASC	International Symposium on Symbolic and Numeric Algorithms for Scientific Computing	Conference	S21
NCCA	IEEE Symposium on Network Cloud Computing and Applications	Conference	S24
PerCom	IEEE International Conference on Pervasive Computing and Communications Workshops	Workshop	S26
CSCS	International Conference on Control Systems and Computer Science	Conference	S30
ISSNIP	International Conference on Intelligent Sensors, Sensor Networks and Information Processing	Conference	S3
CloudCom	International Conference on Cloud Computing Technology and Science	Conference	S29
3PGCIC	International Conference on P2P, Parallel, Grid, Cloud and Internet Computing	Conference	S9

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