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Survey of agent-based cloud computing applications

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HIGHLIGHTS

- The paper reviews the set of applications for combining Multiagent Systems and Cloud Computing.
- A classification for Agents & Cloud Computing applications based on a Cloud Computing perspective is proposed.
- A vast review of the existing applications in the state of the art is provided and classified according to the proposed taxonomy.
- The article highlights the benefits for Agents (increased capabilities) and the Cloud (interoperability, autonomy, proactivity, etc.).
- An analysis of current challenges in merging both technological paradigms is provided.
- The paper also discusses how to face current Cloud Computing challenges.

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ABSTRACT

In the state of the art, there are very few studies on agent-based Cloud Computing. Nevertheless, this is an emerging trend and the number of studies and applications in this field is beginning to increase. Cloud Computing and Agents are complementary technologies. The features of Cloud Computing can provide advanced computational characteristics to multi-agent systems. In turn, the inclusion of agent systems in the core of the Cloud platform makes it possible to incorporate different functionalities, such as reasoning and learning capabilities. This study analyzes the emerging relationship between both distributed systems. Specifically, this study proposes a new classification from the point of view of Cloud Computing, based on the reference architecture proposed by the National Institute of Standards and Technology and the different responsibilities of each of the roles that participate in the Cloud Computing paradigm as identified in the architecture: Provider, Consumer, Broker, Carrier and Auditor.

1. Introduction

The technology industry and the scientific community have made great strides in recent years towards implementing the Cloud Computing (CC) paradigm. This has resulted in a rapid growth of both private and public platforms [1–4] aimed at providing innovative solutions that can resolve the current needs of the CC paradigm. There is no doubt that the general social approval of this paradigm [5] has in large part led to its quick development, in addition to the economic interests of large technology companies which have focused on advancing the purely technical aspects [6,7].

From an external point of view, a CC platform offers three well-known types of services (software, platform and infrastructure) [8], but today the literature already refers to Something as a Service (XaaS) [9–11], assuming that any type of computer service offered over the Internet can be of the Cloud type, which makes it possible to include new services such as FaaS containers (Function as a Service) [12], AaaS (Analytics as a Service) [13], or even HaaS (Human as a Service) [14]. The novelty that distinguishes this technology from previous technologies is its ability to offer any type of computing capacity as a service through the Internet.

The marketing model used in the CC paradigm is also innovative, as it is based on a pay-as-you-go concept [6], in which users must negotiate the terms of the Service Level Agreement (SLA) in order to access services [15]. Once this contract for computing goods has been established, both the users (through regular payments) and the CC system (by maintaining the requirements) are obligated to follow through with their agreement.

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The innovation of the underlying technology (virtualization, service farms, allocation resources, etc.), has moved up the spectrum to such a point that the quality of services is no more influenced by high user demand [16–18]. These new technological possibilities have led to the birth of a new concept called elasticity [19,20], which is based on the just-in-time production method [21], but applied to the production of Internet services.

In this context, the Theory of Agents and Multiagent Systems (MAS) [22] has been explored by the scientific community from the perspective of providing new models for the use and management of CC systems based on the distribution of responsibilities, flexibility and autonomy. However, joining both computational models (MAS and CC) is a great challenge, given the conceptual difference between them. A CC environment is characterized by the properties of its underlying infrastructure and the services (or computational capabilities) it provides to internet users. Those services consume the computational resources that the infrastructure supplies to the system. The main challenge in this context is maintaining the level of quality of service (QoS) when user demand is high. MAS, in turn, are distributed systems which coordinate agents for solving complex problems in complex environments. A MAS includes different levels of intelligence that provide self-adaptation capabilities, dynamism, proactivity and autonomy in decision making. However, a deep analysis of both approaches shows that a CC system can also be described as an open system characterized by its heterogeneity, dynamism and uncertainty. They operate in the type of environments in which MAS applications have already had a notable rate of success [23–25]. Hence, this article proposes a hypothesis that *the union of both models can result in a new method of building CC systems*. The application of MAS in CC environments allows for the inclusion of distinctive features that provide flexibility and responsiveness within a strategy aimed at satisfying the consumer. The use of MAS makes it possible to continue research in techniques, tools and methodologies that allow for intelligent characteristics such as autonomy or learning, to be incorporated into CC platforms. Likewise, the use of CC capabilities in a MAS makes it possible to expand its capacities notably thanks to the use of supercomputing techniques.

In fact, the concept of Agent-based cloud computing is becoming a common concept [26–29], in addition to other types of computing, such as agent-based computing, agent-based cloud computing, agent-based cloud search engine, negotiation agents and agent-based cloud commerce and, finally, agent-based cloud service composition. However, the state of the art analysis shows that no visible trend can be observed in the main areas of application, main advantages and disadvantages. Thus, this article reviews new tendencies that combine both paradigms (CC and MAS) through the in-depth study of current research. The goal of the analysis is twofold. First, to classify all the state-of-the-art studies and create groups with similar functionalities and requirements. Then, thanks to this classification, we propose a new taxonomy. The second objective is to identify any shortcomings, this constitutes a goal in the development of this type of agent-based CC platform, making it possible to identify the solution domain for the identified problems.

This work is organized as follows: the next section provides a description of the current methods for the classification of the literature on CC and MAS paradigms. Section 3 presents a review of the state-of-the-art grouped by a new taxonomy proposed in this work. Section 4 discusses the weakness and strengths of the current state of the art. Finally, the research work is concluded in Section 5.

2. Different approaches to classifying existing research

To develop a classification approach, it was necessary to accomplish an in-depth study of the state of the art, which currently includes many references to architectures, algorithms and applications. First, an initial analysis of the available information allowed us to establish two premises: (i) there are few researches that relate both computational paradigms; (ii) the results of the existing studies are promising, which is why they have drawn the attention of the scientific community.

The subsequent, deep and systematic analysis [30] of the state of the art in the most widespread, public databases (Elsevier, Scopus, Scholar, etc.) made it possible to make a scientific study of the works and authors. Thanks to this study it was then possible to search in less known sources (white papers, author websites, keywords, etc.). This process was followed by the elimination of duplicate or similar articles, selecting the most relevant ones in each area (citations, type of publication, results, etc.). Finally, a meta-analysis was carried out of all of them allowing to identify similarities, strengths and weaknesses.

The results of this analysis are presented throughout this research work; they have confirmed the initial premise: a lack of studies that would attempt to classify existing CC and MAS proposals [31,32]. The innovation of the present study lies in that it organizes existing CC and MAS research. In 2012, only Talia [11,29] has proposed a general and preliminary classification however, it does not follow any kind of methodology. Moreover, it is based on a limited number of references that existed at that time. The taxonomy proposed by Talia is developed from the perspective of MAS where existing groups can be grouped into two general categories: (i) MAS applications that use or are directly deployed in CC services (*Agents using cloud*); or (ii) CC environments that use agent technology to manage their resources (*Cloud using agents*).

The CC and MAS classification proposed by Talia is simple and general, which, in some ways is a positive feature. Nonetheless, our review of the current state-of-the-art research in CC and MAS has revealed that the main drawback of her classification is the difficulty of categorizing existing research into one of the two groups she defined. This is mainly due to the variety of the roles and the various applications from which the union of both technological approaches must be considered. This difficulty is evident in the group of Cloud-using agents, because MAS can act as intermediaries or form part of the internal architecture of the platforms. For this reason, we have concluded that the classification proposed by Talia is limited at a semantic level and as such does not allow for an accurate classification of existing research.

To meet the current requirements, a new taxonomy is proposed within the scope of this work, one with greater semantic strength and which approaches the problem from the perspective of CC, instead of the MAS perspective (as Talia proposed). In other words, an approach that considers the different actors involved in a computational architecture as complete and advanced as the CC one.

According to NIST [8], a CC system is a complex one and is part of an open environment composed of different technologies, users and economic interests [7] that give way to a new computational model, revolutionizing online services. Bearing in mind the existing technical limitations, complex architectures have been developed to coordinate different aspects for the achievement of common objectives. However, in our work, the reference architecture used as the basis is the one proposed by NIST [16] because it is neutral in terms of technology and it mainly concentrates on the interactions of the identified actors and their different responsibilities within the paradigm [33].

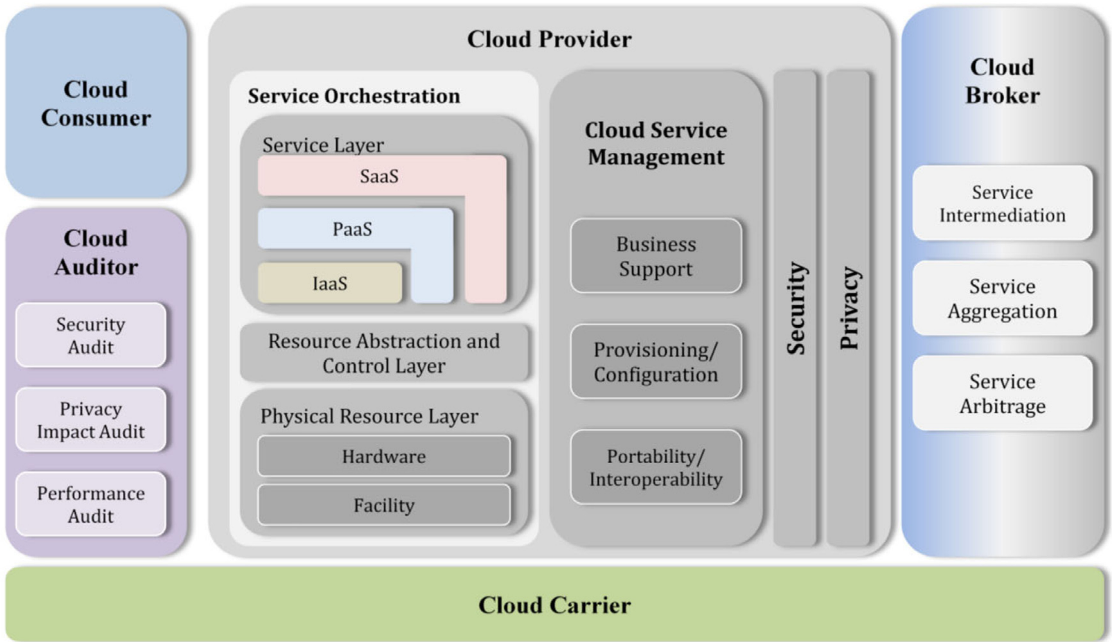

Fig. 1. Cloud architecture proposed by NIST [16], technologically neutral, it identifies five roles within the CC paradigm. These roles can be used to classify existing works in the state of the art.

The roles of the NIST reference architecture [16], shown in Fig. 1, are presented below:

- **Cloud consumer.** The end-user of the services provided by the CC platforms. It is the main stakeholder of the services. End-users need an SLA that can meet the standards of quality, obligations and service limits.
- **Cloud broker.** This agent acts as an intermediary between consumers and providers. It searches for and provides the services best suited to the consumer (quality, availability, etc.), regardless of the provider.
- **Cloud provider.** The role of this agent is (i) coordination, deployment and orchestration of the services which are provided to third parties and therefore require an underlying infrastructure. This role must also (ii) facilitate the management of the services offered through a support layer for marketing and business. Finally, it is responsible for (iii) security and (iv) privacy.
- **Cloud auditor.** This agent is capable of monitoring the service and ensures that the agreed-upon requirements specified in the SLA are being met.
- **Cloud carrier.** Provides connectivity between provider and consumer.

After identifying the different roles in the benchmark architecture, it is easy to notice that the semantic strength of these new roles is much greater than the previous classification proposed by Talia [11,29], because a comparison of both classifications shows that NIST distinguishes five roles while Talia only identifies two large groups (Agents using Cloud and Cloud using Agents). The cloud-using agent group most closely aligns with the role of the Cloud Consumer, while the cloud-using agent group would be associated with three different types of roles (Provider, Broker and Auditor). Therefore, with this taxonomy, it is possible to more adequately classify the current state-of-the-art MAS and CC applications. While NIST also identifies Cloud Carrier as a role, it is not included as a classification because it does not have a real functionality in either MAS or CC systems, and it is only considered as the entity in charge of transporting the information.

The use of this new taxonomy with more groups can be seen as more complex than Talia's classification. However, it is possible to affirm that both classifications, that proposed by Talia and the one that we proposed on the basis of the NIST architecture, have a similar complexity. Our research does not introduce any new roles, its innovation lies in the change of the classification perspective; from the perspective of the CC paradigm classification and not the MAS as Talia had proposed.

After having introduced the scope of reference for the proposed classification, the next section presents, analyzes and classifies current state-of-the-art research that combined MAS and CC platforms.

3. A cloud-based approach to classify the relationship between CC and MAS

This article suggests the use of the roles proposed by NIST [16] as a new taxonomy for classifying systems that combine MAS and CC. This approach was taken to review the state of the art, making it possible to associate studies and applications using MAS with the roles defined by NIST (excluding the Cloud carrier). This section presents the results of this study and the classification of the current works according to their practical abilities and applications. Fig. 2 shows a general overview, along with the main MAS applications in each of the groups.

3.1. *Cloud consumer*

The Cloud consumer role uses the abilities it receives from the CC computational service provider, as shown in Fig. 3. This group is directly aligned with the MAS-using Cloud group identified by Talia [29]. The high-level computational abilities provided by the CC platforms allow the MAS to expand its abilities by reducing calculation time, increasing distribution possibilities, and including the most advanced reasoning models.

Within this group, the three well-known services of CC can be identified (Infrastructure –IaaS–, Platform –PaaS– and Software –SaaS–).

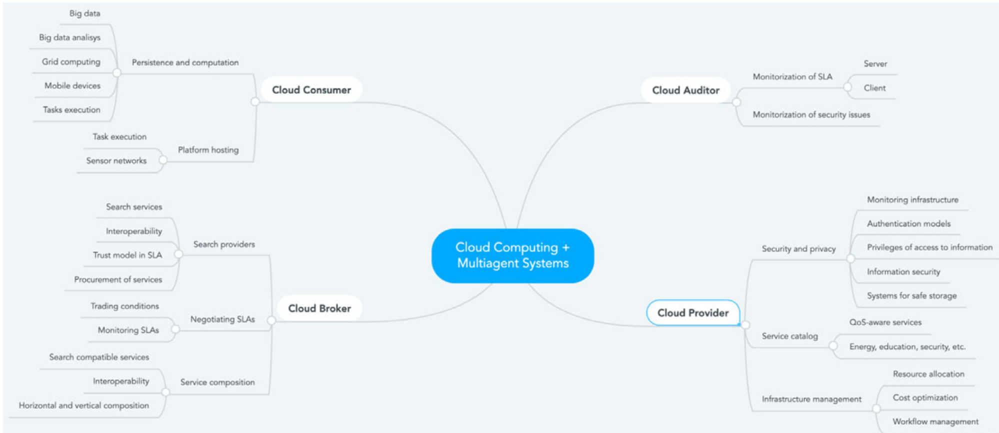

Fig. 2. The state of the art includes studies of MAS acting as part of the internal infrastructure (Cloud Provider), as well as the intermediary infrastructure, acting as Cloud auditor to check the QoS as well as the broker between the CC platform and the user. In the same way, CC provides advanced computational capabilities to different kind of MAS (Cloud Consumer).

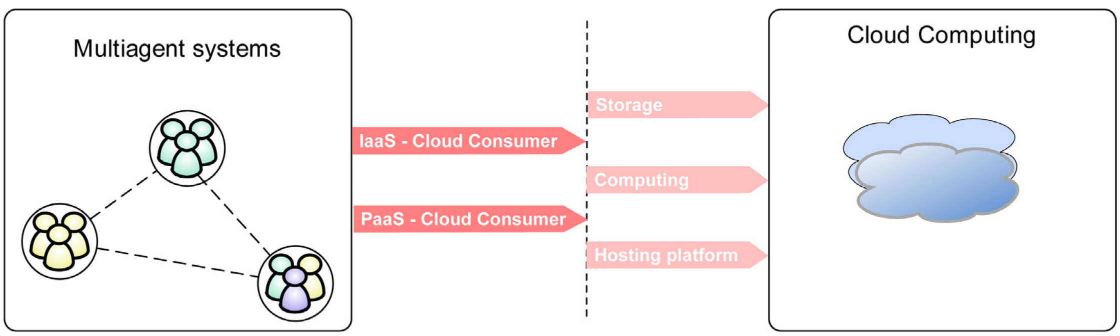

Fig. 3. MAS use mainly IaaS and PaaS services to increase their capabilities. There are no references to SaaS because it is the MAS that acts as the final application.

As explained below, this is a far-reaching field since the performance of MAS applications that use CC capabilities improves visibly. As a result, several MAS applications have been associated with IaaS and PaaS services, however, none have used SaaS, most likely because this kind of service is primarily aimed at end-users.

The following points present the main research in the state of the art, organized according to the services most commonly used by MAS:

- **Persistence and computing services.** These are the most well-known IaaS/PaaS services, within the framework of CC systems. In the field of MAS, they are applied to (i) allow for the storage and analysis of large volumes of data; (ii) eliminate the need to store information on mobile phones; and, finally, (iii) to run parallel tasks for different MAS agents.
  This field contains many diverse works that simply gather information on CC systems, such as information relative to transportation management [34], learning objects [35], storage of security vulnerabilities [36], etc. However, their main application in this field is related to the storage of large volumes of information and their subsequent analysis, falling within the framework of Big Data [44], which use persistence capabilities on CC platforms and require computational power. This field has a wide variety of works applied to different areas, such as market analysis [37,45], information fusion [46] and socio-sanitation [47,48].
  Although these applications use CC platforms, many continue using guidelines marked by the Grid Computing paradigm [18] or MapReduce algorithms [49] for analysis processes. Notable among existing studies is the CASE simulation tool proposed by Decraene et al. [50], the use of cluster Hadoop by Apache [51], the population simulation [52] and sensor networks [53,54] for making new approaches possible, such as Edge and Fog Computing [55]. Also, there are some interesting works on Social Network analytics using CC capabilities [56–59].
  There is also another type of CC application and agents in which the CC environment supplies the computational needs which could not otherwise be performed by the MAS, such as lightweight devices [36,60], or the analysis of large volumes of information using data mining techniques in different fields, such as bioinformatics [61], road traffic management [62], and information gathering and analysis [63].
  Finally, another application is the use of CC platforms to run tasks in parallel sequences. This makes it possible to find tools that allow agents to perform tasks by using planning algorithms [64]. There is another possibility, perhaps one of the most promising in the field since it involves a pioneering modification of the Moise+ methodology [38] known as ParaMoise [65]; it attempts to facilitate and improve the parallel execution of different agents that form a society or organization of intelligent agents using the computational characteristics of a CC environment.
- **Platform hosting services.** In addition to the previously identified computing and persistence services, another great capacity provided by a CC environment in the infrastructure is the ability to offer virtual machines with multiple on demand characteristics. These services have especially been used for agent-based simulation in a supercomputing environment [66,67] or on a specific simulation platform such as Repast HPC [40,41,68,69].

Table 1
Resume of Cloud user applications.

Main uses	Type of service used			Main applications	Descriptions
	SaaS	PaaS	IaaS		
Persistence and computation					
Big data services		X	X	Multiple applications [34,35]	CC systems can reduce calculation time by using Map Reduce computing models.
Mobile devices		X	X	In various contexts [36,37]	CC systems can increase the capability of mobile devices while also increasing battery life.
Task execution		X		Variant platform Moise+ [38,39]	The main advantage of the platform is its ability to run tasks in parallel within a planning system. The use of an HPC system considerably increased the efficiency and speed of the system. The main disadvantage is related to the complexity involved in planning tasks.
Platform hosting services					
Simulation environment		X	X	Repast HPC [40,41]	The simulation environment is deployed in an HPC platform to maximize its characteristics.
Sensor networks		X		Wireless Sensor Networks [42,43]	The infrastructures offered in this type of application are sensor networks. The advantage of these systems over traditional systems is the use of a dynamic high-performance layer for the management of the information that is exchanged in the network, and the ability to configure the network (topology, type, protocols, etc.).

Capabilities provided to MAS by CC platforms.

Finally, it should be noted that there is a growing interest in the scientific community to offer not only a traditional infrastructure within a CC paradigm (that is, high-performance computing), but also another type of infrastructure such as wireless sensor networks in which multiagent systems are very important [42,43,70].

Table 1 summarizes the main uses of the CC services in a MAS environment, including the type of services that are used and whether they can provide services to third parties.

In the previously presented works, it is evident that the use of CC services by MAS applications permits a substantial enhancement of MAS capabilities. Due to these expanded capabilities through the use of high-performance services, MAS may include more complex models of reasoning tasks using high performance computing environments, high availability services, etc. This allows to reduce the processing time and time constraints, which together with the extended storage capacity, make it possible to move one step forward in terms of the qualitative and quantitative features for MAS based applications.

3.2. Cloud broker

The Cloud broker role is the intermediary between providers and consumers and represents a fundamental role within the CC paradigm. The objective of the Cloud broker is to provide the consumer with computational services, independently of the provider, according to the service needs and in line with the consumer's requirements. As shown in Fig. 4, the Cloud broker is in contact with various providers simultaneously, keeping a record of the characteristics of the services offered by each provider and the corresponding price. This allows the consumer, as in this case, to authorize the Cloud broker to select the provider, thus obtaining the best quality and price for the services used by the consumer. In short, the main tasks of the Cloud broker are [71] intermediation, aggregation, and arbitrage.

Similar to a stock broker, the MAS in this type of environment must have certain qualities, including advanced information and service management skills and the ability to negotiate amidst uncertainty. The state of the art contains several studies whose proposals are advanced enough for use in real applications, since they are based on fields that have been widely studied in the recent years (search, composition of services, negotiation, etc.).

In a much-referenced study, Sim [28] presents an application of agents that act as intermediaries within a CC framework, and proposes a variety of groups. However, the present study is more general and realistic in proposing only three key subgroups:

- **Search for Cloud provider.** This group includes a set of searchers of CC service providers, that identify the most suitable services for end users through a reasoning model and a specific set of parameters determined by the end users, such as quality, price, availability, etc.
  Sim [28] proposed the Cloudle search engine, in which a MAS uses a web crawler to gather information on services and prices from providers. The search engine uses an ontology to relate the characteristics it gathers, enabling interoperability among the providers that use different terms to refer to the same service or characteristic. A similar approach was proposed by Parhi et al. [72]. There are other approaches for ranking and classifying cloud services [73]. The study of Alhamad et al. [15,71], is also along these lines, it proposes a trust model based on confidence and reputation, and applies different degrees of importance (weight) to the SLA parameters, thus serving as a reference for authors seeking a service provider. A similar model was proposed by More et al. [74], but in this case it includes a Case-Based Reasoner. There are also other approaches based on security criteria [75].
- **Negotiate SLA agreements.** MAS are included in this group, they provide automatic or semiautomatic hiring service management through making SLA agreements between the consumer and the provider. This frees the consumer from this task and allows for an agreement to be established with various providers at once [76]. One of the first agent-based negotiation models in this field, which was proposed by An et al. [77], uses a state machine that takes into account the phases of negotiation using only time and cost. Sim

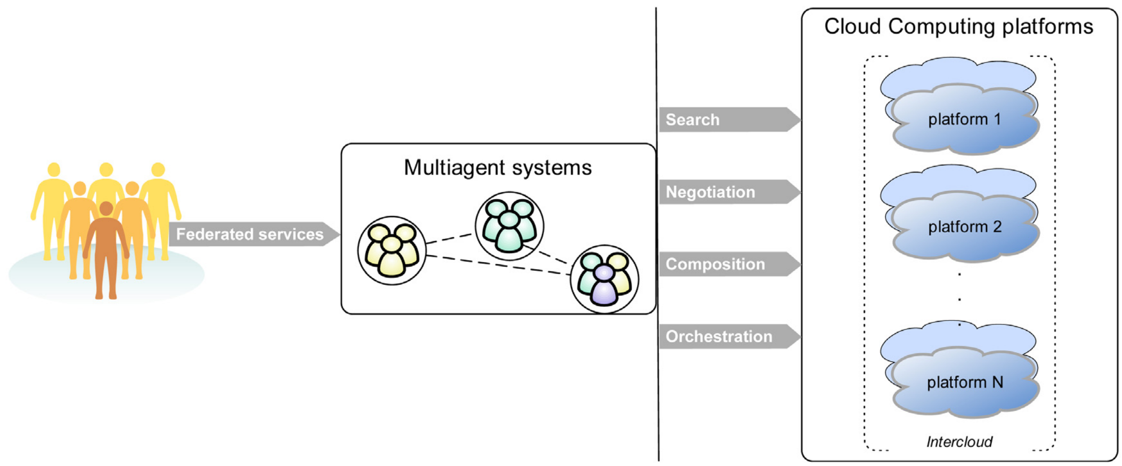

Fig. 4. The use of MAS benefits CC in that it facilitates interoperability among platforms.

also proposes a much more complex negotiation model [28, 78] which makes agreements between various consumers and providers on the basis of a negotiation strategy. This model considers aspects such as time, bargaining, incomplete information and cost estimate. Cloud Agency [79] is another notable study, developed within the scope of the FP7 mOSAIC project [80] that, as with Cloudle, is based on an ontology that facilitates the semantic interoperability between platforms and includes a MAS to perform a negotiation and monitoring of provided services. It enables renegotiation in the case a consumer or a provider need change of services. Finally, there are other models, which are especially designed for their application in lightweight devices [39].

- **Service composition.** Refers to the composition of CC services that give way to a single, more complex service, provided by one or various providers simultaneously. Various authors refer to such a composition of services as Cloud Manufacturing [81,82]. The composition of services in CC can be viewed from two different perspectives [83]: (i) horizontal, which refers to heterogeneous services from multiple providers; and (ii) vertical, which refers to the composition of homogeneous services aimed at increasing service capacity at a certain point in time.
  As for existing applications, Sim [28] proposes an automatic vertical composition service based on FSCNP (Focused Selection Contract Net Protocol) and a previously established service compatibility table, for automatic service selection. Thus, if a CC platform cannot accept the agreed-upon SLA, another service with the same characteristics can be selected. The same author has another model [84] that develops a MAS for vertical service composition in an ontology that provides interoperability, and a composition model based on Petri networks, both of which have been widely used in previous computing paradigms [78].

Table 2 presents a summary of the main applications in the current state of the art which fall within the Cloud broker group of the proposed classification.

The combination of these three components (in addition to the multi-cloud authentication [86]) bring us closer to one of the most significant objectives pursued within the framework of research on CC systems: federation [87], which consists in the ability of the same consumer to work with various providers simultaneously and transparently, and even dynamically being able to modify the contractual agreement with each service provider. A notable work among the several that can be found within the framework of federated CC systems, is the one provided by Singh et Malhotra [88], who propose a model based on intelligent agents that provides infrastructure services. Chen et al. [89] propose an interactive model at the infrastructure level between CC platforms, based on mobile agents. A much more advanced approach, which was tested in a real environment and presented by Venticinque et al. [90], permits the provision, management, execution and reconfiguration of CC infrastructure services provided by third parties. Two other similar models, adaptable to any type of service, not just infrastructure, were developed in parallel by Calheiros et al. [91] and Fan et al. [92]. In this case, the services migrate between CC environments with the aim of satisfying the SLA agreements agreed to by the consumers. Another perspective is the possibility of distributing tasks simultaneously among various environments, as proposed by Palmieri et al. [93], who configured a highly scalable model. Finally, SERA [94] is an alternative approach in which the service distribution model is based on the negotiation with various CC environments, using an ontological inference engine.

To conclude this second group of works in which MAS act as intermediaries for the existing business relationship between the end user and the CC platform, we can observe the strong capabilities of MAS in selecting services, such as automated and simultaneous negotiation of quality of service agreements with different providers; in fact, the state of the art shows an incipient, rapid growth in the use of MAS for Cloud manufacturing services, for example in [95] and in surveys such as [96] the key characteristics and applications of MAS-based manufacturing services are described, and its relationship with Industry 4.0 [97,98]. However, the problem in this field is the incompatibility between platforms, which is usually the result of the providers themselves (lock in). As a result, these studies must implement interoperability models based on uncertain and complex information of the data used in the negotiation and search mechanisms, as well as the complexity of the interaction with multiple heterogeneous CC systems. Nevertheless, the use of agents facilitates the task of service composition offered by different CC providers, which itself constitutes a relevant contribution toward the objective of the federation and interoperability of CC environments, known as InterCloud [86,99,100].

3.3. Cloud provider

The Cloud provider role is responsible for providing services to third parties. The tasks assigned to this role are fundamentally: control, monitoring, resource allocation, service orchestration and the management of the underlying infrastructure, as shown in

Table 2
Applications of MAS as Cloud brokers.

Main uses	Applications	Descriptions
Search for providers		
Automatic search for services	[28]	This type of application is notable for its ability to automatically search and compare CC services to determine which is the best.
Trust model for SLA	[15,71]	Different approaches are implemented based on multifaceted models, trust, reputation, etc.
Based on security	[75]	Notable among existing applications is Cloudle, which includes an advanced system for CC service recovery, and uses ontologies to compare similar services.
Negotiation of SLA agreements		
Negotiate conditions	[78,79]	With this approach it is possible to automatically negotiate the characteristics of a service.
Monitor agreements	[28]	
Composition of services		
Horizontal composition	[84,85]	Finally, with regard to composition of services, the state of the art contains few applications focused on horizontal composition, and none at all focused on vertical composition. All existing services are based on network models (FSCNP, PETRI, etc.), the most complete being the proposal provided by Gutierrez-Garcia et Sim [84], which permits interoperability through the automatic selection of services and the use of a compatibility table.
Vertical composition	See references of the Cloud user	

When a MAS acts as a Cloud broker it is mainly in charge of searching for and composing different kinds of services.

Fig. 5. This makes it necessary to ensure both the privacy and security of the environment and the information it manages, in addition to ensuring compliance with the SLA agreements.

The most important studies are presented below, according to the following groups:

- **Security and privacy.** High performance computational environments, such as CC environments, are often subject to attacks [101]. Therefore, security in the CC platform is considered at both internal and external levels. At the internal level, it is a means of ensuring that the underlying infrastructure functions correctly. At the external level, it emphasizes external communication and ensures that the environment itself is not compromised. Works focused on the external level are primarily related to user authentication in the CC environment, which is a complex task, given that the authentication must be performed simultaneously in different services and levels with multiple components. Some of the examples include: ABAC [102], a client-side authentication model [103] and the study proposed by Habiba et al. [104], in which MAS is based on access policies that give privileged access to information. At the internal level there are some initial studies considering various aspects, such as data privacy [105], platform monitoring [106] and the security of the hardware infrastructure (real or virtual) [107,108]. However, more advanced studies are related to secure data storage, including CloudZone [109], a notable storage project that uses MAS to ensure privacy, information access and other security parameters for storage. The same authors designed the Prometheus methodology [109] closely related to this project, which aims to ensure security in the storage of data in CC environments. There are other studies with different approaches, such as those proposed by Govinda et Sathiyamoorthy [110] and Uddin et al. [111], which attempt to ensure information security through data masking. The final relevant studies concern a multilayer security model, based on agents, for access to persistent information [112] and data security based on active data bundles [113].
- **Offer services.** The CC paradigm is oriented at offering computational services independently of type or complexity [75]. In this field, services are generated through MAS applied to office environments [114], efficient energy management [115], security [36], e-learning [35], etc. There are very different reasons for which the use of agents as a service, AaaS [116] is proposed.
However, when dealing with services within the scope of the CC paradigm, it is necessary to comply with the restrictions and objectives agreed upon with the consumer through the specific SLA agreements, implying that the services must be monitored in order to meet the required level of quality. To this end, the concept of quality of Service aware (QoS-aware) was adopted [117]. In this field, MAS have the potential for extensive application, which has led to many related works in recent years [107]. Although in their initial stage, these studies only partially approach the problem and try to meet the demands for quality of service. Beyond monitoring, an approach must be able to manage the underlying infrastructure (computational resources), which is what provides, in practice, the computational strength required to satisfy the agreements (firstly), or the information needed to know whether new agreements can be established, taking instantaneous demand into account (lastly).
- **Management of the underlying infrastructure.** Managing the underlying infrastructure is one of the most complicated tasks due to the uncertain, dynamic and heterogeneous nature of a CC environment in which there are different physical machines, virtualization systems, network topologies, storage models and so on, in addition to the complexity of the existing hardware and software.
There are a limited number of studies in which MAS provides either centralized [118–120] or distributed [119,121–123] management of resources according to SLA agreements, or assigns resources to services following a workflow model [121]. There is also research in CC platform monitoring [8]. With regards to the allocation of resources, the MASCloud architecture uses MAS to optimize costs within the framework of the CC paradigm [124], and the +Cloud architecture that uses MAS based models to monitor and control a CC platform [119,125]. Finally, there are also approaches that try to allocate resources in real time [117,126].

Table 3 presents a summary of the current state of the art concerning MAS and CC applications that incorporate the role of Cloud Provider.

With the exception of studies related to system security, the number of studies in which MAS assume the role of Cloud Provider are fewer than in the case of previous roles. Therefore, the main contribution of MAS is related to data security and privacy, due to the ability of the agents to monitor, reason and respond proactively to changes in the environment. Nevertheless,

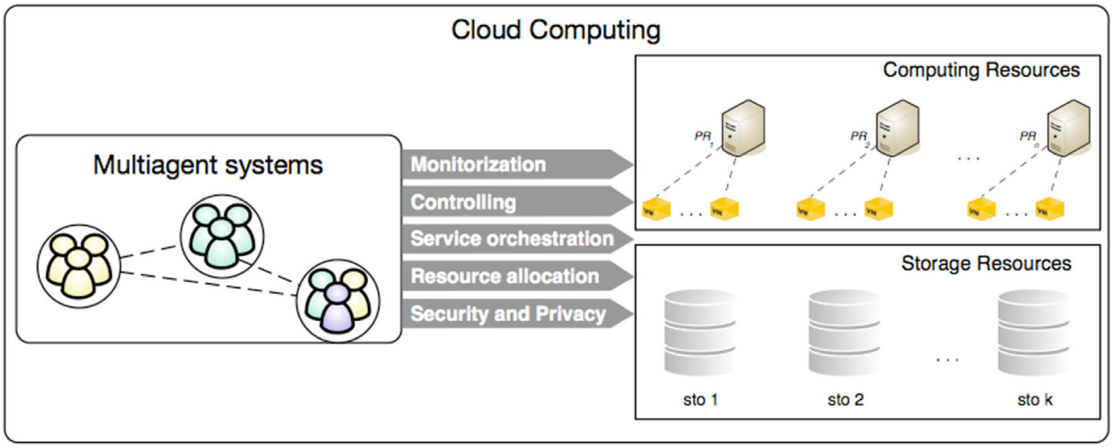

Fig. 5. MAS permits to audit SLA and security of CC services.

Table 3
Applications of MAS as Cloud provider.

Main uses	Applications	Description
Security and privacy		
Authentication Privacy Monitoring Infrastructure security Safe storage	[53,102,127] [104] [106] [107] [109]	There has been more research done in security than in any other field for applications that combine CC and MAS. This problem has been studied from multiple points of view, most notably the highly complex process of authentication, due to the distributed nature of the environment. Included among these studies is the approach proposed by Moghaddam *et al.* [102] in which the authentication and information access model is based on an access policy. Important research has also been carried out in the field of safe storage, the most significant undoubtedly being the Prometheus methodology, which is supported on the CloudZone platform [109] to provide safe storage.
Services offered		
Office environment Energy management Security E-learning	[114] [115] [36] [35]	The state of the art includes various applications that offer Cloud services through the use of MAS. However, these applications do not include CC services, since they do not track quality of service (QoS-aware), leading to the conclusion that they are simple computational services deployed on a CC platform
Manage underlying infrastructure		
Manage resources	[119,120, 128]	Notable studies in these subgroups include those that allow the distribution of computational resources (centralized and distributed), as well as those that monitor and control the CC environment itself.
Monitor and control	[119,121, 124]	Notable among this research is the +Cloud platform proposed by De la Prieta *et al.* [119], an agent-based CC platform that uses virtual organizations and dynamic and adaptive algorithms to automatically monitor and control a CC platform.

Applications of MAS as a Cloud provider is focused on Security and allocation of resources.

it is difficult to find MAS to control the underlying infrastructure, the orchestration of services and allocation of computational resources. As previously established, the state of the art only contains promising and incipient studies related to the quality of service or provision of computational resources.

The low presence of research is undoubtedly due to the heterogeneity and complexity of the underlying technologies used. Despite these difficulties, research of MAS in this area has given way to much more complex CC environments with intelligent capabilities, which could be provided by MAS. This is because a CC platform is an open environment due to its dynamic nature, heterogeneity and uncertainty; there is no doubt that a MAS application in this context would contribute relevant characteristics such as the automatic detection of errors, monitoring of services and advanced operations, automatic negotiation of quality of service, interoperability, dynamic planning, efficient management of resources, learning, etc.

3.4. Cloud auditor

Finally, the Cloud auditor is the last role whose responsibilities include ensuring, from an external and objective point of view, that the SLA agreements are met satisfactorily, as shown in Fig. 6. This role, where MAS have the least number of examples of their applications, is found in only two noteworthy references: (i) the FOSII architecture [129], in which a multiagent architecture automatically detects violations in the SLA agreements; and (ii) the study presented by Ramaswamy et al. [130] in which the client-side MAS detects possible violations in the SLA agreements; and, finally, a study focus on security detection [131].

4. Analysis of open issues and opportunities

After analyzing existing research among both computational paradigms, one can easily conclude that the joint use of MAS in CC environments remains incipient. However, the variety of presented research shows that there is much interest, among the scientific community, in the development of techniques and tools that combine the advantages of both technological environments.

In general terms, when MAS assumes the role of a Cloud Consumer (Agents using Cloud in Talia's classification [29]), the CC environment offers high performance technology; it is highly efficient and has scalable availability [29]. MAS capabilities are notably increased thanks to the use of the main platform and infrastructure services (persistence, computation, platform hosting, etc.) which facilitates the application of MAS in a large variety of complex scenarios (mobile applications, simulations, parallelization of tasks, etc.).

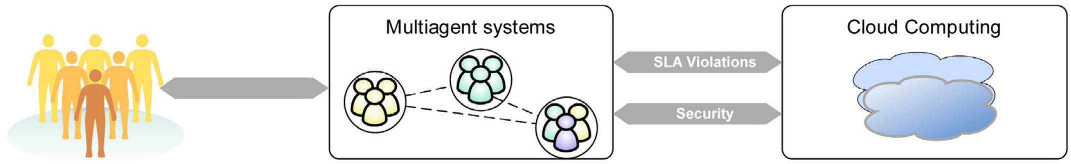

Fig. 6. MAS can improve the management of CC by incorporating intelligence to its internal algorithms: services orchestration, allocation of resources, security, etc.

When they act as intermediaries, either Auditor or Broker (Clouds using Agents in Talia's classification [29]) their many advantages are also evident. In this case however, the advantages are observed from the viewpoint of CC platforms, due to the ability of MAS to interact with complex and heterogeneous systems and perform advanced tasks (orchestration, negotiation, searching, etc.). In fact, MAS are able to use different strategies and mechanisms such as ontologies, web service exchange formats, automatic adaptation, etc. Finally, when MAS act as a Cloud Provider within a cloud platform (also, Clouds using Agents in Talia's classification [29]), it is possible to identify the numerous benefits that CC platforms obtained from the integration of MAS characteristics, such as autonomy, distributed decision process, social skills, proactivity and learning, which are opening the way to new generations of platforms with vast capabilities in monitoring, allocation of resources, etc.

After analyzing these groups, it is possible to observe the different strengths derived from the union of both MAS and CC. The advantages of overcoming some of the obstacles that currently hinder the development of CC systems will now be analyzed.

Firstly, when the Cloud Provider group uses MAS to monitor and manage computational resources in a CC system, two main advantages are evident: availability, and the distribution of computational needs. The analysis of the existing studies in this field [132,133], leads to the conclusion that research efforts are directed towards the search for energy efficient solutions in the distribution of computational resources in CC environments. This makes it possible to ensure compliance with the QoS levels agreed on with the user through the SLA agreements, while also identifying energy consumption and ensuring a balanced use of existing computational resources [7]. A design model based on MAS applies a distributed approach to resolve the problem, setting it completely apart from current research in the state of the art. To begin, this approach has advantages with regard to its availability, since there is no single component responsible for the distribution of resources; instead, the system reorganizes itself in terms of the individual adaptation of its components. Traditional research is centralized and the state-of-the-art shows that the execution of algorithms to assign computational resources is a complex task that requires high levels of processing power and computational time. However, a model based on MAS shows various advantages such as (i) the distribution of computational needs among different nodes; (ii) a smaller range of values to consider, since each node must only consider the data related to its own resources and does not require a global understanding of the platform; and, finally, (iii) each node can apply a partial solution to the problem autonomously, thus eliminating the need for a global level of coordination on the platform.

Secondly, a CC environment has several standards, models, protocols, etc., most of which are proprietary, giving way to a clear problem of lock-in, which makes it difficult to achieve interoperability between platforms. However, from the agent perspective, considering the CC system as an open system, it would be possible to allow external agents to access the system and provide certain functionalities in exchange for their acceptance and compliance with a set of rules that will guarantee the stability and survival of the system. This type of architecture design is satisfactory and widely accepted within the MAS framework; it opens a new path for research focused on solving the current interoperability problem among Cloud Computing platforms. Along these lines, the design of a CC platform that follows an open architecture model and is based on its basic functionalities (roles, objectives, norms, etc.) makes it possible to define a design based on an analysis of the responsibilities and needs of each of the actors participating in the architecture. This design approach allows to incorporate advanced models, new techniques and external tools, which act as internal components of the architecture but must meet the needs and requirements of the other members. Within the scope of the proposed taxonomy, any role (Consumer, Broker, Auditor and Provider) can be clearly designed as an external role. Concrete agents, which play those roles, can evolve into new models. It is worth noting that the many references within the Cloud Broker group are an advantage from the CC platform, derived from using a MAS based architecture model, which facilitates interaction and deals with complex negotiations.

Thirdly, on a technical level, a MAS based design can ensure independence among the software strata, including the execution of actions on the basis of the decisions made. In a CC environment, this separation of responsibilities is particularly important since current platforms are highly heterogeneous and dependent on the technological environment (virtualization tools, work balancing, distributed file systems, etc.). This dependency represents a great limitation and hinders evolution, since a change in any of the hardware or software components requires a change in the algorithms and techniques that facilitate the proper operation and elasticity of services. A design based on MAS results in a high-level model, making it possible to completely abstract the design of the subsequent implementation. A MAS methodology, such as that of Gaia [134], among others [135], allows to create a software system that uses high-level concepts such as roles, tasks, interactions, services, etc. Thanks to this kind of methodology, we can simplify the design of any software system, in particular a CC one. Besides, thanks to the concept of open-MAS methodologies [105], the authors of [106] include the concept of environment; they allow for communication with the environment via ports that abstract the underlying complexity.

Finally, there is no doubt that a change in the capabilities offered by the underlying technology will also make it necessary to modify the proposed reasoning models, as with any traditional design. However, in these cases, MAS also offer a satisfactory solution. In a system such as the one proposed here, the agents that form part of the society carry out one or several specific roles. Each role abstractly defines the objectives, responsibilities and privileges of the individual. Thanks to this high-level definition, if the technology develops new functionalities in the future, the task of adapting them to the system would be simple; it would consist in modifying only the individuals that perform specific tasks, instead of having to change the society as a whole.

In short, the use of an approach such as the one proposed in this study makes it possible to model novel CC platforms based on MAS; in other words, an Agent-based Cloud platform. This new approach could extend the scope of application of the CC paradigm, increasing its capabilities and maximizing the advantages derived from its use. Not only would there be external

Table 4
Applications of MAS under the frame of CC.

Main uses	Internal level			External level				
	Monitor.	Config.	Security privacy	Alloca. resources	Negotiat. SLA	Offered services.	Service compos.	QoS audit
Search for provider								
Search for services	X	X	X			X	X	
Interoperability					X	X		
SLA trust model	X	X			X		X	
Enlist services		X	X		X		X	
SLA agreements negotiation								
Negotiation conditions		X				X		
Monitoring agreements	X	X	X		X		X	
Composition of services								
Search for compatible services						X	X	
Interoperability	X		X			X		
Horizontal and vertical composition	X	X	X			X		
Security and privacy								
Infrastructure monitoring	X				X			X
Authentication models			X				X	
Access to privileges			X				X	
Information security			X			X		X
Safe storage			X			X		
Service offer								
Quality aware services	X	X			X			X
Offer services						X		
Infrastructure management								
Resources management	X				X			X
Cost optimization		X		X	X			X
Workflow management				X		X		

The relationship between MAS and Cloud environments is very fruitful, with many examples in different areas.

advantages from the application of a MAS (negotiation, interaction, etc.), but there would also be advantages for the internal characteristics of the platform (service management, resource allocation, etc.).

Table 4 considers the advantages from the perspective of all roles participating in the architecture, which ultimately contribute to the improvement of services and capabilities that can be offered to the end user.

To conclude this analysis, an effective integration of MAS and CC platforms will, nevertheless, require the use of the latest innovations within the scope of MAS. To this end, organizational models and modern software development methodologies have been aligned with engineering models. This approach will make it possible to develop new platforms that ensure stable and scalable high-quality services. Furthermore, modelling a CC environment using societies of intelligent agents permits for the dynamic and automatic adaptation of the system according to the environmental conditions, thus simplifying the dynamic adaption of the whole platform and not just the individual users. Likewise, it will also permit for the inclusion of specialized agents with advanced reasoning capabilities for system modelling. This design model is considered adequate, since it permits for the division of the different responsibilities of a CC system among groups of agents with specific objectives and the reasoning models are suitable for resolving the problems that CC systems deal with.

5. Conclusions

This study has explored an incipient but promising relationship that currently exists between MAS and the new CC paradigm. Within the framework of this study, we have systematically looked at the vast majority of existing research in the state of the art, thanks to which it has been possible to clearly identify the areas in which the scientific community is most active. In addition, the works that are most relevant to each of the areas have been identified, providing an accurate and insightful view of the current reality which will support future research in this area. This study has allowed us to view the problem from many different perspectives which made it possible to propose a new taxonomy for the classification of the current and future works that address this topic.

In conclusion, this study has resulted in the following contributions toward research in this area, which can be summarized as follows:

- A detailed analysis of a large part of the researches that address CC and MAS paradigms. Although similar works had been proposed in the past [11,29,31,32], all of them lack the breadth and rigor of the methodological and systematic state of the art analysis carried out in this research work.
- The study has identified a set of fields (shown in Table 4) of application to which MAS can contribute through the development of CC systems.
- The scope of this study also included an analysis of existing classifications and determined that those with an agent-based approach are not powerful enough semantically to group existing studies. As a result, we have proposed a new classification that provides the semantic strength required to classify existing and future studies. This is achieved by looking at the problem from the perspective of the paradigm, contemplating the various roles that can participate in a CC system. This new approach simplifies the classification and provides greater semantic capability by allowing the Cloud using agents role [29] to be divided according to the task that they develop (Provider, Broker or Auditor).
- Finally, this study has analyzed the advantages derived from the application of MAS within the framework of CC systems. All the previously defined classification groups benefited from the application of MAS, including increased autonomy, proactivity and learning ability, which also make it easier to face today's challenges.

In conclusion, the lessons learned from this research work will enable us to implement new systems based on organizational MAS that will allow us to expand the capabilities of CC systems by providing advanced capabilities derived from intelligent distributed systems. In fact, the preliminary results have already been obtained by applying virtual organizations of MAS to resource allocation in CC systems [125].

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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