Intercloud and HetNet for Mobile Cloud Computing in 5G Systems: Design Issues, Challenges, and Optimization

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Abstract

Emerging 5G systems will feature a closer collaboration between mobile network operators and cloud service providers to meet the communication and computational requirements of modern mobile applications and services in a mobile cloud computing (MCC) environment. In this article, we show how the marriage between heterogeneous wireless networks (HetNets) and multiple clouds (a collection of which is referred to here as *Intercloud*) stands out as an effective response for the mobile data deluge. First, we review the building blocks of a HetNet and an Intercloud as well as the resource management entities in both domains. Second, we outline how they might be orchestrated to better support the task offloading process. Third, we identify the key design criteria and challenges related to interoperation between an Intercloud and a HetNet. We then formulate a revenue sharing approach for a coalition between a mobile network operator and cloud service providers. The approach achieves the maximum revenue for the coalition by optimally associating the users to the clouds through the base stations. Next, the concept of Shapley value is applied to individualize the contribution of each player based on the maximum revenue for the optimal user association. Numerical results illustrate the benefits of the coalition for all players.

Introduction

In order to cope with the ever-growing demand for mobile data service in emerging 5G systems, mobile network operators (MNOs) are encouraged to invest in two distinct but complementary technologies: heterogeneous wireless networks (HetNets) and mobile cloud computing (MCC). HetNet, which allows wireless networks with different characteristics (e.g., coverage and data transmission) to work in synergy, has been recognized as a viable alternative to increase overall network capacity while enabling mobile users to achieve high data rates over a much larger coverage area. On its turn, MCC arises as an instrumental technology to augment user equipment (UE) capabilities (e.g., computation resources and battery lifetime) beyond its physical boundaries by wirelessly transferring the computation-burden from it to the resource-rich clouds where the computation-intensive task will be processed in virtual machines (VMs).

This sophisticated ecosystem, which comprises a massive deployment of overlapping radio access networks (RATs) and a cloud data center, will become even more intricate when multiple cloud service providers (CSPs) with diverse and heterogeneous features (elasticity, pay-as-you-go pricing, geo-location, processing speed, security, energy consumption) come into the game to realize an Intercloud over a HetNet. An Intercloud is a coalition of CSPs that enables the utilization of each other's infrastructure in order to accomplish better resource utilization and revenue maximization.

The realization of an Intercloud over a HetNet will allow MNOs, CSPs, and mobile users to negotiate and deliver their services in a more affordable, transparent, competitive, and flexible manner. For instance, for a mobile user, it will set a higher degree of flexibility where the RAT selection as well as the cloud selection will be conveniently performed with the aim to meet the budgetary and technical needs. At the same time, it might overcome existing issues in the design of MCC for emerging 5G systems. Current MCC solutions are facing major challenges in dealing with the increasing latency over a standalone wireless deployment when there is a large amount of data to be offloaded. The minimization of latency is vital for a running application in a UE to enjoy the full benefit of cloud computing through the task offloading process. For instance, reduced latency might be extremely critical for the success of interactive applications in MCC since it may totally jeopardize the much-needed interactivity. Thus, for emerging 5G systems, the latency minimization problem will be a key design goal that could be efficiently addressed if these different players get along.

From a resource management standpoint, the interoperation between the Intercloud and the HetNet will call for an optimal orchestration among MNOs, CSPs, and UEs. Although HetNet and MCC have been receiving increasing attention in recent years individually, there is a clear need for a holistic design for emerging 5G systems in which the common pool of wireless resources in a HetNet and VMs in an Intercloud could be jointly and optimally allocated. Figure 1 shows that to accomplish this, a cooperation and/or collaboration between the resource managers in both domains has to be put in place. Thus, the Common Radio Resource Management Server (CRMS) in a HetNet and the Cloud Service Broker (CSB) in the Intercloud should exchange management information in order to make the system integration effective. In addition to optimizing the resource allocation, the interoperation between

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the CRMS and the CSB should maximize the total obtained revenue. From this point onward, a challenge arises in how to individualize the monetary gains of each player based on their marginal contributions. The concept of Shapley value, which fairly divides a given revenue within members of a coalition, is a compelling approach to address this challenge.

In the context of optimizing the design, deployment and operation of an Intercloud over a HetNet, we present a mathematical framework for revenue sharing among a MNO and CSPs when they form a coalition. The proposed framework achieves fairness and optimally associates UEs to the CSPs through BSs, maximizing revenue for the coalition. By applying the concept of Shapley value, the obtained revenue is shared among the players in the coalition. Numerical results illustrate the benefits of forming a coalition over a non-cooperative setting.

The rest of this article is organized as follows. We present the network components of a HetNet and an Intercloud. We introduce the resource management entities in both domains, wireless and cloud. Next, we outline how they might be orchestrated to streamline system integration. We identify the key design criteria and challenges that will drive the interoperation between an Intercloud and a HetNet. As a design example, we visit the resource sharing problem for an optimal resource allocation in an Intercloud over a HetNet system. We formulate the problem as an integer linear programming model whose goal is to maximize the total system revenue. Next, the concept of Shapley value is invoked to equitably share the total obtained optimal revenue among the MNO and the CSPs. Numerical results illustrates the benefits of the cooperation. Finally, we conclude the article.

Overview of HetNet and Intercloud Ecosystems

HetNet and CRMS

In recent years, we have witnessed a paradigm shift where stand-alone wireless and mobile network-based design has been replaced by a more flexible, efficient, and effective approach that promotes cooperation among RATs and exploits the intrinsic diversity in cell sizes and layers as well as the technology in existing wireless network deployments to successfully cope with mobile data traffic growth. A cornerstone of this process is the concept of Common Radio Resource Management (CRRM), whose functions are to provide optimal resource management and to optimize HetNet performance by enabling trunking gain, lower interference, and QoS management [1]. To suppor radio channel allocation in a HetNet, the 3rd Generation Partnership Project (3GPP) defined a logical entity called the CRRM server (CRMS) [1]. The CRMS's role is to collect the radio resource management information from each individual RAT and make a better decision based on its knowledge of the entire system.

As for the system operation, CRMS is in charge to perform the following CRRM procedures: network selection, admission control, and inter-system handoff. The network selection procedure aims to choose the most suitable RAT to connect a mobile device to. In this respect, features such as coverage, signal strength, data rate, access price, network load, system geometry, and security have been taken into account to select the RAT that will best fulfil the expectations of mobile users. The admission control procedure is then executed to verify whether a service request impairs the service level agreement (SLA) established with the ongoing mobile users. If not, the service request is admitted into the RAT. Otherwise, the service request is blocked. In its turn, the inter-system handoff ensures seamless mobility support to users who roam across different access technologies. To successfully manage user mobility, the inter-system handoff procedure is broken down into three consecutive phases: system discovery, handoff decision, and handoff execution. During the first phase, the information on which RATs and which services are available is gathered. Next, based on that knowledge, a set of criteria (battery power, required QoS, network delay, and signalling overhead, to name a few) is used to determine whether the handoff will be performed and to which RAT. Finally, the action is enforced in the last phase.

Based on the previous discussion, CRRM algorithms have been devised to handle two network selection problems, where the first one copes with initial access and the second one deals with handoff access. Since it is more annoying to drop an ongoing call than rejecting a service request, the inter-system handoff becomes the most critical algorithm running in a CRMS.

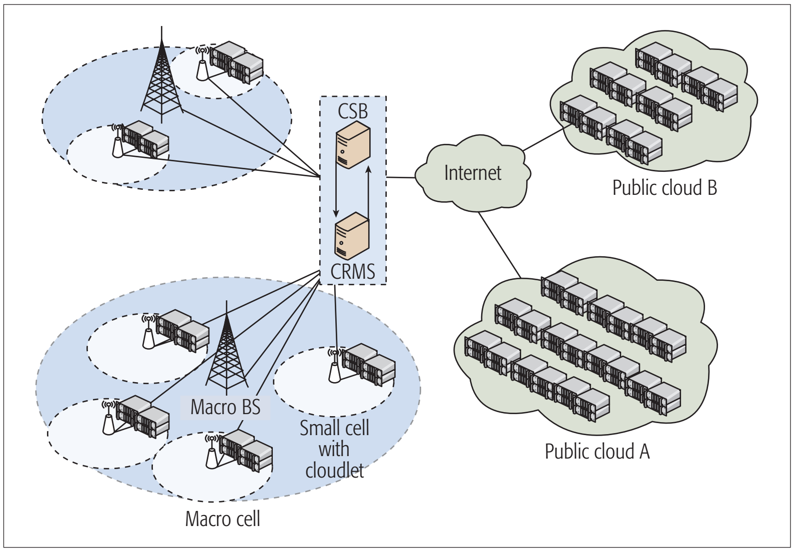

FIGURE 1. Intercloud and HetNet for MCC applications.

Intercloud and CSB

By breaking the physical boundaries of the UEs' limitations, MCC makes it possible for developers to exploit the unlimited computing resources offered in remote clouds while designing applications. This new paradigm in software development has gained enormous momentum and promoted tremendous growth in the mobile cloud market worldwide. As a consequence, traditional CSPs are constantly expanding their mobile computing portfolios to attract new clients while holding the loyalty of the existing ones. However, requirements such as high availability, elasticity, reliability, scalability, legislation-adherence services, low-la-

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tency, SLA compliance, geo-location awarenesses, affordability, and fair price make it hard for a single CSP to meet the entire demand. Thus, the rise of Intercloud computing, where multiples CSPs operate in collaboration/cooperation, became inevitable.

In this ecosystem, despite the appeal of having multiple CSPs to choose from, issues such as the selection of the CSP that best meets the functional requirements, non-functional requirements, and budgetary requirements naturally arise. To perform this task, a new key networking entity, the cloud service broker (CSB), has emerged, whose function is to intermediate the negotiation between users and CSPs in order to reach an agreeable service functionality and QoS levels. Ideally, a CSB should be able to allocate and de-allocate VM resources across multiple clouds, deploy and manage the application's execution over the provisioned VMs, and perform scheduling and load balancing procedures [2].

Network Architecture

Figure 1 shows that to realize the full potential of an Intercloud over a HetNet, the CRMS and CSB should be communicating entities. While the CRMS coordinates the UEs' access to macro cells and possibly a large number of small cells, the CSB manages their running applications across the multiple clouds, which could be cloudlets attached to the base stations (BSs) at small cells or public ones.

Unified CRMS and CSB Framework

In order to intelligently exploit the common pool of wireless resources in a HetNet while optimizing VM allocation in an Intercloud, an efficient CRMS and CSB orchestration is crucial for emerging 5G systems. Notably, the individual design of the CRRM algorithm and the cloud brokering algorithm is left up to system designers, which will make it feasible to optimize their operations. To better define the design criteria, policy, and methods to regulate how CRMS and CSB might operate, we present in the following a taxonomy based on the nature of the operation between these entities and their ownership.

Nature of the Operation

Operation-free design: In this case, the CRMS and CSB are totally independent from one another, and their designs should be correspondingly conceived to individually maximize their revenues or minimize their latencies. Greedy algorithms for RAT and cloud matchmaking, which optimize a specific target, arise as viable alternatives.

Collaborative design: In this case, the CRMS and CSB exchange management information to leverage each other's performance and operate collaboratively to meet each other's requests. However, due to the loose coupling between them, not all requests have to be fulfilled. For instance, to comply with a SLA, the CSB might ask the CRMS to hand a UE off to a RAT with low latency. However, this action could increase overall system interference or energy consumption, and because of that, the CRMS could ignore the CSB's request. Bearing this in mind, a resource reservation-based algorithm would be a useful solution to guarantee the minimal end-to-end system performance.

Cooperative design: In this case, there is a tight coupling between the CRMS and the CSB. To maximize their synergy, a single controller could be conceived to dictate how they have to jointly operate. A semi-Markov decision process (SMDP)-based decision theoretic model can be used for this. However, due to the curse of dimensionality, the application of traditional methods such as linear programming, policy iteration, and value iteration algorithms may not be practically feasible. In this case, reinforcement learning methods might be more appropriate.

Ownership

CRMS and CSB belong to the same owner: From a resource allocation viewpoint, this is the best-case scenario. As such, a holistic design can be more easily implemented since both networking entities are under the same administrative domain. Furthermore, the mobile user information retrieval as well as SLA verification are quickly, privately, and securely performed since information sharing is kept within the service provider perimeter. In this case, operation-free design, collaborative design, and cooperative design are all supported.

CRMS and CSB belong to different owners: Because both networking entities are under distinct administrative domains, information sharing is more sensitive and must be regulated by a SLA between both parties. In this case, operation-free design and collaborative design are more appropriated since network overhead could be costly for a cooperative design to be put in place.

Design Aspects and Challenges

Centricity

The location of centricity plays an important role in the CRMS and CSB operations since it defines where the decision making process is performed. In a user-centric system, the UE is responsible for choosing the RAT and the cloud that best suit its needs, while in the network-centric system, decision making is carried out by the network. For the hybrid-centric system, decision making is performed by means of a collaboration between the user and the network.

The decentralized nature of the user-centric design has brought down the overhead traffic volume in MCC [3], but considering a HetNet and an Intercloud setting, it will ask for a cooperation, or at least a collaboration, between the CRMS and CSB to enforce the UEs' decisions. Due to the selfishness of UEs, the user-centric design tends to be non-optimal. On the other hand, the optimality of the network-centric system comes at the expense of higher overhead traffic, which ultimately poses a challenge in its deployment, especially when a large number of RATs and clouds is available. Because of the existing trade-off between the optimality and the overhead traffic, a hybrid-centric design appears to be a compelling solution to efficiently and effectively deal with system complexity by combining the benefits from both the network-centric and the user-centric designs.

Multi-party SLA

SLA is a negotiated contract between the user and the service provider that clearly specifies the services the customer receives, but not how they are delivered [4]. It allows for a partnership between the MNO and the CSP that will make their operations flexible and optimize their service delivery by investing in a joint operation.

From a customer perspective, in addition to naturally overcoming the vendor lock-in drawback, the Intercloud ecosystem increases application resilience. The possibility to diversify the access to cloud computing resources by the full exploitation of the existing overlapping structure of RATs in urban areas makes SLA compliance more flexible, especially when it comes to hitting targets such as pervasiveness, mobility, and latency minimization.

Recently there have been efforts to establish a multi-cloud environment, e.g., Optimis, Contrail, and mOSAIC. However, to truly enable seamless interoperability, management, and load migration among not only CSPs but also among different RATs in a HetNet, one needs to take into account the SLA established between the UE and the MNO, and possibly the SLA between MNOs when the HetNet is owned by multiple MNOs. These tasks are non-trivial, especially because multi-party sensitive information will be exchanged over the Internet. Privacy protection and security measures are therefore mandatory to pave the way for a holistic operation, and consequently for a multi-party SLA specification and compliance.

Decoupling Uplink and Downlink Access for the Task Offloading Process and Traditional Web Applications

Contrary to other Web applications, the task offloading traffic is heavier in the uplink direction than in the downlink direction. For instance, for a face recognition application, a typical image size is 420 KB [3], while the cloud response is either the recognition result, which is a label containing the identified object or person, or a message stating the unsuccessful recognition. Because of this, emphasis on resource allocation has been placed on the uplink allocation [3].

At the same time, the ultra dense deployment of small cells has promoted the idea of decoupling uplink and downlink access where a mobile user may receive the downlink traffic from one BS and transmit the uplink traffic through another BS. In [5], Smiljkovikj *et al.* have obtained the device-association probability for decoupling access in HetNet and have shown that with the densification of femto BSs, more users choose to connect with a femto BS in the uplink and with the macro BS in the downlink.

Considering the freedom between uplink and downlink allocations in a HetNet as well as the traffic asymmetries of task offloading and traditional Web applications, the optimal decoupling downlink and uplink access strategies for task offloading traffic and traditional Web traffic arises as an important research avenue to be explored. In this respect, the user-association issue will have to be re-thought in order to include the locations of clouds and their respective links with the BSs as well as the presence of cloudlets.

> With the rise of small cell densification in a HetNet where every BS will potentially host a cloudlet, mobile users will likely transit over several small cells and frequently be performing handoff operations between the macro cell and small cell or between the small cells.

Handoff and VM Migration

Due to the user mobility in a MCC environment, it is recommended [6] to bring the VM, which runs the UEs' applications, closer to the sites where the UEs are, so that the latency is kept under acceptable levels. The mechanism in charge of transferring the *state* of a VM from the source physical machine (PM) to the destination PM is known as VM migration.

With the rise of small cell densification in a HetNet where every BS will potentially host a cloudlet, mobile users will likely transit over several small cells and frequently be performing handoff operations between the macro cell and small cell or between the small cells. In such a setting, a key design aspect is whether the handoff and VM migration have to be always jointly performed.

The relevance of this question stems from the fact that the network overhead required to manage and realize a wide-area migration scenario could be considerable [7]. At the same time, the VM traffic load through the backhaul might become critical if a large number of VMs is requested to follow their UEs across the HetNet. Thus, a natural performance trade-off is placed between the latency and the network traffic (overhead and migrating VM) where the decrease of one implies the increase of the other. Considering the overlapping nature of HetNets and the overhead traffic only, the following settings can be envisioned.

User moving from a small cell to a double coverage region: In this case, the CRMS will hand the UE off to another small cell or to the macro cell. The CSB may choose to keep the VM in its cloudlet or follow the CRMS decision. Design criteria in this case are to perform the VM migration or not to perform the VM migration. The former case will increase both the network overhead and the latency if the macro cell is chosen, or increase the network overhead but keep the same level of original latency if the small cell is selected. The latter case will also cause an increase in latency but not in network overhead. Additionally, the CSB still has to take into account the service price in the public cloud and the exchange of sensitive information over a wide-area network. Figure 2 presents the VM migration alternatives along with the corresponding data flow for each of them.

User moving from a small cell to a macro cell region only: In this case, the CRMS has no option but to hand the UE off to the macro cell to ensure the continuation of the service. From a VM migration perspective, the CSB can choose between staying in the cloudlet or selecting the public cloud. Regardless of the selected cloud, the latency will increase due to the lengthy path taken by the data. Due to the existing performance trade-off, keeping the VM in its cloudlet will avoid the network overhead that is necessary to migrate the VM to the public cloud. The data flow in this setting can be inferred from Fig. 2. For instance, considering the no VM migration option, we will end up in a scenario like Fig. 2b, but with the connection established with the macro BS. The second VM migration option corresponds to the scenario depicted in Fig. 2d.

User moving from a macro cell to a small cell region: In this case, the CRMS and CSB may choose to perform a joint handoff and VM migration, which will enable the UE to enjoy shorter latency, but at the expense of network overhead, or to perform the handoff but not the VM migration, which will keep the same level of the original latency without incurring any network overhead.

User moving from a macro cell to a macro cell: In this case, the CRMS will perform the handoff while the CSB may keep the VM in the same public cloud (which will avoid unnecessary network overhead), or to switch it to another public cloud. In this case, the latency will depend on the geo-location of the destination public cloud. Regardless of the selected cloud, latency will not change considerably since the data will transit over the Internet, but the network overhead will depend on the action taken. Figure 3 shows the VM migration alternatives along with the corresponding data flows for each of them.

Table 1 summarizes the points that we have presented so far in a *rule of thumb* fashion.

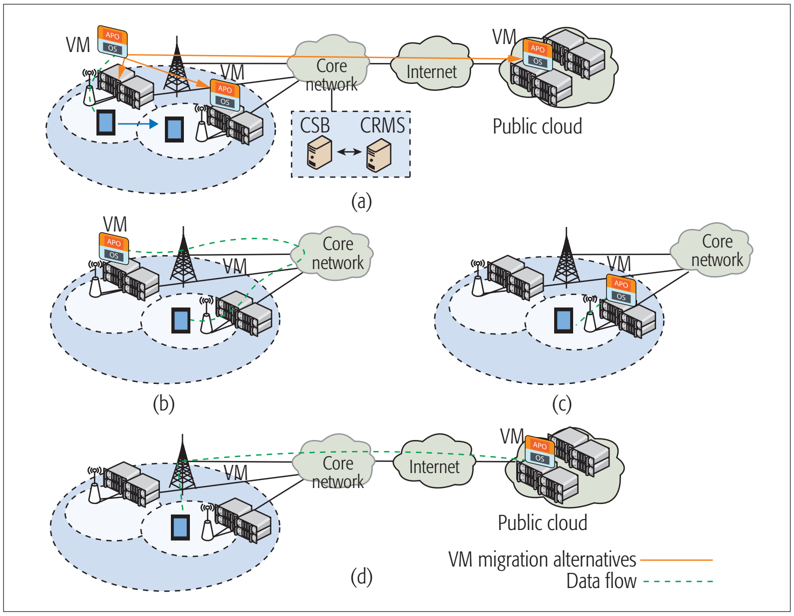

FIGURE 2. User moving from small cell to double coverage region: a) VM migration alternatives; b) no VM migration; c) VM migration to Cloudlet; and d) VM migration to public cloud.

From	To	Handoff	VM migration	Latency	Network overhead
Small cell	Small cell	Yes	Yes	Low	High
Small cell	Small cell	Yes	No	Medium to high	Low
Small cell	Macro cell	Yes	Yes	High	High
Small cell	Macro cell	Yes	No	Medium to high	Low
Macro cell	Small cell	Yes	Yes	Low	High
Macro cell	Small cell	Yes	No	High	Low
Macro cell	Macro cell	Yes	Yes	High	High
Macro cell	Macro cell	Yes	No	High	Low

TABLE 1. Analysis of handoff and VM migration.

Development Mismatch

There is a clear mismatch when it comes to the maturity level of the development process between the wireless industry and the cloud industry. In 2002, the 3GPP's vision of the CRRM procedure paved the way for the success of HetNet [1]. In 3GPP Release 8, the recognition that UEs should be able to access non-3GPP RATs and 3GPP legacy RATs marked an important milestone in the pathway of the LTE HetNet. With the introduction of the evolved packet core (EPC), new network entities were devised to assist network interoperability. Examples include the access network discovery and selection function (ANDSF), whose main objectives are to enable network discovery and network selection by a UE, and the evolved packet data gateway (ePDG), whose function is to establish a secure connection between an untrusted non-3GPP RAT and the EPC for data transmission with the UE. With the successive Releases, the small cell-based LTE HetNet and LTE-Advanced (LTE-A) became a driving force in the telecommunications sector as an effective answer for the mobile data deluge. Parallel to that, WiMAX-WiFi HetNet also reached worldwide penetration. The rise of *digital cities*, where an entire city was set as a wireless zone, and the affordability of that solution when compared to the cable installation counterpart, have made the WiMAX-WiFi HetNet one of the best last mile options to boost Internet access in underdeveloped countries and emerging economies. Currently, DenseNets, which is the next generation of HetNets and will entail an ecosystem with ultra dense deployment of small cells, have been proposed as one of the major tenets of 5G that feeds both industry and academia with hot R&D topics.

On the other hand, cloud interoperability, which would provide a seamless cross-cloud workload migration, is still in an embryonic state when compared to its wireless counterpart. Technical problems such as distinguishing virtualization and API technologies, as well as incompatibility of services and pricing specifications, have overwhelmed software engineers and IT managers and have made the realization of Intercloud a very challenging task [8]. While the definition of a common service and pricing policy is a matter of finding common ground among the CSPs' viewpoints in the way the cloud products are advertised and delivered over the Internet, circumventing the differences in virtualization technologies will require the adoption of flexible platforms such as the Open Virtualization Format (OVF) or ISO 17203, ehich was proposed by the Distributed Management Task Force (DMTF). The OVF standard attempts to provide the industry with a standard packaging format for software solutions based on virtual systems. By providing an open and platform-independent as well as an extensible packaging and distribution format, which facilitates VM migration, OVF suits the needs of software vendors and CSPs. As for the API divergences, initiatives such as the Simple Cloud API that sets developers free to write portable codes that can interoperate with multiple cloud vendors stands out as an enabling technology to make Intercloud attainable. However, in order to obtain further system gains, performance optimization studies to ensure full cross-cloud compatibility and transparency with minimum overhead should still be pursued to leverage the users' satisfaction as well as the revenues of the CSPs.

Last but not the least, the unwillingness to share the market and unveil the business strategies of some CSPs also emerge as roadblocks in the development process of the Intercloud ecosystem and might seriously postpone its massive worldwide launch. This will ultimately impede the efforts of small CSPs and mobile application developers to fully enjoy at short and medium terms the immense potential of the Intercloud ecosystem.

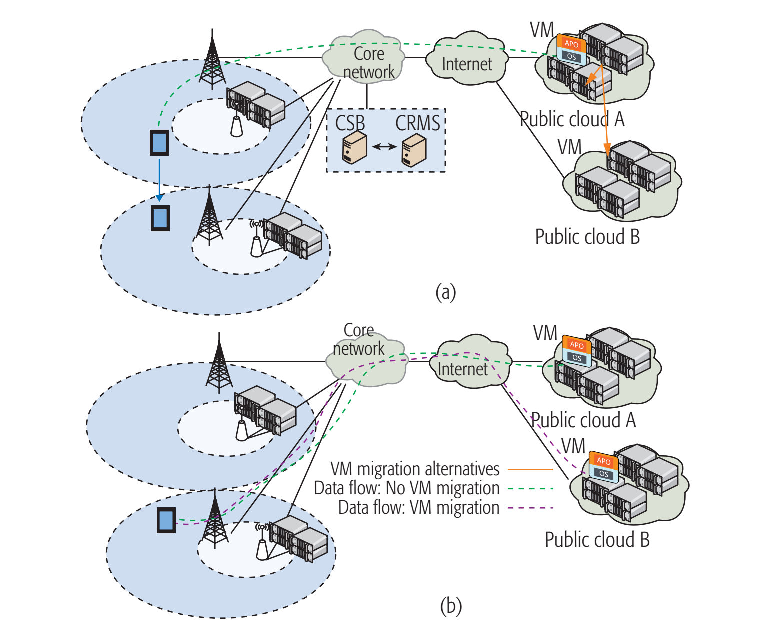

FIGURE 3. User moving from macro cell to macro cell: a) VM migration alternatives; and b) with and without VM migration.

Massive Storage for Mobile Big Data

As cloudlets become more pervasive, cloud storage service at massive scale for mobile big data will arise as a promising and profitable service to be offered by MNOs. The coalition with an Intercloud will enable CSPs to back up the mobile user big data when cloudlets are running out of space or to successfully deal with spikes in storage needs. Furthermore, multiple clouds will lead to a more robust service since the storage redundancy may be spread across them. Finally, a data replication strategy may be engineered in such a way that the data could chase the UE and be stored in the closest cloudlet or local CSPs, so that the UE could rapidly retrieve it when needed.

From a design perspective, the problem of massive storage for mobile big data turns into the problem of shipping goods from the supply nodes to the demand nodes where the supply nodes are the UEs, the goods are the big data, and the demand nodes are the clouds. Considering this abstraction, network optimization techniques can be applied to find the best transmission and storage strategy.

Exploitation of Ecosystem Diversity

The inherent diversity of technologies is undoubtedly the most attractive feature of a realization of an Intercloud over a HetNet to meet the increasing variety of applications and services as well as the volume of mobile data traffic. In the wireless domain, advanced CRRM schemes might be designed to intelligently and instantaneously switch among RATs that offer the better QoS and QoE conditions. Similarly, in the cloud domain, virtualization may perform a similar task by taking the VMs close to UEs automatically and allocating as many VMs as needed even over different CSPs on a as-needed basis.

More sophisticated schemes can exploit parallelism in both domains to speed up the offloading process. From the perspective of a running task, it becomes obvious to exploit as many connections as possible to reach the cloud in a timely manner as well as being processed as quickly as possible or stored in multiple clouds. Challenges for parallelism stem from both domains. For instance, parallelism over wireless networks, which was investigated in [9] and references therein, consists in simultaneously transmitting over multiple wireless networks. Extending these results for MCC applications arises as a relevant open issue to be investigated in particular if decoupling uplink and downlink access are taking into account. Enabling simultaneous processing of MCC applications across multiple cloud data centers, which do not necessarily belong to the same CSP, will equally demand technical challenges such as efficient management strategies to fragment the application into smaller pieces, send them across different channels, synchronize their execution, and ensure their possible communication and information exchange in a timely manner, as well as a well-rounded SLA specification and compliance among the parties to ensure data protection and timely communications.

Energy Efficiency

As the energy footprint of the information and communications technology sector soars, wireless networks and cloud data centers, which operate on a 24/7 basis to respond to ever-growing demand, must have their designs overhauled to meet the environmental, social, and economic expectations. Sustainable design has been investigated in cloud computing and HetNets individually. For instance, from the HetNet side, the utilization of energy-aware CRRM schemes, which coordinate the switching on and off of some BSs under light load, stand out as one of the most important eco-friendly strategies to achieve network-wide energy savings. From an individual BS perspective, the dynamic deactivation of some BS sub-units has been proved to be a successful approach to diminish power consumption as well

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[10]. From the cloud data center side, one of the most important green techniques is the adoption of energy-proportional dynamic voltage and frequency scaling (DVFS) [11], which adjusts the voltage and clock frequency to match the application demand and thereby reduce energy consumption. From a management perspective, VM migration and VM placement have been receiving a great deal of attention by optimizing where the VM shall be processed in terms of geo-location and physical machines [12]. Such a high degree of granularity in controlling VM resources enables the application of power management protocols to green the system operation [11].

Considering a coexistence between a BS and a cloudlet in the same site and the potential replication of this architecture due to the small cell densification, the design of energy-aware policies that jointly manage the BSs and the servers is an important open topic to be investigated in order to reach a steady sustainable network operation. In such an environment, answering questions such as *should the servers be independent from the BS operation in an activation and deactivation scheme*, or *how to coordinate VM migration, VM placement, and CRRM to achieve energy-efficiency*, will be paramount.

Revenue Sharing

Revenue sharing, which refers to a fair division of the monetary gains due to the service providers' cooperation, is one of the most important aspects related to the realization of an Intercloud over a HetNet. In [13], a revenue sharing method was analyzed where cooperative players in an MCC environment can share radio and computing resources with one another by forming coalitions with the objective to maximize their revenues. After presenting a set of optimization models, the authors devised a revenue management approach, which relies on the concept of Shapley value to define the revenue sharing among the service providers (application owners), the MNO, and the CSPs. For this setting, the mobile user must pay the service provider that is responsible for ensuring the execution of his MCC application as well as sharing the monetary gains with the MNO and the CSPs for ensuring the communications and computing resources. The results showed some evidence of the benefits collected by cooperative mobile CSPs in terms of an increase in their revenues.

For the cloud resource management problem, the work in [14] proposed an Intercloud economic framework for regulating the negotiation among users and CSPs as well as the formation of coalitions among CSPs. While the interactions between users and CSPs is based on a many-to-many negotiation model, the formation of an Intercloud coalition is regulated by a game-theoretic model, and the Shapley value is used to quantify the pay-off of each player.

In the next section, we will present a joint resource allocation and revenue sharing approach in a HetNet and Intercloud setting. Unlike [13], our goal is to define a UE association that maximizes the revenue and optimizes resource allocation between the MNO and the clouds (cloudlets and third party clouds). We will use the concept of Shapley value which ensures a fair sharing of the total revenue. Unlike [14], our work embraces a coalition between the CSPs and the MNO within a vision of Intercloud and HetNet interoperation.

Optimal Resource Allocation and Revenue Sharing

Among the many design aspects and challenges discussed in the previous section, we focus on the problem of optimal joint resource allocation and revenue sharing in a coalition formed by a MNO and CSPs for an Intercloud over a HetNet. To optimize the resource allocation and thereby maximize the revenue for a coalition, it is necessary to find the best association between a UE and a cloud through a particular BS.

Problem Formulation

We consider a system such as the one shown in Fig. 2a where a coalition is formed between an MNO and the CSPs to serve UEs to run their mobile cloud applications. Our goal is to define a formal framework to provide an optimal and fair revenue sharing strategy among each player in the coalition, given their individual contribution. To achieve this goal, we first present an integer linear programming model that provides the maximum revenue for each coalition while giving the optimal UE association. Second, we use the concept of Shapley value to individualize the contribution of each player based on the maximum revenue for the optimal user association.

Let $\mathbf{R} = \{1, ..., R_e\}$ be the set of covered regions where R_e is the total number of regions. Let $\mathbf{R_{sc}} = \mathbf{R} - \{R_e\}$ denote the set of regions covered by the small cells and $\{R_e\}$ denote the macro cell coverage only. Let $\mathbf{U}^r = \{1, ..., N^r\}$ denote the set of UEs in the r^{th} region where N^r is the total number of active UEs in the given region. We define $N^r = N^r_{sc}$ if $r \in \mathbf{R_{sc}}$ and $N^r = N^{Re}$ if $R = \mathrm{R}_e$. Let $N = \Sigma_{r \in \mathbf{R}} N^r$ be the total number of active UEs in the coverage area.

Let $\mathbf{B} = \{1, ..., B_s\}$ be the set of BSs where B_s is the total number of BSs. Let $\mathbf{C} = \{1, ..., C_d\}$ be the set of all clouds where C_d is the total number of clouds. Let $\mathbf{C_{cl}} = \mathbf{C} - \mathbf{C_t}$ be the set of cloudlets and $\mathbf{C_t} = \{R_e, ..., C_d\}$ be the set of third party CSPs. Note that since there is no cloud directly supporting the macro BS, then the set of third party cloud starts on R_e. Since every region is covered by at least a BS, $\mathbf{B} \equiv \mathbf{R}$. Additionally, since every small cell has a cloudlet, $\mathbf{R_{sc}} \equiv \mathbf{C_{cl}}$. It is assumed that a UE in a double coverage region ($r \in \mathbf{R_{sc}}$) can connect either to its small cell BS or the macro cell BS, while a UE in the single coverage region ($r = R_e$) can connect to the macro BS only. Similarly, a UE in a double coverage region can access its immediate cloudlet or any third party CSP. while a UE in the single coverage area can only access the third party CSPs.

$$v(\mathbb{C}) = \max_{x_{r,u,b,c}} \sum_{r\in\mathbf{R}} \sum_{u\in\mathbf{U}^r} \sum_{b\in\mathbf{B}} \sum_{c\in\mathbf{C}} x_{r,u,b,c}\Pi_r \qquad (1)$$

subject to:

$$\mathfrak{C}1: \sum_{r\in\mathbf{R}} \sum_{u\in\mathbf{U^r}} \sum_{c\in\mathbf{C_t}} x_{r,u,b,c} \le N, b = R_e$$

$$\mathfrak{C}2: \sum_{u\in\mathbf{U^r}} \sum_{c\in\{\{r\}\cup\mathbf{C_t}\}} x_{r,u,b,c} \le N^r_{sc}, r\in\mathbf{R_{sc}}, b = r$$

$$\mathfrak{C}3: \sum_{b\in\{\{r\}\cup\{R_e\}\}} \sum_{c\in\{\{r\}\cup\mathbf{C_t}\}} x_{r,u,b,c} \le 1, r\in\mathbf{R_{sc}}, u\in\mathbf{U^r}$$

$$\mathfrak{C}4: \sum_{c\in\mathbf{C}_t} x_{r,u,b,c} \le 1, r = R_e, b = R_e, u\in\mathbf{U}^{R_e}$$

$$\mathfrak{C}5: \sum_{r\in\mathbf{R}} \sum_{u\in\mathbf{U^r}} \sum_{c\in\mathbf{C_t}} x_{r,u,b,c}\delta \le \Delta^{R_e}_{bs}, b = R_e$$

$$\mathfrak{C}6: \sum_{u\in\mathbf{U^r}} \sum_{c\in\{\{r\}\cup\mathbf{C_t}\}} x_{r,u,b,c}\delta \le \Delta^r_{bs}, r\in\mathbf{R_{sc}}, b = r$$

$$\mathfrak{C}7: \sum_{r\in\mathbf{R}} \sum_{u\in\mathbf{U^r}} \sum_{b\in\{\{r\}\cup R_e\}\}} x_{r,u,b,c}\upsilon \le \Upsilon_c, c\in\mathbf{C_t}$$

$$\mathfrak{C}8: \sum_{u\in\mathbf{U^r}} x_{r,u,b,c}\upsilon \le \Upsilon_c, r\in\mathbf{R_{sc}}, b = r, c\in\mathbf{C_{Cl}}$$

$$\mathfrak{C}9: x_{r,u,b,c} \in \{0,1\}, r\in\mathbf{R}, u\in\mathbf{U}^r, b\in\mathbf{B}, c\in\mathbf{C}.$$

The optimization formulation (which is an integer linear program) is given above whose objective function is given by Eq. 1 subject to the constraints $\mathfrak{C}_1$ to $\mathfrak{C}_9$. The objective function is to maximize the revenue that is attained from the coalition between the MNO and CSPs. In this sense, $\upsilon(\mathbb{C})$ is the worth of the coalition for the optimal UE association. Thus, $x_{r,u,b,c}$, which is a binary variable as specified in the constraint $\mathfrak{C}_9$, can be interpreted as an association between the u^{th} UE, which is in the R^{th} region, and the c^{th} cloud through the b^{th} BS where Π_r is the revenue obtained per admitted UE. As a way of prioritizing the UE attachment to its small cell BS, we set Π_r ($r \in \mathbf{R_{sc}}$) > Π_{Re}, which is the revenue obtained per UE associated to the macro cell. The reasoning behind this setting is to make the optimizer look for a biased association of the UEs to the small cells rather than to the macro cell in order to offload traffic from macrocells to small cells.

The constraint $\mathfrak{C}_1$ ensures that the number of active UEs attached to the macro BS will not surpass the number of active UEs in the region under analysis. The constraint $\mathfrak{C}_2$ states that the number of active UEs attached to a particular small cell BS will not surpass the number of active UEs in the respective region regardless of the destination cloud. The constraint $\mathfrak{C}_3$ implies that a UE within a double coverage region will connect to a single cloud over a single BS, while the one in $\mathfrak{C}_4$ ensures that the UE in a single coverage area will connect to a single CSP through the macro BS. The constraint $\mathfrak{C}_5$ maintains the amount of wireless resources utilized at the macro BS to be less than or equal to its available capacity, while the one in $\mathfrak{C}_6$ can be equally interpreted for small cells. In $\mathfrak{C}_5$ and $\mathfrak{C}_6$, δ and Δ^r_{bs} ($r \in \mathbf{R}$) are the bandwidth required per UE and the capacity of the b^{th} BS, respectively. The constraint $\mathfrak{C}_7$ ensures that the total amount of computing resources must not exceed the maximum resource capacity offered by the third party CSP, while the one in $\mathfrak{C}_8$ has the same significance but is applied for the cloudlets. In $\mathfrak{C}_7$ and $\mathfrak{C}_8$, υ and Υ_c ($c \in \mathbf{C}$) stand for the server utilization required per UE and the number of servers, respectively.

In order to fairly divide the optimal revenue within members of the coalition, we apply the concept of Shapley value. The Shapley value for revenue sharing is based on the premise that a member in a coalition should receive a pay-off that is proportional to her marginal contribution.

In order to fairly divide the optimal revenue within members of the coalition, we apply the concept of Shapley value. The Shapley value for revenue sharing is based on the premise that a member in a coalition should receive a pay-off that is proportional to their marginal contribution. Considering the optimal revenue $\upsilon(\cdot)$ obtained from Eq. 1, the Shapley value for the i^{th} service provider in the coalition $\mathbb{C}$ is given by Eq. 2, where $\mathbb{S}$ is a sub-coalition:

$$\phi_i(v) = \sum_{\mathbb{S}\subseteq\mathbb{C}\setminus\{i\}} \frac{|\mathbb{S}|!(|\mathbb{C}|-|\mathbb{S}|-1)!}{\mathbb{C}!}\left[v(\mathbb{S}\cup\{i\}) - v(\mathbb{S})\right]. \qquad (2)$$

The interpretation of Shapley value of the i^{th} service provider in (2) is as follows. The quantity $[\upsilon(\mathbb{S} \cup \{i\}) - \upsilon(\mathbb{S})]$ is the amount which the ith service provider adds to the coalition $\mathbb{S}$. The quantity

$$\frac{|\mathbb{S}|!(|\mathbb{C}|-|\mathbb{S}|-1)!}{\mathbb{C}!}$$

denotes the probability that, upon their arrival, the ith service provider finds that the coalition has already been formed. The numerator in

$$\frac{|\mathbb{S}|!(|\mathbb{C}|-|\mathbb{S}|-1)!}{\mathbb{C}!}$$

represents the different ways in which the $|\mathbb{S}|$ service providers might join the coalition prior to the arrival of the ith service provider, while the denominator is the total number of permutations of the service providers.

Numerical Results

Consider a system where the MNO forms a coalition with a CSP. In the system under analysis, the HetNet is formed by a macro cell and two small cells. In each double coverage region there are five active UEs, and in the single coverage area there are 10 active UEs. We consider that all active UEs are running a speech recognition application whose communication and computation requirements are 3 Mb/s and 22 percent of server utilization, respectively [13]. Also, we set $\prod_r$ = 10 monetary units per UE for an association to a small cell ($r \in \mathbf{R_{sc}}$), and $\prod_{Re}$ = 8 monetary units for per UE for an association to a macro cell. We implement and solve the integer linear programming model using the AMPL/CPLEX solver running in the NEOS Server, a free Internet-based service to solve numerical optimization problems [15].

Figure 4a and Fig. 4b illustrate the benefits of the cooperation between the MNO and the CSP. Figure 4c and Fig. 4d show the number of UEs connected to the small BS #1 and its cloudlet and the cloud belonging to the CSP based on the optimal resource allocation model. Notably, we can see that for the non-cooperative setting, the MNO is limited to its cloudlets to support the MCC applications. Consequently, MCC applications from the UEs into the macro cell region only are not monetized. Similarly, the CSP, which is unable to sell broadband wireless services, does not make profit without forming a partnership with the MNO.

For Fig. 4a and Fig. 4c, the initial setup considers that each cloudlet has two servers and the CSP has five servers, and the capacities of the macro BS and each small cell BS are 25 Mb/s and 10 Mb/s, respectively. From this point onward, the bandwidth of each BS is increased by one Mb/s. Without cooperation, there is growth in the MNO's revenue only, which is due to the support of more UEs in the double coverage. Figure 4c ratifies this observation by showing that the number of UEs in the BS #1 with and without cooperation coincide, and the number of UEs served by the macro BS is zero. However, when the cooperation is triggered, the revenues of both MNO and CSP improve considerably, especially because the UEs, which are only under the coverage of the macro cell, become activated and their contributions increase with the increase in macro BS capacity.

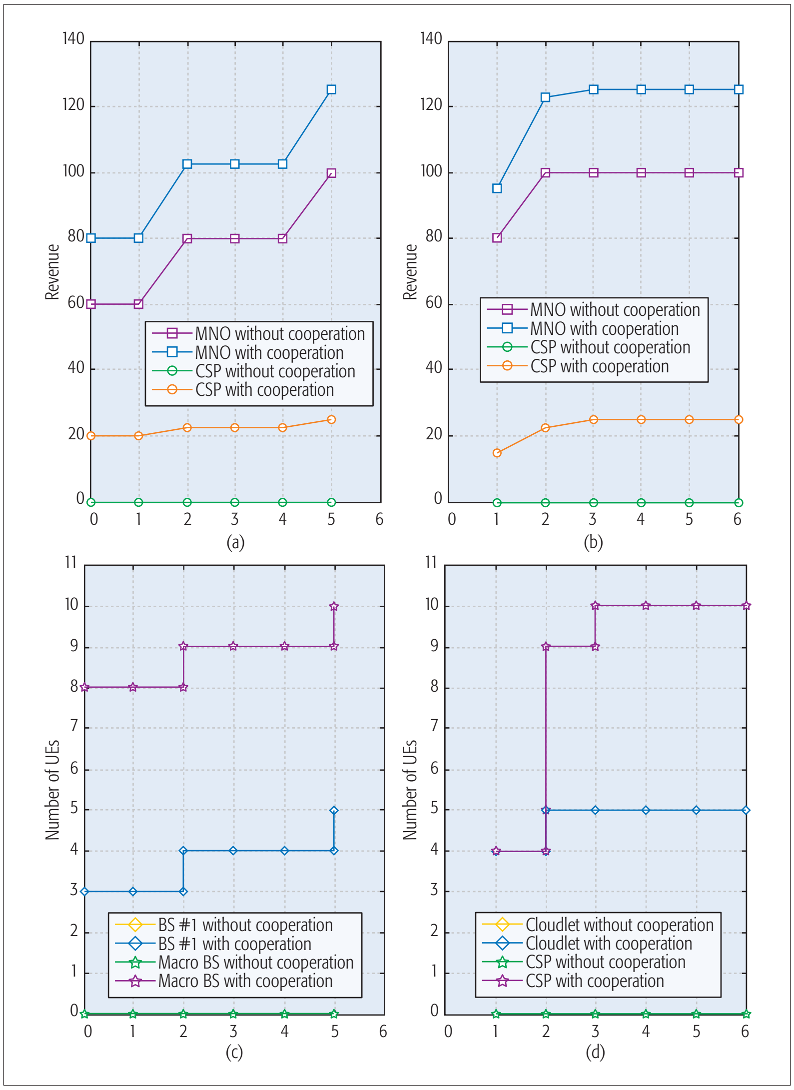

FIGURE 4. a) revenue of MNO and CSP with and without cooperation versus bandwidth per cell (Mb/s); b) revenue of MNO and CSP with and without cooperation versus number of servers per cloud; c) number of users versus bandwidth per cell (Mb/s); and d) number of users versus number of servers per cloud.

For Fig. 4b and Fig. 4d, we set the capacity of the macro BS and each small cell BS as 30 Mb/s and 15 Mb/s, respectively, which is the last wireless configuration of Fig. 4a where all UEs are assisted due to the HetNet capacity. For this case, our objective is to understand the effect of cloud capacity on system performance. Thus, we vary the number of servers in each cloud from 1 to 6. Figure 4b shows that after an initial upward shift, the revenues of the MNO and the CSP reach a steady trend, because the additional capacity provided by the growing number of servers outgrows the demand, which stabilizes the revenue. Figure 4d confirms this observation, showing that all UEs are being served after the deployment of two and three servers in cloudlet #1 and in the third party cloud, respectively. It also shows that the cooperation unleashes the potential to support UEs into the macro cell region only, which in turn culminates in increased revenue.

Summary and Outlook

We have presented how HetNets and Intercloud can be jointly considered to meet the increasing demand for mobile cloud computing. We have discussed some challenges and criteria that can be taken into account in the system design, and put forward an approach to optimize revenue sharing among mobile network operators and cloud service providers when cooperatively attending a given service region. The proposed approach initially maximizes the coalition's revenue while performing an optimal user association considering the resources from the HetNet and the Intercloud as well as the UE location. After that, it applies the concept of Shapley value to equitably divide the revenue among the mobile network operator and the cloud service providers. In the proposed optimal resource allocation model, we consider that all applications have the same requirements in terms of communications and computing. We are currently considering to generalize the optimal resource allocation model to support multiple applications with different requirements.

Given the NP-hardness of integer linear programming, the application of the proposed user association model to large-scale deployment might be intractable. In this case, heuristic methods will be required while the use of Shapley value would remain the same.

A few potential directions for future research are outlined as follows.

Design of advanced resource allocation and pricing models: The problem of resource allocation among UEs in an Intercloud over HetNet scenario should be investigated, considering both cooperative and non-cooperative behaviors among the CSBs and/or among the MNOs. In this context, different market models as well as auction models (e.g. multiple seller-multiple buyer multi-commodity auctions) can be investigated.

Design of efficient handoff and VM migration schemes: As has been discussed earlier, due to user mobility, a key problem is the design of efficient handoff management and VM migration schemes under different network settings. Distributed solutions (e.g., those based on Markov Decision Process formulations) with low network overhead and complexity will be desirable.

Design of optimal computation offloading strategies: In the presence of multiple cloud service providers as well as local cloudlets in the access network, optimal strategies for computation offloading can be designed considering the availability of wireless resources in the HetNet as well as computation resources in the clouds, the cost of computation offloading, and energy efficiency resulting from computation offloading. Distributed strategies will be preferable for better system scalability. In this context, game theoretic models (e.g., minority game models) can be developed, and optimal distributed strategies can be designed.

Cloud-centric solutions for Internet of Things (IoT) over HetNets: The anticipated IoT data deluge, where devices will ubiquitously and wirelessly acquire and convey data, will call for the development of cloud-centric solutions for IoT over HetNets. IoT can heavily exploit the ubiquity and high-capacity of HetNets to implement massive data transmission and the resource-richness of Intercloud to achieve massive data storage. However, how to engineer such a solution considering the characteristics of massive IoT applications and the related QoS requirements in the presence of different cloud service providers is an important research problem that will need to be addressed.

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