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RESEARCH ARTICLE

Mobile ad hoc cloud: A survey

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ABSTRACT

The unabated flurry of research activities to augment various mobile devices in terms of compute-intensive task execution by leveraging heterogeneous resources of available devices in the local vicinity has created a new research domain called mobile ad hoc cloud (MAC) or mobile cloud. It is a new type of mobile cloud computing (MCC). MAC is deemed to be a candidate blueprint for future compute-intensive applications with the aim of delivering high functionalities and rich impressive experience to mobile users. However, MAC is yet in its infancy, and a comprehensive survey of the domain is still lacking. In this paper, we survey the state-of-the-art research efforts carried out in the MAC domain. We analyze several problems inhibiting the adoption of MAC and review corresponding solutions by devising a taxonomy. Moreover, MAC roots are analyzed and taxonomized as architectural components, applications, objectives, characteristics, execution model, scheduling type, formation technologies, and node types. The similarities and differences among existing proposed solutions by highlighting the advantages and disadvantages are also investigated. We also compare the literature based on objectives. Furthermore, our study advocates that the problems stem from the intrinsic characteristics of MAC by identifying several new principles. Lastly, several open research challenges such as incentives, heterogeneity-ware task allocation, mobility, minimal data exchange, and security and privacy are presented as future research directions. Copyright © 2016 John Wiley & Sons, Ltd.

KEYWORDS
mobile cloud computing; mobile ad hoc cloud; cloudlets; offloading; mobile cloud; ad hoc cloudlets

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1. INTRODUCTION

With the bustle advancements and increasing miniaturization in computing technologies, mobile devices' capabilities have significantly increased over the years [1]. Concurrently, mobile applications have also become more sophisticated and complex in nature [2]. Despite unceasing development in the competencies, mobile devices have still limitations in terms of memory, processing power, network bandwidth, and battery lifetime compared with desktop computer systems [3]. These limitations hinder the uninterrupted execution of compute-intensive applications such as high-definition gaming and video streaming. Some of these deficiencies can be overwhelmed by enabling the mobile devices to leverage the services and resources furnished by cloud computing [4]. This approach of leveraging cloud resources and services for enhancing the capabilities of mobile devices is referred as MCC [5]. In MCC, mobile devices migrate their data processing, application execution, and data storage tasks to the cloud, and only the results are displayed back [6]. It enhances the capabilities of mobile devices to run compute-intensive applications. However, relying on the cloud server for application execution is not always feasible because of weak, intermittent network connectivity or no Internet availability at all [7].

In such situations, mobile ad hoc cloud (MAC) comes and plays its role to run the compute-intensive applications [8]. To effectively execute such applications, MAC exploits share resources of a group of mobile devices, which usually have some common objectives to achieve [9].

Despite a number of these research efforts, the research in MAC is still in its infancy. There is a need to conduct the research for enabling optimal task partitioning and offloading, efficient resource management, fault tolerance, heterogeneity-aware task allocation, mobility management, authentication, authorization, and ensuring the privacy of personal data on mobile devices.

Although several surveys have studied various aspects of MCC [10–17], a new type of MCC called MAC has not been surveyed. To the best of our knowledge, this is the first survey on MAC. The contributions of the survey are as follows: (i) We survey the state-of-the-art research efforts carried out in the domain of MAC; (ii) we analyze several problems inhibiting the adoption of MAC and review corresponding solutions by devising a taxonomy; (iii) we compare the existing proposed solutions by highlighting the advantages and disadvantages; (iv) we devise another taxonomy based on conducted survey of MAC; (v) we compare the literature based on objectives; (vi) we identify and discuss the key principles for successful deployment of MAC; and finally, (vii) we present open challenges as future research directions.

The remainder of the paper is organized as follows: Section 2 briefly describes the background of MAC. The significance and motivation of the MAC are highlighted in Section 3. Section 4 presents the state-of-the-art research efforts carried out in the domain of MAC. The devised taxonomy of MAC is elucidated in Section 5. Section 6 identifies and elaborates the key principles for successful deployment of MAC. Open research issues and challenges are discussed in Section 7. Section 8 concludes the paper.

2. BACKGROUND

This section briefly provides the necessary background information related to cloud computing, MCC, and MAC. The purpose is to familiarize the readers with the emerging computing paradigms.

2.1. Cloud computing

Cloud computing is a paradigm for provisioning ubiquitous, convenient, and on-demand network access to a shared pool of configured computing resources (e.g., networks, servers, storage, applications, and services) that can be rapidly provisioned and released with minimal management effort or service provider interaction, as National Institute of Standards and Technology [18] stated. Figure 1 depicts a typical environment of cloud computing. Cloud computing provides users with different capabilities to store and process their data in third-party data centers [19,20]. It focuses on optimizing the effectiveness of the dynamically shared resources in an on-demand manner [21]. For instance, cloud computing resources allocated to North American users during their working hours with a specific application (e.g., a web server) can be reallocated to their European counterparts during respective job timings with a different application (e.g., email).

2.2. Mobile cloud computing

Mobile cloud computing has emerged as a distributed computing paradigm that enables the execution of compute-intensive applications by augmenting the resources of constrained mobile devices [22]. Figure 2 articulates a simplified environment of MCC. MCC alleviates resource limitations of mobile devices by using various augmentation strategies, such as storage augmentation, energy augmentation, screen augmentation, and application processing augmentation [23]. It has three types of computing model to augment the resources of mobile devices: (i) remote cloud; (ii) server-based cloudlet; and (iii) mobile ad-hoc cloudlet [11,24]. In the first model, mobile devices act as a thin client while accessing the cloud through wireless technologies [25]. This model can provide many benefits such as low computation time, high computation power, and on-demand availability of resources [26,27]. However, the application suffers from high latency, jitter, and packet losses [26]. In the second case, mobile devices offload their computations to the

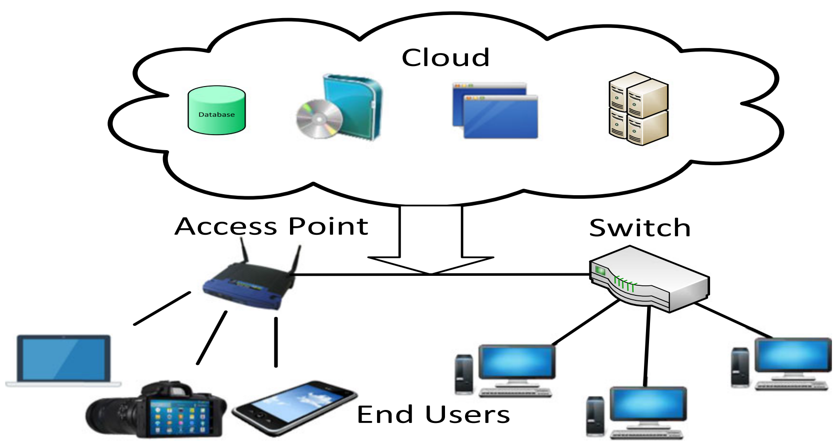

Figure 1. Illustration of cloud computing.

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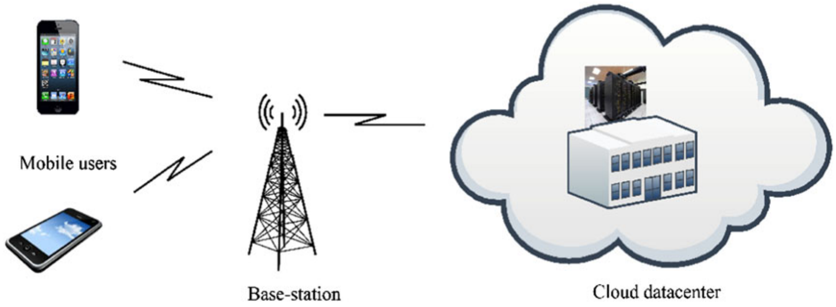

Figure 2. A simplified example of mobile cloud computing [10].

locally available resource-rich device such as servers. In the absence of any server-based cloudlet, the mobile devices share their resources to enable the execution of compute-intensive applications. This computing model is known as MAC [28].

2.3. Mobile ad hoc cloud or Mobile cloud

Mobile ad hoc cloud is a group of mobile devices in the vicinity willing to share their resources with each other by taking some incentives as shown in Figure 3. MAC is a new type of MCC. It is usually deployed over mobile ad hoc networks [29], which allows the execution of compute-intensive applications by leveraging the resources of other mobile devices [9]. As an alternative solution, MAC is an emerging paradigm that mitigates several bottlenecks of server-based cloudlet such as longer delay and low throughput. Moreover, MAC offers a viable solution for a mobile device to execute an application when there is no or weak wireless Internet connection to the remote cloud or the nearby server-based cloudlet is not available. In MAC, mobile devices are expected to manage the cloud, authenticate the users, monitor the resources, and schedule the tasks besides executing the application. Such additional functionalities consume mobile device energy and processor cycles. Finally, local stationary devices such as personal computers and set-top boxes can also become members of MAC [30].

3. MOTIVATIONAL SCENARIO FOR MOBILE AD HOC CLOUD

The recent advancements in MCC have cemented the way toward a new computing paradigm called MAC. MAC enables the users to run their real-time compute-intensive tasks by leveraging the services and resources of available mobile devices in the local vicinity. To improve the performance of MAC, real-time compute-intensive tasks are partitioned and allocated to participating devices.

The motivation for MAC can be expressed through the example of real-time conference attendance [30], where a mobile user takes the snapshots of the participants and matches the captured faces against the stored photos, with the aim of figuring out that who is attending which session. Moreover, for the logistics planning, conference organizers want to get updates of the attendees in various sessions. In this scenario, the mobile user may not have sufficient resources such as communication bandwidth and power to perform this task on his individual device. Therefore, he decided to form a MAC to perform the specified task in real time. Let us assume that there are

Figure 3. A typical mobile ad hoc cloud environment.

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50 attendees in each session, and 10 of them are willing to participate in MAC. Let us assume that the following steps are required to accomplish the task with or without using MAC: (i) Detect the number of faces in the snapshot and crop a small image for each face; (ii) submit each face separately for recognition; and (iii) return the list of attendees to the user. Let us assume that the first step requires 15 s, the second step requires 10 s for each face, and the third step requires 6 s. The mobile user would take $15 + 10 * 50 + 6 = 521$ s without using MAC to accomplish the task. On the other hand, the task will be divided into 10 MAC contributors (provider nodes), so the time will be reduced significantly, because task two can be distributed among 10 providers. If we assume that the overhead of communication with all the provider nodes is 3 s, then the total time with MAC would be $15 + 3 + 10 * 5 + 6 = 74$ s.

This scenario clearly demonstrates how the adoption of MAC can enable real-time execution of compute-intensive tasks. However, there are a number of challenges that remained to be addressed. The discovery of mobile devices to form MAC is the prime concern which requires attention. Moreover, optimal task partitioning and offloading, efficient resource management, fault tolerance, heterogeneity-aware task allocation, mobility management, authentication, authorization, and ensuring the privacy of personal data on mobile devices are other common challenges that need to be addressed.

4. STATE-OF-THE-ART IN MAC

As stated earlier, MAC is in its infancy, and a very limited literature is available on the subject. The purpose of this section is to discuss these research efforts carried out in the MAC domain. In this context, we investigate several problems inhibiting the adoption of MAC and review corresponding solutions by devising a taxonomy shown in Figure 4. Furthermore, we compare the existing solutions in the context of task offloading, task scheduling and allocation, MAC formation, security and privacy, mobility and incentives, and resource management in Tables I to VI, respectively.

4.1. Task offloading

The authors in [7] focused on the decision problem about how to offload computation-intensive applications in MAC. To address the problem, a set of online and batch-scheduling heuristics, namely, MinHop, MetComm, MCTComm, MinMinComm, MaxMinComm, and SufferageComm, were proposed that offload the independent tasks among nodes in a dynamic manner. The MinHop heuristic assigns a task based on a minimum number of hops from the client node. The MetComm heuristic assigns task to that device that can take minimum execution time to complete the task. The MCTComm heuristic assigns tasks based on the minimum expected completion time on a device. The remaining heuristics were used to assign a task by considering the communication cost. To investigate the performance of proposed heuristics, different metrics such as average makespan, the average waiting time, the average slowdown, and the average utilization are used. The results suggested that the expected completion time must be taken into account while mapping the tasks. Moreover, the proposed heuristics are efficient in terms of performance, but only the matter of problem is complexity.

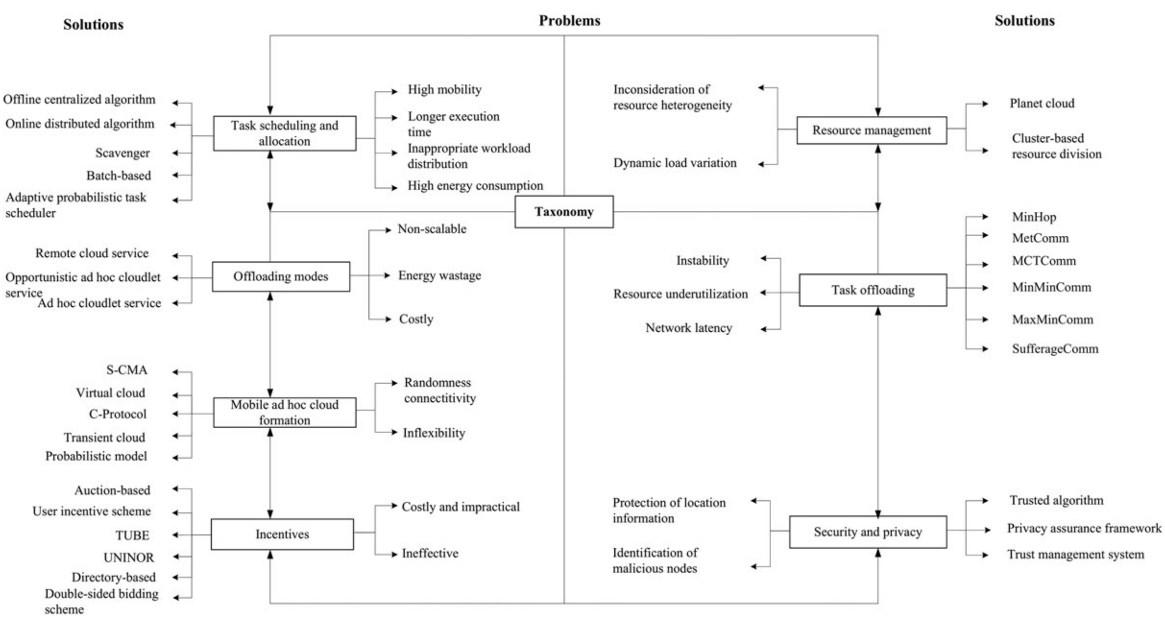

Figure 4. Context-based literature taxonomy.

Table I. Comparison of task offloading-based proposed solutions.

Proposed solutions	Specified focus	Advantages	Disadvantages
MinHop, MetComm, MCTComm, MinMinComm, MaxMinComm, SufferageComm [7]	To focus on the decision problem about how to offload computation-intensive applications in MAC	•High performance optimal task offloading	•Complexity, longer time in decision-making process
OCS, RCS, CCS [31]	To enable the energy-efficient and intelligent strategy to offload compute-intensive task using ad hoc cloudlet	•Cost-effective flexible	•Selection of reliable and secure nodes is difficult.

Table II. Comparison of task scheduling and allocation-based proposed solutions.

Proposed solutions	Specified focus	Advantages	Disadvantages
Scavenger [33]	To enable the task distribution and scheduling mechanism among the nodes taking part in communication	•Performance enhancement, energy saving	•Wastage of time
Offline centralized and online distributed [32]	To minimize average task response time for an entire set of tasks by determining whether tasks need to be distributed to a mobile device or not and on which mobile device it should be executed	•Fast task execution, energy efficient	•Imbalance load balancing
Adaptive probabilistic scheduler [34]	To schedule the tasks while keeping low energy consumption	•Energy-efficient scheduling, scalable, flexible	•High complexity
Task allocation mechanism [28]	To enable task allocation for ad hoc mobile clouds	•Optimal task allocation helps to reduce energy consumption and computational cost	•Inconsideration of mobile device resource and operational heterogeneity

Table III. Comparison of MAC formation-based proposed solution.

Proposed solutions	Specified focus	Advantages	Disadvantages
C-Protocol [9]	To manage and deploy p2p mobile cloud over MANET	•Ubiquity, availability, affordability, spontaneity	•Lack of incentive schemes
Transient cloud [35]	To enable the nearby mobile devices to form mobile ad hoc network and share their resources as a cloud	•Enable compute-intensive task execution in distributed manner	•Partial implementation, lack of incentive schemes
S-CMA [36]	To enable the users to lend the resources from ad hoc cluster of moving mobile devices	•Noticeable computation, minimized communication cost, low network latency	•Negligence of mobility factor
Ad hoc cloudlet [37]	To propose a gaming architecture that is based on ad hoc cloudlet	•Alternative solution for infrastructure, less environment	•Costly because of incentives
Hyrax [38]	To provide a distributed platform of mobile devices in a local proximity to execute the compute-intensive tasks on available mobile devices	•Interoperability, parallel task processing	•High overhead complexity
A fine-grained cloudlet architecture [39]	To enable the users to dynamically form the cloudlet by finding mobile devices with available resources within a local area network	•Fast execution, rapid data analysis	•Inefficient scheduling, complex calculation
Ad hoc mobile cloud [42]	To enable the mobile devices to form ad hoc mobile cloud	•Secure formation	•Partial implementation, lack of rigorous evaluation

M. Chen *et al*. [31] proposed a novel service mode called opportunistic ad hoc cloudlet service (OCS). Moreover, a new architecture of cloudlet is also presented. The classification of the offloading has been categorized into three modes, namely, remote cloud service, connected ad hoc cloudlet service, and (OCS). In addition, the OCS is

Table IV. Comparison of security and privacy-based proposed solutions.

Proposed solutions	Specified focus	Advantages	Disadvantages
TMC [45]	To prevent the malicious mobile nodes from participating in MAC	•Trust assurance, reliability, security	•Overhead of trusted value storage
Location privacy [44]	To ensure the location privacy while allocating the task to mobile devices in MAC	•Location privacy assurance, low system overhead, high quality of service	•Lack of confidentiality and integrity of data
Trust Assurance [43]	To ensure the reliability and security of the nodes responsible for transmission and communication in MAC	•Secure communication	•Delay in communication
A probabilistic model for vulnerability detection [47]	To detect vulnerabilities and synchronizing mobile sensors using ad hoc and secure Bayesian networks in cloud computing	•Reliable detection, recognition of condition	•Complex implementation and evaluation
A pairwise key establishment scheme [46]	To enable pairwise key establishment for the devices participating in MAC	•Minimization of number of SekGens executions, secure communication	•Lack of parallel execution support

Table V. Comparison of incentives and mobility-based proposed solutions.

Proposed solutions	Specified focus	Advantages	Disadvantages
Stochastic programming approach [49]	To distribute the workload by considering the randomness of the connection time among the cooperating devices by adopting a multi-stage stochastic programming approach	•Optimal workload distribution, randomness of connection time	•Low-level QoS
Virtual cloud computing [48]	To enable ad hoc cloud computing using the mobile devices in the local vicinity	While forming cloud incorporate: •Mobility pattern, stability of node	•Significant delay while forming ad hoc cloud as a result of decision involvement
Incentive scheme [30]	To motivate the mobile user to opt-in MAC participation	•Nominal, truthful	•It is not designed by considering the rationality of individual mobile users.
Directory-based architecture [51]	To keep track of the retribution and reward valuations	•Provide motivation to the user to participate in MAC	•Third party involvement can raise security and privacy concerns
Double-sided bidding mechanism [50]	To facilitate the user and supplier by providing a double-sided bidding mechanism	•Attractive, nominal	•Unnecessary energy consumption

further classified into three categories, namely, OCS (back and forth), OCS (one way-3G/4G), and OCS (one way-WiFi). The OCS mode is treated as intermediate between RCS and connected ad hoc cloudlet service mode. The OCS mode can enable the energy-efficient and intelligent strategy to offload compute-intensive task using ad hoc cloudlet in a cost-effective and flexible manner. Despite many advantages of the OCS, selecting reliable and secure nodes to form ad hoc cloudlet to offload the task is a major problem.

Table VI. Comparison of resource management-based proposed solutions.

Proposed solutions	Specified focus	Advantages	Disadvantages
MMADC [52]	To improve the resource utilization and also cope with the scalability and connectivity issues in MAC	•Scalability, memory space, processing capabilities	•Cluster head selection causes wastage of time
PlanetCloud [53]	To provide intrinsic support for highly mobile and heterogeneously compostable MACs	•Fast task execution, minimum delay overhead	•Complexity

4.2. Task scheduling and allocation

The authors in [32] proposed algorithms to solve the task allocation problem in the heterogeneous wireless environment. The objective of this study was to minimize average task response time for an entire set of tasks by determining whether they need to be distributed or not and on which device they should be executed. Moreover, the algorithm also considered the parameters such as communication delay, processing delay, and queuing delay while allocating the task. Furthermore, the authors proved the task allocation problem as NP-hard and proposed two approaches named as, offline centralized and online distributed, to solve the problem. The results were very promising in terms of response time in different scenarios. Despite many benefits of the proposed approaches, imbalance load balancing problem will remain a challenging issue that needs to be solved in the future.

M. D. Kristensen *et al*. [33] proposed a new cyber foraging-based system called Scavenger that enables the task distribution and scheduling mechanism among the nodes taking part in communication. To perform the scheduling, scavenger considers multiple factors such as data locality, network capability, device strength, and task complexity. Moreover, the scheduler helps to determine whether the task execution would be feasible on the local device or in a remote environment. The proposed system shows significant performance improvement in mobile application execution and also results in saving energy consumption. However, scheduling a small task in Scavenger leads to time wastage because it requires more time than the actual execution time.

The researchers in [34] formulated the high energy efficient task scheduling problem in local mobile clouds. In this context an adaptive probabilistic scheduler has proposed that helps to schedule different tasks by satisfying the task's time constraints while keeping the low energy consumption for compute-intensive real-time applications. The proposed scheduler can provide many advantages such energy-efficient scheduling, scalability, and flexibility. However, high complexity is one of the disadvantages.

A new task allocation mechanism with the aim of reducing the energy consumption and the computational cost was proposed in [28]. Moreover, a two-stage Stackelberg game is also formulated to determine the number of execution units that slave nodes are willing to offer, while master node sets the price strategies for the different slave nodes according to their shared resources. Although proposed solution helps to solve the task allocation problem in the ad hoc mobile cloud, however, inconsideration of resource and operational heterogeneity of mobile devices while allocating the tasks is one of the disadvantages.

4.3. MAC formation

The authors in [9] proposed c-protocol that is responsible for the management and deployment of p2p mobile cloud over MANET. To establish the MAC, c-protocol uses four types of message such as cloud setup, add provider, add customer, and cloud setup. The proposed protocol manages the mobile nodes in a dynamic manner. In the infrastructure-less environment, mobile nodes can easily divide their compute-intensive tasks to perform the execution by using the proposed architecture of the MAC platform. The establishment of MAC can provide several advantages such as ubiquity, availability, affordability, opportunity, and spontaneity. However, challenges such as how to convince users to contribute through their mobile devices as provider nodes and lightweight formation require attention.

A collaborative platform named Transient Cloud was proposed in [35] that allows nearby mobile devices to form a mobile ad hoc network and share their resources. Moreover, a modified version of Hungarian method to perform the task assignment within the ad hoc cloud is proposed that provides many advantages such as load balancing and collocating executions. The proposed platform allows users to create MAC using on-the-fly mobile devices available in the vicinity. The only limitation of the work is that the current technologies only allow partial implementation of transient cloud, but still, it can show the potential of MAC.

E. F. Ord′o˜nez-Morales *et al*. [36] proposed a sporadic cloud-based mobile augmentation (S-CMA) solution that enables the users to lend the resources from ad hoc cluster of moving mobile devices. The virtualization layer is used to tackle the complexity that is derived from the mobility of the cluster. S-CMA enables sharing and allocation of resources in mobile ad hoc cluster. Moreover, it provides a solution to existing approaches that can improve the experience of mobile users toward adapting the mobile ad hoc cluster platform. Furthermore, the proposed S-CMA helps to cope with many challenges associated with traditional CMA such as noticeable computation, communication cost of migrating compute-intensive tasks to remote servers, and network latency. Despite many merits of S-CMA, challenges such as enabling autonomy and coping with mobility problem are yet to be investigated.

An ad hoc cloudlet-based gaming architecture was proposed in [37]. The architecture is comprised two modules. The first module enables the mobile users to download the gaming resources from the cloud servers or nearby mobile users. The second module is based on cloudlet-based task allocation that enables the users to execute their tasks on local nearby available mobile devices in a dynamic manner. To formulate the problem for both of modules, several algorithms have been proposed that result in minimizing the energy consumption cost as compared with cloud-based gaming architecture. The only problem in the proposed algorithms is ignoring heterogeneous resources of mobile devices forming mobile ad-hoc cloudlet while allocating a task that causes wastage of resources in terms of energy consumption and execution time.

The authors in [38] proposed a distributed platform (i.e., Hyrax) that allows mobile devices in the vicinity to execute compute-intensive tasks. It uses the fault tolerance mechanism of Hadoop to minimize frequent disconnections with mobile servers. Mobile devices can access remote cloud if the nearby resources are not available.

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Hyrax server has two client-side MapReduce processes, called *NameNode* and *JobTracker*, to manage computation process among a group of mobile devices. These devices employ two Hadoop processes (i.e., *TaskTracker* and *DataNode*) to receive tasks from the *JobTracker*. These devices connect to the server and other devices via IEEE 802.11g technology. The Hyrax transparently uses distributed resources and provides interoperability across heterogeneous platforms. However, the Hyrax has high overhead because of the complexity of Hadoop algorithm.

A fine-grained cloudlet architecture was proposed in [39] that helps to manage applications at the component level. The proposed architecture enables the users to dynamically form the cloudlet by finding mobile devices with available resources within a local area network. Moreover, the proposed cloudlet architecture also provides a framework that is responsible for managing and distributing component-based applications. These applications usually have strict real-time requirements. Despite many benefits of the proposed architecture such as fast execution of compute-intensive applications and rapid data analysis, several challenges with respect to deployment, calculation, and scheduling are yet to be considered.

Considering the ad hoc nature of MAC, the authors in [40,41] proposed a localized and distributed algorithm for segregation of critical and non-critical nodes. Based on limited topology information (i.e., 1-hop, 2-hop), each node determines whether it is critical or not. A node is determined as critical if its removal (as a result of failure or movement) partitions the network into disjoint segments, non-critical otherwise. The proposed algorithm can help to avoid engaging critical nodes for compute-intensive task execution.

The authors in [42] proposed the ad hoc mobile cloud computing-based solution called m-cloud. Because of the openness of the Android platform's source code, the solution is implemented in it. Proof-of-concept application can dynamically download modules from a server, and then it is possible to run them. The proposed m-cloud enables the mobile devices to use the mobile technologies in emergency situations. In addition, a security policy has also been introduced to avoid the downloading and running of malicious code. Despite the many advantages of the work, lack of full implementation and rigorous evaluation are some of the limitations that would be investigated in the future, as discussed in the study.

4.4. Privacy and security

The authors in [43] proposed a trusted algorithm that enables the secure spontaneous ad hoc mobile cloud network. The algorithm ensures the reliability and security of the nodes responsible for transmission and communication in the MAC. Furthermore, the algorithm also helps to manage the joining and leaving node mechanism. The algorithm is based on AES encryption that employs simple key management feature. The algorithm can ensure the secure communication among nodes forming MAC. The only problem of the algorithm is delay caused by an encryption mechanism as compared with the one without security procedure.

Y. Gong *et al*. [44] investigated the privacy issues and proposed a framework that ensures the location privacy while allocating task to mobile devices in MAC. The framework is based on differential privacy and geo cast that enables the devices to share their resources in mobile ad hoc cloudlet by ensuring the privacy of location information. Moreover, analytical model and task allocation strategies have been developed. The proposed framework is not only ensuring privacy without affecting the quality of services but also minimizes the system overhead in MAC. Despite many benefits of the proposed framework such as location privacy assurance, low system overhead, and high quality of service, integrity and confidentiality of user data are the remaining concerns.

A trust management system (TMC) for ad hoc mobile clouds was proposed [45]. The goal of the proposed system is to prevent the malicious mobile nodes from participating in ad hoc mobile cloud. TMC has built over PlanetCloud that was introduced in terms of ubiquitous computing. It monitors the nodes once ad hoc cloud is formed and identifies good and bad nodes by looking at their behavior. After observing the behavior, TMC computes the trust value and stores it in the cloud repository. The mobile devices validate the trust value from the stored values and then allow any mobile node for participating in ad hoc mobile cloud. The node with larger trust value will be considered more reliable and secure. The only problem associated with TMC is the overhead of trusted value storage in the cloud.

S. Mandal *et al*. [46] proposed a solution that helps in enabling pairwise key establishment and distribution for the devices participating in the MAC. The aim of this study was to enable secure communication among the mobile devices forming the MAC. The results demonstrated that the solution reduced up to 75% in the number of SekGens required to establish keys in the MAC as compared with non-optimized naive schemes. However, the proposed scheme is based on a centralized approach instead of distributed, which results in a lack of parallel execution support.

The authors in [47] explained how the quality of service can be improved for critical infrastructure systems using probabilistic model. The model can help in detecting vulnerabilities, synchronizing mobile sensors using ad hoc, and securing Bayesian networks in cloud computing. The proposed model ensures high quality of services in critical infrastructure protection by deploying SaaS and PaaS in cloud computing. Moreover, the proposed model helps in monitoring and predicting wireless node behavior to mobile users. The proposed model can provide many advantages such as reliable detection and recognition of a condition that can enable to mitigate the risk for the critical system protection. The only problem with the proposed model is its implementation and evaluation that seems very complex.

4.5. Incentives and mobility

The authors in [30] presented a vision of new MCC architecture called MAC and also provided its initial design considerations. The concept of the cloud provider and cloud customer nodes were also introduced. Moreover, the incentive scheme with mathematical examples was also proposed. The authors envisioned that mobile devices will be able to form an ad hoc cloud as a result of their high processing and memory capabilities. The goal of the study was to provide a vision to the researchers that in future, MAC will be a new computing paradigm that can enable the users to execute their compute-intensive task in the dynamic and infrastructure-less environment.

G. Huerta-Canepa *et al*. [48] proposed a virtual cloud framework that enables MAC computing using the mobile devices in the local vicinity. The framework detects the nodes available in a specific area by checking its stability and mobility pattern and form a virtual cloud that can allow the mobile devices to execute compute-intensive tasks. The architecture of the proposed framework is comprised five components, namely, application manager, resource manager, context manager, p2p component, and offload manager. The work was a preliminary and open door for future research in terms of task management (when the node executing the task suddenly leaves the cloud) and selection of secure mobile node for job execution.

A workload distribution scheme was proposed in [49] that considers the randomness of the connection time among the cooperating devices by adopting a multi-stage stochastic programming approach. The scheme enables the mobile devices to form MAC and distribute their workload with each other by considering the mobility factor. Once the ad hoc cloud is formed, and the workload is distributed to the neighboring devices, difficulty arises when provider nodes may move out of the range before sending results back to the source node. To cope with this problem, stochastic programming approach is employed that enables optimal decision making. Furthermore, to make the optimal workload distribution, parameters such as computing capacity, network bandwidth, and energy constraints have been proposed. The evaluation results show that the stochastic approach not only enables optimal workload distribution but also deals with the randomness of connection time problem that occurs after the workload distribution. Nonetheless, to motivate users to participate in the execution of compute-intensive tasks, incentive mechanisms must be provided.

The authors in [50] proposed and analyzed a double-sided bidding mechanism where each user who wants to execute his task and the supplier who is willing to share his device resources can submit a bid though demand resource-price function and supply resource-price function respectively. Despite many advantages of the proposed mechanism such as attractive and nominal, however, the bidding mechanism causes unnecessary energy consumption. In [51] a directory-based framework was proposed to keep track of the retribution and reward valuations (in terms of energy saved and consumed) for devices even after they move from one ad-hoc environment to another. The proposed framework can help to motivate the mobile users to share their devices in MAC environment. However, the involvement of the third party that keeps track of retribution and reward valuations can raise some management, privacy, and security concerns.

4.6. Resource management

A multihop MAC framework was proposed in [52]. The framework improves the resource utilization and also copes with the scalability and connectivity issues in MAC. The multihop MAC is comprised three types of node, namely, mobiles nodes (CN), consumer nodes, and matchmaker node (MN). If CN wants to execute some task, it first sends a request to MN that keeps the list of available consumer nodes; in this way, a cloud is formed. The MN is usually multiple hops away from the CN that can degrade the performance of the task in terms of overall system performance. The proposed framework coped with this problem by dividing the ad hoc network into static and dynamic clusters. While the former divides the cluster into fixed size, the latter divides into dynamic sizes. The proposed framework can help to solve many problems related to scalability, memory space, and processing capabilities. The only disadvantage of the work is the extra time that is required to select cluster head.

The authors in [53] proposed PlanetCloud that can provide intrinsic support for highly mobile and heterogeneously compostable MAC. Moreover, it enables the MAC to adapt the real-time dynamic variations in its underlying infrastructure by isolating the hardware and code management concerns. The PlanetCloud is powered by an application layer that is responsible for encapsulating cloud applications and enable safe and reliable execution in the resource heterogeneous MAC environment. The evaluation results of the PlanetCloud platform show that it can perform very well in terms of execution time with very less number of virtual machine migrations even in the case when a large number of nodes left the MAC. Despite many advantages of PlanetCloud such as fast execution time and minimum delay overhead, complexity is a major concern.

5. TAXONOMY OF MAC

Figure 5 shows the taxonomy of MAC, where the following parameters are considered for the classification of the research work: (i) architectural components, (ii) applications, (iii) objectives, (iv) characteristics, (v) execution model, (vi) scheduling type, (vii) formation technologies, and (viii) node types. Furthermore, in this section, a comparison of literature based on objectives is also presented in Table VII.

5.1. Architectural components

Mobile ad hoc cloud is comprised five main components that are responsible for performing various functions to maintain the system. These components are application manager, resource manager, context manager

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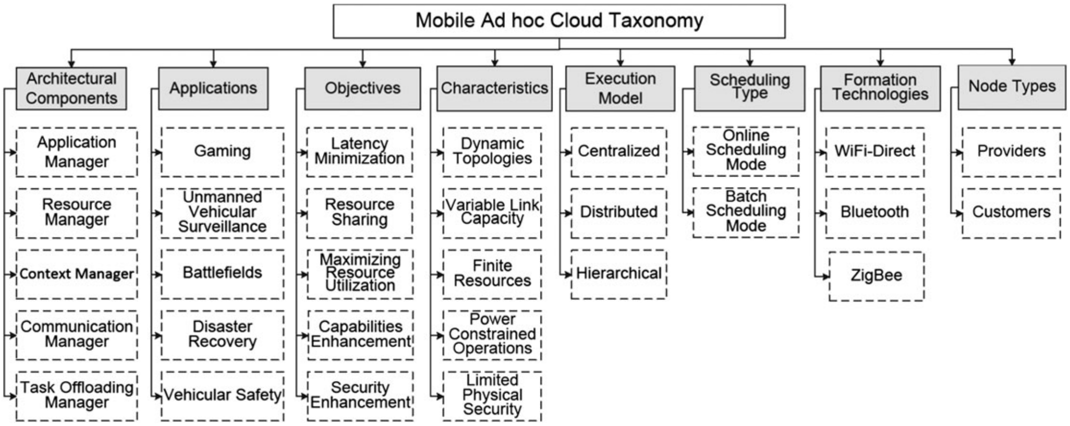

Figure 5. Mobile ad hoc cloud taxonomy based on literature.

Table VII. Literature comparison based on objectives.

	MAC formation	Mobility	Incentives	Quality of service	Resource management	Task offloading and allocation	Energy-efficient	Cost-effective	Security	Privacy
[7]						✓		✓		
[33]						✓	✓			
[9]	✓					✓				
[43]									✓	
[47]				✓					✓	
[37]	✓			✓						
[39]				✓				✓		
[32]						✓	✓			
[30]	✓		✓							
[52]					✓			✓		
[48]		✓								
[53]		✓			✓					
[44]										✓
[36]	✓							✓		
[45]									✓	
[38]						✓				
[49]		✓								
[31]						✓		✓		
[35]	✓									
[46]									✓	
[42]	✓									
[50]			✓							
[51]			✓							
[34]						✓	✓			
[28]						✓		✓		

communication manager, and task offloading manager. The application manager is in charge of launching and modifying an application to add the offloading support and proxy creation. The resource manager is responsible for application profiling and monitoring of resources on the mobile devices. For each application, the profile is defined in terms of a number of mobile devices required to form the MAC and amount of resources required for offloading. The context manager collects and synchronizes the contextual information from different widgets and provides it to other processes. The communication manager handles the communication across consumer and mobile devices. The offloading manager is responsible for dispatching jobs from consumer to provider mobile devices, getting back the results, and creating protected space for the offloaded jobs coming from other devices.

5.2. Applications

Mobile ad hoc cloud enables the execution of various applications on resource-constrained mobile devices by sharing their resources. Few example, applications can be gaming, unmanned vehicular surveillance, battlefields, disaster recovery, and vehicular safety. In gaming, players share the resources of the MAC to run the game in the distributed manner. The device connectivity is considered stable, as the players tend to stay in the same place while playing the game. In the unmanned vehicular surveillance, a group of unmanned vehicles forms the MAC to monitor the area and run the information fusion algorithms. Similarly, the battlefields, disaster recovery, and vehicular safety applications can also be run on the group of cloud provider nodes to perform the compute-intensive tasks on the resource-constrained mobile devices.

5.3. Objectives

The objective attribute indicates the primary objective of the proposed work in MAC. Current MAC solutions aim to attain a number of objectives, such as latency minimization, resource sharing, maximizing resource utilization, capability enhancement, and security enhancement.

5.4. Characteristics

The MAC has some special characteristics that make it unique from server-based cloudlet and the remote cloud. These characteristics are mainly inherited from the mobile ad hoc network on which the cloud will be deployed. These characteristics are namely dynamic topologies, variable link capacity, finite resources, power-constrained operations, and limited physical security. The key factor that contributes in the dynamic topologies is the user mobility. The variable link capacity is a result of the varying noise and interference level for each device as well as the data rate supported by the device. The mobile device-manufacturing companies keep the finite resources for making them more portable. The size of mobile devices increases if the resources increase. The operations performed in the MAC are power constrained because of the battery-powered nature of the devices. The frameworks and algorithms designed for mobile ad hoc networks should be lightweight. The physical security in MAC is limited because of the more prone nature of wireless networks to physical security threats than that of fixed wired networks.

5.5. Execution models

The execution models for the MAC can be categorized into two main categories, namely, centralized and distributed. In centralized MAC, a server node is responsible for managing the execution and distribution of the application in the ad hoc cloud of mobile devices. On the other hand, a group of mobile devices is responsible for the management of the application execution in distributed MAC without centralized control.

5.6. Scheduling types

In the MAC, task scheduling can be categorized into online and offline. The former takes task-scheduling decisions at the runtime, considering the process characteristics and context of the MAC. However, in the batch scheduling, also known as offline scheduling, task scheduler makes task-scheduling decisions before the actual execution of the application in the MAC. In batch/offline task scheduling, a table is created that contains possible scheduling decisions for use at runtime. The table generation completely depends on the prior knowledge of application execution behavior.

5.7. Formation technologies

To establish the MAC, three wireless communication technologies are prominent, that is, WiFi-direct, Blue-tooth, and ZigBee. WiFi-direct is a new addition to the android operating system that enables the mobile devices to connect with other over WiFi and exchanges data. In WiFi-direct, one device acts as a group owner, and rest of the devices need to be connected with the owner in order to perform the specified task, whereas Blue-tooth is a wireless technology standard that comes in mobile devices for short distance communication. Blue-tooth enables the mobile devices to form piconet to communicate with each other. Piconet comprises master nodes and slave nodes. The master node can talk with seven slave nodes in a piconet. Blue-tooth is better for mobile devices, as it consumes less power. However, ZigBee is a high-level communication protocol that can help in forming the personal area network with low-power digital radios.

5.8. Node types

Mobile ad hoc cloud comprises two types of mobile node, namely, providers and consumers. The provider nodes share their resources to facilitate the other mobile devices in terms of running their applications. The consumer nodes leverage the resources of provider nodes to perform their compute-intensive tasks. A device can be a consumer node at one time and a provider at another.

6. PRINCIPLES FOR ENABLING MAC COMPUTING

We have identified several principles from the literature, as presented in Section 3. These principles provide straightforward guidelines for designing the frameworks that can satisfy the performance metrics for the mobile user's compute-intensive application execution in the MAC. The principles for enabling MAC are categorized into six main categories, namely, attractive incentives, optimal task allocation, lightweight formation, agile security, stability, and autonomy. Here, we discuss each of the principles in detail. Figure 6 shows the principles for deployment of successful MAC.

6.1. Attractive incentives

Enabling the MAC computing by leveraging the resources of nearby available mobile devices requires some attractive incentive schemes. The designing of incentive schemes should be comprised three steps, namely,

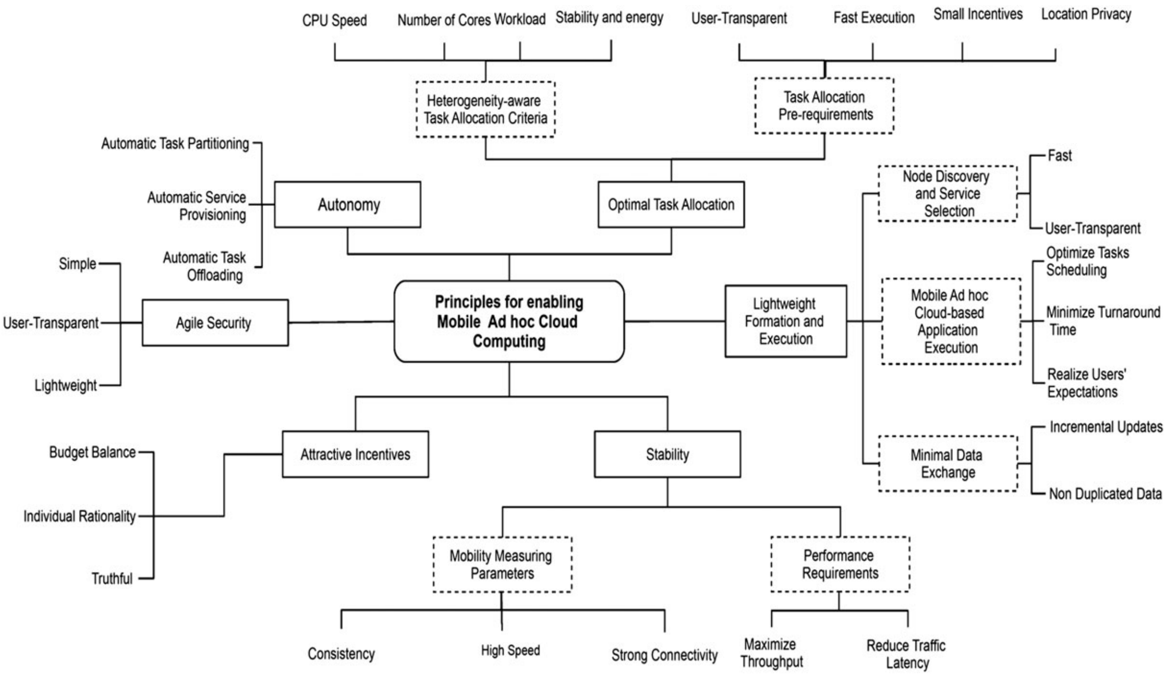

Figure 6. Identified key principles for deployment of successful mobile ad hoc cloud.

analysis, design, and evaluation. The term analysis means investigating about the mobile user's incentive choices. For example, what type of incentives mobile users want to participate in the MAC. After conducting an analysis, the incentive schemes should be designed according to the need of the mobile users. Finally, the incentive schemes should be evaluated by applying appropriate evaluation methods. Moreover, while proposing any incentive scheme in the MAC, the factors, namely, budget balance, individual rationality, and truthfulness, must be taken into account. Without any attractive incentive scheme, mobile users may not agree to share their device in the MAC because it will not give any benefit to them. Therefore, the framework designers should incorporate all possible incentives to enable the successful deployment of MAC.

6.2. Optimal task allocation

Facilitating the mobile users to execute compute-intensive tasks in an optimal manner requires new task-allocation mechanisms. The task-allocation framework should have the ability of dynamic decision making regarding partitioning matters such as individual or distributed processing. After the partitioning phase, the framework must be able to allocate the task to other mobile devices by taking into account the heterogeneity of mobile device resources in terms CPU speed, number of cores, background workload, stability, and energy level. The consideration of these parameters while allocating the task can enable proper utilization of the resources that can result in fast task execution and energy saving.

6.3. Lightweight formation

To make the MAC adoptable, the formation mechanism must be lightweight. Before designing any framework with regard to resource discovery, maintenance, and releasing information, the constraints of the mobile devices such as limited processing capabilities and battery should be incorporated within the framework. The node discovery mechanism should be transparent and lightweight. Once the MAC is formed, scheduling of tasks should be optimal enough to execute the given tasks in minimum turnaround by meeting the expectation of mobile users. The latency in forming MAC can cause wastage of resources that may not be free of cost because of incentive mechanism. Moreover, only minimal data should be exchanged while forming a cloud of mobile devices. In addition, non-duplicated and incremental update-based mechanism can ensure the minimal data exchange that can result in saving energy and processing of mobile devices opted in the MAC participation.

6.4. Agile security

To facilitate the adoption of the MAC, proper agile security mechanisms are required. The agility can be achieved by using the lightweight and user transparent and simple techniques. The MAC framework designers should incorporate off-the-shelf authorization and authentication mechanisms for ensuring proper security in a lightweight manner. The authentication and authorization mechanisms should be designed in such a way that it requires minimal interaction and time from the mobile user to enable task execution. Apart from the principles presented in the preceding texts, quality of service (QoS) of the communication channel is also mandatory to be monitored for enabling smooth collaboration among mobile devices. The incorporation of these presented principles can help the mobile users to enable secure MAC computing.

6.5. Stability

In the MAC, only the nodes having higher stability value should be selected for task execution. The stability pattern of the nodes needs to be incorporated dynamically while developing any new framework for the MAC. The nodes participating in the MAC are of dynamic nature in terms of movement that can lead toward incomplete task execution. The stability of nodes can be measured by taking into account the mobility measuring parameters, namely, consistency, high speed, and high connectivity. Once the node stability is measured, the mobile user demand such as maximum throughput and reduce traffic latency can be fulfilled. After classifying the nodes into lower and higher stability pattern categories, it does not mean that lower stability pattern devices are not useful, but these devices can be used to run a backup of the task by giving fewer incentives to overcome the failure chances.

6.6. Autonomy

The MAC platform requires minimal human interaction to access the devices for task execution purpose. The automated service should be based on automatic task partitioning and its offloading. Once the controller device receives some compute-intensive task, its partitioning and the offloading decision should be taken in an automatic manner. The MAC-based automated service provisioning can be implemented in three steps: (i) developing a model that can predict the resources and QoS required for the given compute-intensive task; (ii) allocating task according to the prediction model; and (iii) periodically monitoring of tasks in terms of defined QoS rules. Despite difficulties involved in all the three steps of automated service provisioning, the automated service access process is essential for the MAC.

7. OPEN RESEARCH CHALLENGES

This section discusses the open research challenges related to the MAC. The purpose of discussing the open challenges is to give research directions to new researchers in the domain.

7.1. Heterogeneity-aware task allocation

In the MAC, where heterogeneous resource-constrained devices participate to execute some compute-intensive tasks, inefficient task allocation has become a significant problem. The negligence of the heterogeneous mobile device resources such as CPU speed, background workload, the number of cores, and battery life while allocating task can cause inefficient resource utilization that results in longer execution time and wastage of energy consumption. The incorporation of these parameters has become very challenging as a result of complexity and overhead. As can be seen in a scenario, where the controller node has measured the workload on available devices and decided to allocate the task, but whenever the controller node had taken the decision to assign a task to a particular device which selected according to workload parameter, the background workload had changed on that device later. In this scenario, it has become very difficult to cope with this challenge because the load is changing dynamically. In the context of task allocation, several research efforts have been carried out in [7,32,54,55]. These proposed research works are in its infancy and require further optimization and extension.

7.2. Incentives

To convince the mobile users to opt-in to MAC participation requires nominal incentive mechanisms. Without giving some advantage, it would be very difficult to convince a mobile user to share their available device resources with others. Therefore, to enable the MAC computing, some proper incentive mechanisms are required to be proposed that can motivate the people to share their mobile device resources. The finding of proper incentive mechanisms that can motivate the mobile users encountered to agree on the load offloading has become very difficult because of individual rationality and different demands of the mobile user. Although several researchers have proposed some incentive mechanisms, theses solutions are in their infancy [30,50,51,56]. Designing appropriate incentive mechanisms requires some future research.

7.3. Mobility

Once the MAC is formed, and subtasks of a task are distributed to the selected mobile devices, the mobility can affect the overall task execution time. As can be seen, in a scenario where the mobile device leaves the MAC after taking some subtask to execute, it can cause all the subtasks to be rescheduled that results in wastage of resources of mobile devices in terms of energy and processing. Moreover, rescheduling of the tasks can be costly in terms of incentives. To cope with the mobility problem, several research efforts have been carried out in mobile ad hoc networks that can be applied in the MAC after applying some modifications [29,36,53,57–60]. In the future, high attention needs to be paid to address the mobility-related challenges in the MAC.

7.4. Minimal data exchange

Once the compute-intensive task is divided into subtasks and distributed to mobile devices, the devices usually share their task execution state in terms of processing after a specific interval of time that can affect the battery power consumption. The mobile devices usually have limited resources, and no one wants to waste their device resources for unimportant purposes. Therefore, the amount of data exchange is required to be minimized to perform task execution in the MAC. In this context, several research efforts have been carried out in MCC, wherein to cope with the problem of minimal data exchange, researchers have classified data into three categories: (i) configuration data, such as states information; (ii) input data; and (iii) OS image and application migration data [11]. The amount of the configuration data transferred can be reduced by only moving the essential configuration data. Although these research efforts cannot be applied directly in the MAC, they can provide basic guidelines to the researchers for designing minimal data exchange-based frameworks.

7.5. Security and privacy

Because of a random selection of mobile nodes that usually participate in the MAC, security and privacy have become a major concern. Most of the applications of MAC are very sensitive in nature; therefore, security risks are needed to be measured at first priority. The joining of any malicious node in the MAC can increase the overall task execution time that can lead toward performance degradation. Moreover, the privacy of the location is also a serious concern for the users who share their devices. To cope with the security and privacy problems, off-the-shelf authentication and authorization mechanisms are required that can prevent the malicious node to participate in the MAC by protecting the location privacy. To cope with security and location privacy in the MAC, several research efforts have been carried out in [43–45], but these efforts are in its infancy. The further extension is required within these proposed mechanisms, which can ensure more reliable and secure communication.

8. CONCLUSIONS

Momentous advancements in MCC have paved the way toward a new computing paradigm called MAC. Although there are many research studies in mobile cloud computing and ad hoc computing, the convergence of these two areas grants further academic efforts for the flourishing of MAC. In this context, we investigated the state-of-the-art research efforts carried out in the MAC domain. We analyzed several problems inhibiting the adoption of MAC and review corresponding solutions by devising a taxonomy. We compared the existing proposed solutions by highlighting the advantages and disadvantages. Moreover, we devised another taxonomy based on conducted survey of MAC. In addition, we compared the literature based on objectives. Furthermore, we indentified and discussed the key principles that can guide the framework designers to incorporate the specific features for enabling successful MAC. Finally, we presented open challenges as future research directions. We concluded that MAC is in its early stage of development, and it is required to pay high attention to address the presented challenges to facilitate the adoption of MAC that will be a core component of the future computing landscape.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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