Cloud Assisted HetNets Toward 5G Wireless Networks

To support the massive growth of mobile data, a large number of small cells are expected to be deployed, giving rise to HetNets, considered to be the key path toward 5G. With such large-scale HetNets, network operators face many serious challenges in terms of operation and management, cost-effective small cell deployment, and intercell interference mitigation. To deal with those issues, the authors introduce a cloud based platform designed to simplify the deployment, operation, and management, and facilitate round-the-clock optimization of the network, to pave the way for the development of 5G.

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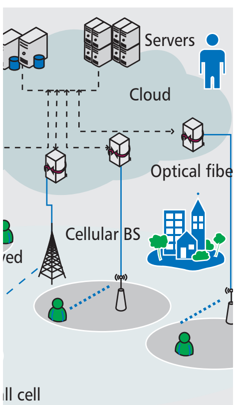

Abstract

With the proliferation of connected devices and emerging data-hungry applications, the volume of mobile data traffic is predicted to have a 1000-fold growth by the year 2020. To address the challenge of this data explosion, industry and academia have initiated research and development of 5G wireless networks, which are envisaged to cater to the massive data traffic volume, while providing ubiquitous connectivity and supporting diverse applications with different quality of service (QoS) requirements. To support the expected massive growth of mobile data, a large number of small cells are expected to be deployed indoors and outdoors, giving rise to heterogeneous networks (HetNets), which are considered to be the key path toward 5G. With such large-scale HetNets, network operators face many serious challenges in terms of operation and management, cost-effective small cell deployment, and intercell interference mitigation. To deal with those issues, a cloud based platform is introduced, aiming to simplify the deployment, operation and management, and facilitate round-the-clock optimization of the network, to pave the way for the development of 5G. Two case studies are provided to illustrate the benefits of the cloud based architecture. Finally, the related standardization activities are provided and some research topics essential for a successful development of 5G are discussed.

Introduction

There has been an explosive growth in mobile data traffic volume, which almost doubles every year. According to the Cisco Visual Networking Index (VNI) [1], mobile data traffic volume is expected to grow at a compound annual growth rate (CAGR) of 61 percent from 2013 through 2018. Furthermore, it is predicted that data traffic volume will continuously grow up to 1000 times its value in 2010 by 2020, referred to as the 1000x data challenge.

The main factors accounting for the significant growth in mobile data traffic are two-fold: the proliferation of devices and the emergence of data-hungry applications. It is predicted by Qualcomm that 25 billion devices will be connected by 2020, due to the ever increasing use of smart phones and the promise of machine-to-machine (M2M) communication, Internet of things (IoT), and Internet of Vehicles (IoV) [2]. Data-hungry applications such as high resolution image transfer and video streaming will furher add to the volume. A standard definition and a high definition movie have 2.49 GB and 5.93 GB of data, respectively. Moreover, diverse types of applications have various quality of service (QoS) requirements. For instance, a high-definition movie transfer requires a very high data rate, while a safety message exchanged by a connected car requires a very low latency. Consequently, wireless networks are facing great challenges to accommodate such a large volume of data and meet the users' service demands [3].

The 5G wireless network promises to address the 1000x data challenge and handle a multitude of applications with diverse QoS requirements. It is expected to be a fully connected network and provide different QoS provisioned services to anyone and anything, at anytime and anywhere. It requires 1000x of 4G capacity, latency as low as 1 millisecond, and high energy and cost efficiency. Due to the urgency and importance of 5G, industry and government agencies initiated the research worldwide to facilitate the development of 5G. For instance, the European Commission pledged 50 million Euros in 2013 to fund 5G research, and a project called METIS has started to establish the foundation of 5G.

To develop 5G, efforts have been made in three areas: spectrum expansion, spectrum efficiency enhancement, and network densification. Network densification is considered to be the paramount and dominant approach to address the data challenge. It can be achieved by deploying a large number of small cells, such as microcell, picocell, femtocell, relay nodes, and Wi-Fi access points, which are low-powered radio access nodes and have smaller coverage areas compared with marcocells. Due to the dense deployment of small cells on a very large scale, the increased level of complexity, coupled with reduced control over applications and data, network operators are facing great challenges:
- Difficult to manage and control.
- Costly to deploy small cells densely.
- Intercell interference.

Those factors affect and limit the development of 5G.

In this article, to overcome the above issues, a cloud based platform is introduced, where small cells are connected to the cloud for management and control. With the cloud based platform, the operation and maintenance can be easily performed. Furthermore, centralized management facilitates round-the-clock optimization of the network, allowing the network operator to efficiently use network resources to support different applications while adapting to the changing service demands. Three main applications are discussed: operation and maintenance, a cloud assisted business model for small cell

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Compared with conventional cellular communication, only half of the resources are required in direct communication. As a result, it can significantly improve the spectral efficiency. Moreover, transmission power can be saved since the communication is carried out between two adjacent nodes.

deployment, and cloud assisted interference coordination. Two case studies are provided, where the cloud is utilized for deployment and interference mitigation. Finally, the related standardization activities and some research topics are provided.

The remainder of this article is organized as follows. The evolution of 5G is presented. The main challenges to achieve 5G are discussed. The cloud platform for 5G is introduced, followed by the case studies. Standardization progress is provided, followed by the conclusion and future works.

Evolution of 5G

To meet the tremendous demand for data, three approaches can be considered: spectrum expansion, spectrum efficiency enhancement, and network densification.

Spectrum Expansion

To meet the expected explosive growth in data traffic and the diverse QoS requirements, it is necessary to exploit more spectrum by means of spectrum expansion. Specifically, the low spectrum bands with good penetration and signal propagation properties, e.g., the TV whitespace ranging from 572–698 MHz around 700 MHz, can be utilized to improve the building penetration and provide improved coverage for connectivity. The standards IEEE 802.22 and IEEE 802.11af specify how to exploit TV whitespace. In contrast, spectrum in the high frequency bands have larger bandwidths and can support higher data rates, such as spectrum around 3.5 GHz or millimeter wave frequency spectrum around 60 GHz. Moreover, because of the large path loss, high spectrum bands are well suited to small cells with a short communication range.

Spectrum Efficiency Enhancement

Network capacity can also be enhanced by improving spectrum efficiency. In this regard, various wireless technologies have been continuously evolving to improve spectrum efficiency.

Massive MIMO: Massive MIMO is typically comprised of a few hundred inexpensive antenna components, which can focus transmission energy in certain directions and consequently increase throughput and save energy significantly. Moreover, it can also facilitate concurrent transmissions to serve multiple users at the same time. With massive MIMO, capacity can be increased by 10 times or more and the radiated energy efficiency can be improved in the order of 100 times. For implementation, a 100 × 100 massive MIMO testbed based on xTCA standards, namely TitanMIMO, has been developed by a company called Nutaq to enable practical 5G massive MIMO development.

Cognitive Radio: Cognitive radio (CR) has been considered as a powerful technique to increase spectrum efficiency by enabling unlicensed users to access unused spectrum opportunistically [4, 5]. Two main paradigms to efficiently utilize spectrum are spectrum sensing and spectrum database. For the former, unlicensed users sense the spectrum to detect the availability of channels before transmission, and access the channels only when idle. For the latter, unlicensed users can acquire the availability of channels through spectrum databases before accessing the channels. Google and Microsoft have launched spectrum database products for TV white spaces, enabling users to easily obtain the available TV channels for access.

Device-to-Device Communication: The emerging device-to-device (D2D) communication paradigm enables devices in close proximity to communicate with each other directly without sending data to the base station (BS) or the core network [6–8]. Compared with conventional cellular communication, only half of the resources are required in direct communication. As a result, it can significantly improve spectral efficiency. Moreover, transmission power can be saved since the communication is carried out between two adjacent nodes. In addition, D2D communication can reduce delay, which is favorable for latency-sensitive applications.

Network Densification

Compared with spectrum expansion and spectrum efficiency enhancement, network densification is considered to be the dominant approach to boost capacity [9]. It is achieved by densely deploying small cells, such as microcells, picocells, or femtocells, which bring access points closer to users so that network capacity can be dramatically increased and latency can be reduced. Those small cells are the access points with lower transmission power and smaller coverage areas, such as LightRadio from Alcatel-Lucent, LiquidRadio from Nokia Siemens Network, and AtomCell and LampSite from Huawei. Moreover, data traffic originated from indoor users can also be served by Wi-Fi, such as the next generation Wi-Fi 802.11ac, which expects to support multi-gigabit data transmission rates. Such multi-tier networks with a variety of radio access technologies are referred to as heterogeneous networks (HetNets).

For more details on the paths toward 5G, please refer to the [10].

Challenges for Dense Deployment of Small Cells

Although HetNets play a vital role for 5G, the excessive deployment of small cells will pose significant challenges for network operation and management, deployment, and so on.

Network Deployment

Non-technical users may have difficulty deploying their small cells. Furthermore, the inappropriate configuration or installation done by users may cause a negative impact on the existing systems. Additionally, even though users may deploy some small cells for their own service, the network operator still needs to deploy a large number of small cells, which is very challenging due to the following reasons:

- Network operators are on a tight budget since they are buckling under the strain of continuously adding network infrastructures.

- The large-scale deployment of small cells is costly to network operators, in terms of the operating and capital expenditure, such as site lease, installation costs, additional costs for electricity and backhaul[1], and operating expenses. Therefore, the issue of how to deploy the small cells densely in an easy and cost-efficient way needs to be carefully addressed.

Operation and Management

With a large number of small cells, network operation and management becomes very complex as it needs lots of human effort to install, configure, monitor, and maintain the small cells. Additionally, the traffic may change frequently, depending on the location and time, so it is difficult for the network operator to efficiently use the network resources by managing the small cells at different sites to adapt to the changing demands. Further, small cells can be switched On/Off or moved at any time by the users and they are beyond the reach of the network operators, making optimization and management of the network very challenging [11].

Intercell Interference Mitigation

As the network density increases, inter-cell interference is more likely to happen, which significantly limits the gain achieved by the densely deployed small cells. In HetNets, intercell interference can arise in different scenarios. For example, the macrocell may create severe interference to the users in the small cell and the users of macrocells might receive interfering signal from the adjacent small cells. The interference is reflected in a lower signal to interference plus noise ratio (SINR), which degrades the network performance and the user experience. Without mitigating interference among different cells, HetNets cannot be successfully deployed. One way to cope with intercell interference is spectrum splitting, where the whole spectrum is divided into different parts for different cells. However, this leads to inefficient spectrum usage. Intercell interference coordination (ICIC) is introduced in 3rd Generation Partnership Project (3GPP) release 8 to mitigate interference. It coordinates the network resources among different cells by exchanging messages. However, due to the unplanned deployment of small cells by users, it is hard to coordinate the small cells in that manner.

Cloud Assisted HetNets

Cloud computing is becoming increasingly important in today's business due to benefits such as greater flexibility, increased security, scalability, and low cost. To address the challenges stated in the previous section, we introduce a cloud based architecture for HetNets, which utilizes the cloud as the control and management plane of the network[2]. By doing so, the installation, monitoring, management, and upgrade can be easily performed. Furthermore, the centralized management facilitates the round-the-clock optimization of the network, which helps the network operator make efficient use of network resources to satisfy different QoS requirements and adapt to changing demands [13].

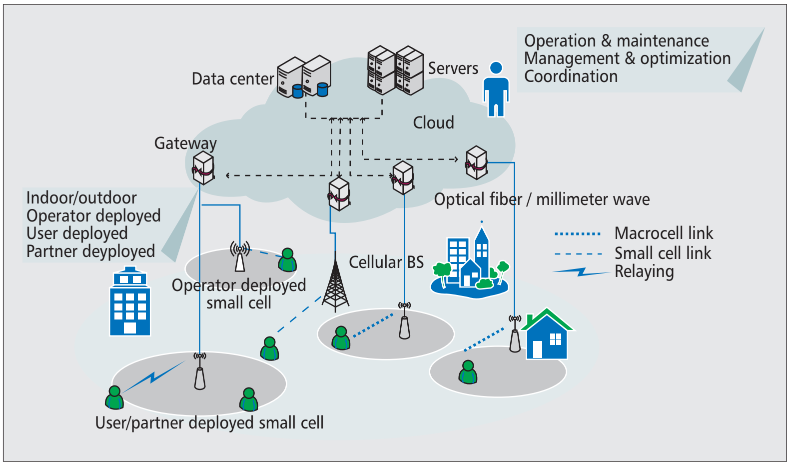

Figure 1. Cloud managed HetNets.

A similar concept is the cloud radio access network (C-RAN), which distributes radio head ends at different locations and pools the baseband processing elements in the cloud. The distributed radio head ends are only responsible for providing an air interface to users, while the cloud processes the users' data from the radio heads. Different from C-RAN, the cloud in the proposed architecture does not process the users' data and the small cells do not to send the users' data to the cloud for processing. Instead, it mainly focuses on operation, maintenance, and management of small cells to provide services by efficiently using network resources.

As shown in Fig. 1, the small cells are deployed densely in the network, either in indoor environments such as homes and offices, or in outdoor scenarios such as road intersections, squares, stadiums, etc. The network operator and the end users or third parties can deploy small cells with open and closed access modes, respectively. Small cells are connected to the cloud through high-speed optical fiber or mmWave. Monitoring, configuration, optimization, and mobility control is centralized in the cloud. The centralized nature also allows the network operators to manage the networks in a more efficient way. Since the traffic demand may dramatically vary, the cloud based architecture helps the network operator to allocate resources on demand and coordinate small cells efficiently to provide services with seamless coverage, high data rates, and low latency. The users or third parties can make some basic configuration changes to their own small cells from a web browser, such as changing the access mode and setting the data rate limit, etc. In summary, the cloud can bring the following advantages to the wireless networks.

Easy maintenance and management: The cloud streamlines provisioning, management, and troubleshooting of multiple sites from a single platform. It can provide services such as remote monitoring, real-time diagnostics, central configuration, and device management. With the cloud, administrators or users can access the network data at any time and anywhere from a web browser.

Scalability: The cloud assisted architecture can simplify the deployment by configuring small

[1] Optical fibers are usually required to connect all the small cell base stations, which is costly. An alternative is mmWave-based high-speed wireless backhaul.

[2] The feasibility of introducing the cloud to manage the wireless network can be verified by Cisco's Meraki, which is a cloud controlled WLAN [12].

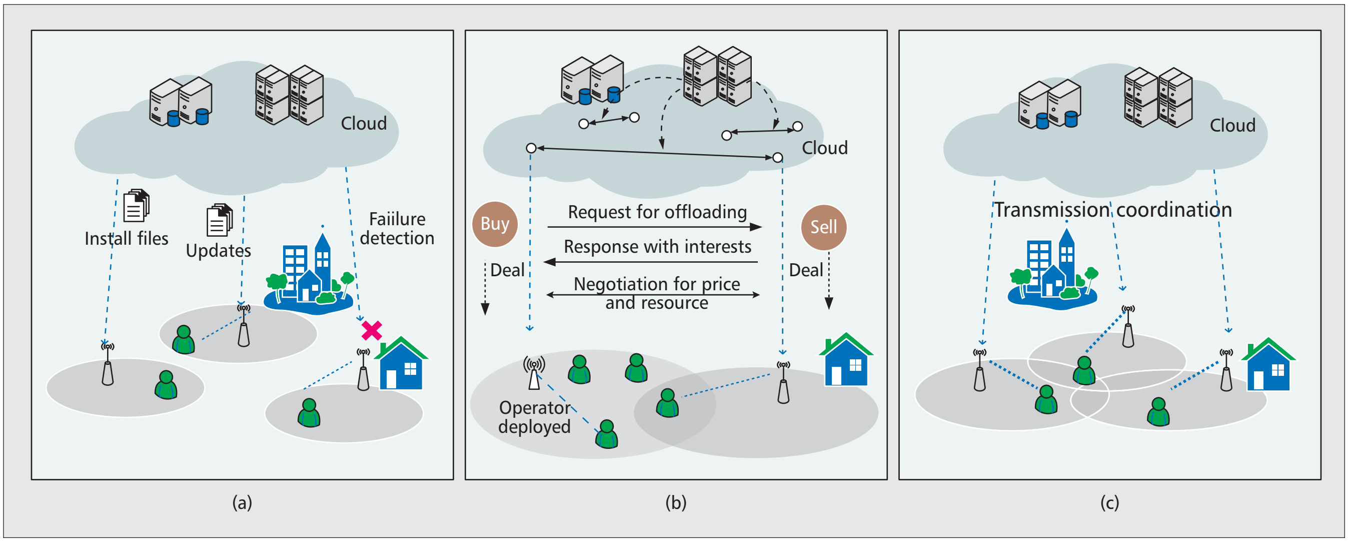

Figure 2. Typical cloud assisted applications in HetNets: a) operation and maintenance; b) cloud assisted business model for deployment; and c) cloud assisted interference mitigation.

cells through the cloud in order to facilitate a simple and quick installation of small cells when network expansions are required.

Efficiency: The cloud enables network operators to rapidly reallocate network resources to meet fluctuating and unpredictable user demands. For instance, in non-peak hours some small cells can be turned off and turned on again during peak hours through the cloud. Furthermore, the cloud helps optimize the performance of the network and intelligently balance the network load.

Low cost: The cloud can reduce the costs and burden to maintain the onsite management. With less need for people resources and more efficient management of network resources, the cloud can reduce the capital expenditure (CAPEX) and operational expenditure (OPEX) for deployment and operation of small cells.

With the cloud, many promising applications can be facilitated. We will now describe in detail three typical applications, as shown in Fig. 2.

Operation and Maintenance

As shown in Fig. 2a, the cloud based architecture provides the function of plug-and-play, where the small cells can be integrated into the existing network with minimal human involvement. When the small cell is initially powered, it automatically connects to the cloud and downloads necessary software and configuration data for installation and configuration. The cloud based architecture can also help monitor the status of small cells at different sites and automatically detect faults to reduce manual efforts. When there are some updates, the cloud can push the notification to the end users or automatically update the small cells. Moreover, it is easier to manage the small cells for the network operator and users or third parties. Users can have accounts in the cloud to change the setting of the small cells through a web browser such as enabling automatic update, setting maximum download/upload speed, changing access modes, etc.

Deployment

To meet traffic demand, the small cells need to be deployed densely. The expense for dense deployment will be huge for network operators. To facilitate the deployment of small cells, a cloud assisted business model is introduced, as shown in Fig. 2b. To encourage users or third parties (e.g., enterprises, facility owners, building proprietors, etc.) to deploy more small cells, the network operator can pay monetary rewards whenever the user-deployed or third party-deployed small cells provide service to the network operator. The users or third parties can set their small cells to be in open access mode for potential monetary rewards, allowing for providing better service to the customers of the network. For instance, those small cells can offload the traffic from the macrocell, or improve the transmission rate of the other users through relaying, etc. Since both the network operator and the users or third parties can receive benefits, it creates a win-win situation. The cloud can coordinate the service trading among different entities and keep the trading data (e.g., price, time, entities). Then the network operator grants the monetary rewards to the contributors based on the service data.

Interference Coordination

When the small cells are connected to the cloud, their transmissions can be coordinated through the cloud. This application can be regarded as an extension of coordinated multipoint transmission/reception (CoMP) included in 3GPP Release 11. Therefore, intercell interference mitigation can be facilitated, where the small cells are coordinated to transmit in different time slots or using different frequency bands, as shown in Fig. 2c. Moreover, the cooperation among the adjacent small cells can be enabled by the cloud, where joint transmission or joint beamforming can be leveraged to mitigate intercell inference. In other words, the small cells can serve a set of users simultaneously without interfering with each other through either precoding or interference cancelation schemes.

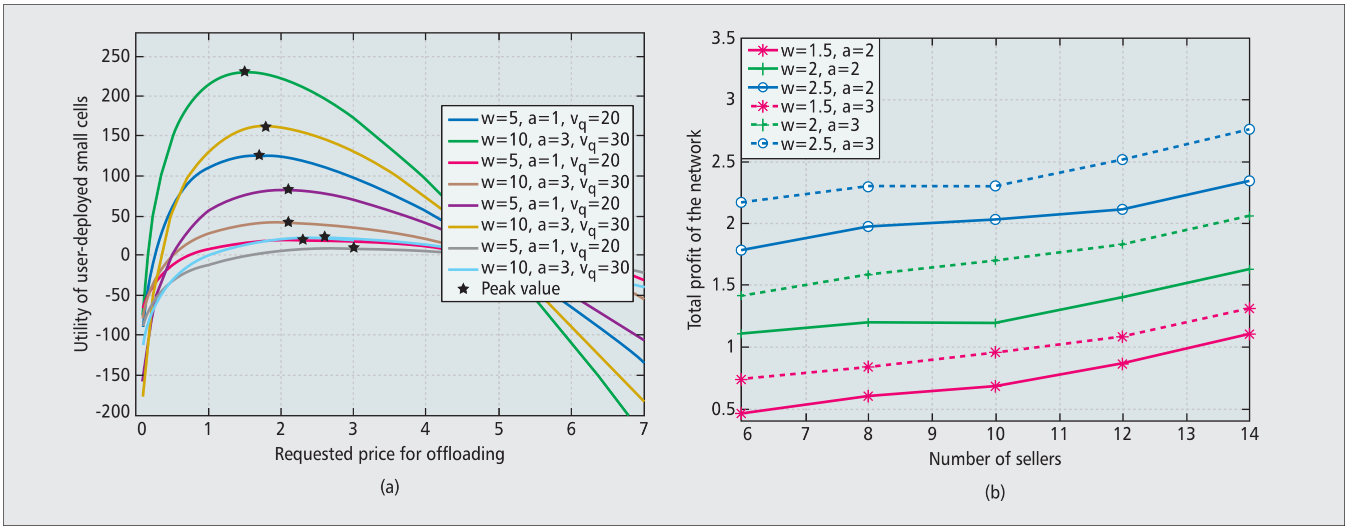

Figure 3. Cloud assisted business model for small cell deployment: a) utility of cooperative small cells versus the requested price; b) total profit of the network versus the number of cooperative small cells.

Case Studies

Cloud Assisted Business Model for Deployment

In what follows, we study a special case in which the network operator deployed cells are overloaded in specific locations or time slots. In such a case, the operator deployed cells intend to recruit some potential user deployed small cells in close proximity for offloading. In return, the network operator pays a certain amount of credits to the contributors. To negotiate the payment and offloading volume, a buyer and seller game is applied. For the operator deployed cell (the buyer), the utility function U_b is given by $U_b = \omega f(v) - p \cdot v$, where $f(v)$ is the satisfaction with respect to the offloading volume v, ω is the equivalent revenue per unit of satisfaction contributed to the overall utility, while p is the price for offloading a unit of traffic (e.g., 10 MB). Note that $f(v) = 1 - e^{-a \cdot v/v_q}$, where $a > 1$ is the satisfactory factor and v_q is the required offloading volume. The utility of the user deployed cell (the seller) is $U_s = p \cdot v - c \cdot v$, where c is the cost to offload a unit of traffic. The strategies for the buyer and seller are the offloading amount v and the unit price p, respectively. In other words, the user deployed small cell selects a price p, while the network deployed cell chooses the offloading volume v to maximize their own utilities.

The buyer-seller game can be analyzed by the backward induction method. First, for a given requested price p, the buyer chooses a suitable offloading volume to maximize its utility U_b, which is a function of p. Based on the result, the seller can then select the best price to maximize its utility U_s. After that, all the trading parameters can be determined, i.e., the price and the offloading volume.

In the network, there might exist multiple operator deployed cells requesting service and multiple user deployed small cells interested in earning credits. Note that the sellers might have different cost coefficients c and the buyers may have different offloading demands v_q. The cloud can facilitate the trading process to maximize the profits of the network, which is the summation of utilities of all sellers and buyers. Initially, the sellers and buyers send the cost coefficients and offloading demands to the cloud. Then the cloud matches the optimal pairs of the seller and buyer by generating a graph, where the sellers and buyers are the vertices and the profit summation of each pair of seller and buyer is the weight of each edge. To find the optimal pairs, the maximum weighted bipartite matching algorithm is applied. Finally, the selected pairs of buyers and sellers perform trading according to the negotiated parameters.

Figure 3a shows the utility of the small cell with respect to the price requested under different system parameters. It can be seen that there exists an optimal price such that the overall utility of the small cell can be maximized. For different values of a, v_q, and w, the optimal prices are adjusted accordingly by the small cell.

Figure 3b shows the total profit of the network versus the number of cooperative small cells. The number of buyers is set to six and the required offloading volumes are equally likely to be 100, 150, and 200 MB, respectively. The costs for the sellers are equally likely to be 0.2, 0.3, and 0.4. It can be seen that the network profit can be increased when more user deployed small cells participate in the trading, because more user deployed small cells can lead to more options to choose the best contributors.

Cloud Assisted Interference Mitigation

With the cloud based architecture, the transmission of small cells can be coordinated, opening the possibility of interference mitigation. In the following, we study the case where the cloud coordinates the transmission of the multiple neighboring small cells to mitigate interference. For instance, a set of small cells denoted by **S** are coordinated to serve the user A while creating no interference to other active users, denoted by the set **U**[3]. Specifically, each small cell broadcasts a weighted version of the message $w_i m$ to the destination user D, where w_i is the weight of small cell i. To maximize the through-

[3] Note that the number of coordinated small cells needs to be greater than the number of potential victim active users.

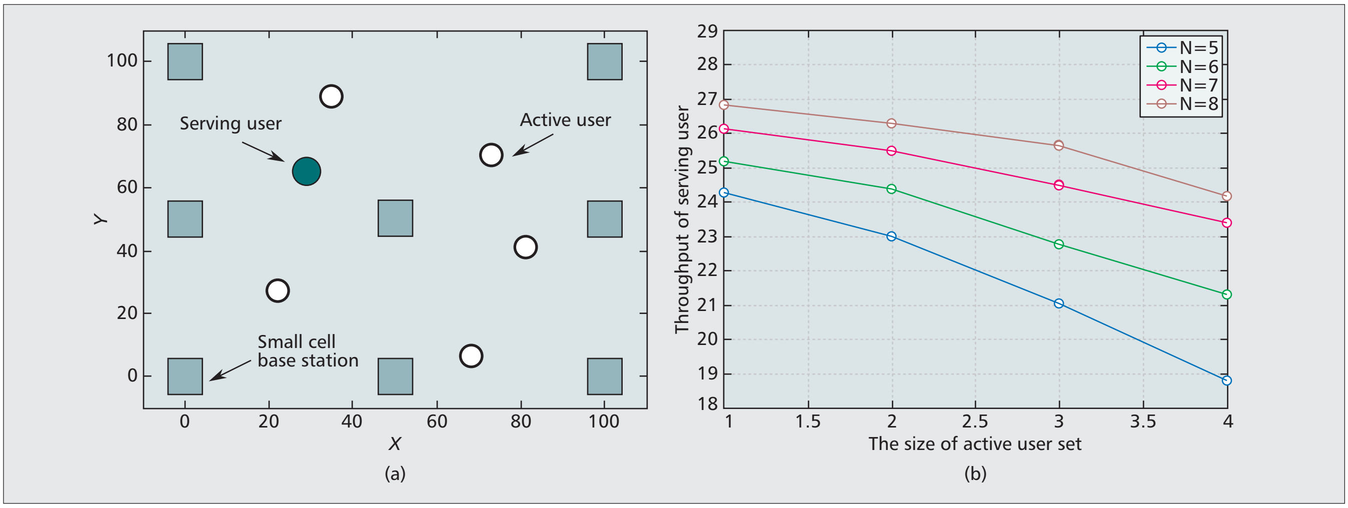

Figure 4. Cloud assisted interference mitigation: a) network topology for simulation; and b) throughput of the serving user versus the number of active users.

put of the serving user while protecting other active users in **U**, the cloud selects suitable weights for small cells. To accomplish this, **w** should be in the null space of $\mathbf{h}_{SU}^{\dagger}$ such that $\mathbf{h}_{SU}^{\dagger}\mathbf{w} = 0$, where $\mathbf{h}_{SU}$ is the channel matrix from small cells to the users in **U**.

The optimal $\mathbf{w}^{\star}$ can be selected to maximize the transmission rate of the destination user, under the constraint of no interference at the users in **U**. Therefore, $\mathbf{w}^{\star}$ should maximize $|\mathbf{h}_{SU}^{\dagger}\mathbf{w}|^2$ under the conditions that $\mathbf{h}_{SU}^{\dagger}\mathbf{w} = 0$ and $\mathbf{w}^{\dagger}\mathbf{w}^{\star} \leq P_{\max}$, where $P_{\max}$ is the total power. It can be seen that **w** is orthogonal to $\mathbf{h}_{SU}$, which means **w** belongs to the subspace of $\mathbf{h}_{SU}^{\perp}$, i.e., the null space of $\mathbf{h}_{SU}$. As a result, $\mathbf{w}^{\star}$ should be selected in the direction of the orthogonal projection of $\mathbf{h}_{SD}$ onto $\mathbf{h}_{SU}^{\perp}$.

Figure 4a shows the network scenario for simulation, where the squares represent the possible locations for small cells and the users are randomly distributed in the area. The number of coordinated small cells $N = 5, 6, 7, 8$, while the total power constraint is set to 2 W. The simulation results are obtained by a Monte Carlo simulation consisting of 5000 trials. Figure 4b shows the throughput of the targeted user versus the size of **U**. It can be seen that as the number of the protected active users increases, the throughput of the targeted user drops. Moreover, as the number of coordinated small cells increases, the throughput of the targeted user increases.

Related Standardization Activities

The Next Generation Mobile Networks (NGMN) Alliance is a mobile telecommunications association of mobile operators, vendors, manufacturers, and research institutes. The alliance's project results have been acknowledged by 3GPP and IEEE. In Feb. 2014, the NGMN Alliance announced the launch of a global initiative for 5G, with the objective of guiding the development of technologies and standards to satisfy the needs of the future. In this beginning phase, the NGMN Alliance has defined the requirements for 5G in terms of user experienced data rate, latency, mobility and so on.

Since HetNets play a key role in the evolution of 5G, 3GPP standards aim to guide the operation and management of small cells. For instance, inter-cell interference coordination (ICIC) was introduced in 3GPP Release 8 where BSs can communicate with each other via the X2 interface. Enhanced ICIC (eICIC) was introduced in 3GPP Release 10, which integrated almost blank subframes (ABS) to mitigate interference in the time domain. In 3GPP Release 11, ICIC has evolved to further enhanced ICIC (feICIC). In 3GPP Release 12, mechanisms for efficient operation of the small cell layer were introduced, such as interference mitigation through optimally powering On/Off small cells. Moreover, HetNet mobility, Wi-Fi cellular interworking, self-optimizing network, M2M application, etc, are included in Release 12.

For the cloud, the IEEE Intercloud Working Group is working on the project P2302-Standard for Intercloud Interoperability and Federation. This standard aims to create an economy among cloud providers that is transparent to users and supports evolving business models. It defines the topology and functions, and guides the interoperability of clouds.

Conclusion and Future Work

In this article we have introduced a cloud assisted HetNet architecture to realize 5G, which can simplify the complexity in terms of operation, maintenance, and deployment, caused by large-scale small cells. Meanwhile, it provides the centralized management to efficiently use network resources by coordinating the transmissions of small cells. Case studies on cloud assisted deployment and interference mitigation have been provided, which demonstrate the benefits of the cloud based architecture. It is anticipated that the cloud will accelerate the pace of 5G development, and further diversify wireless applications and services. In the future, the following research topics can be studied:

Security and Privacy: Since the cloud is involved in the operation, maintenance, and management of small cells, the security of the cloud is of significance. For instance, malicious insiders can manipulate the small cells, which threatens the normal operation of the network. Besides, account or service traffic hijacking is another great security risk. Moreover, since small cells can be deployed by third parties or users, malicious users can easily deploy their own small cells to compromise the security of the users in the coverage, by performing man-in-the-middle attacks. In addition, considering that the network is split into a large number of small cells, the user's privacy, such as location privacy, can be easily revealed.

Energy Efficiency: With large scale deployment of small cells, energy consumption will be a critical issue. To make efficient use of energy while satisfying performance requirements, a cloud assisted small cell coordination mechanism is necessary, which can determine whether the small cell stays active or inactive and how the traffic can be balanced in real time [14].

Mobility Management: Mobility management is performed to maintain the users' connectivity when moving across different cells. Due to the densely deployed small cells, it is expected that users may handoff frequently. It is very critical to provide smooth handoff to the moving users for seamless connectivity [15]. To enable mobile users to have seamless connectivity anywhere and anytime, a cloud based intelligent handoff and location management scheme for HetNets is necessary.

Mobility management is performed to maintain the users' connectivity when moving across different cells. Due to the densely deployed small cells, it is expected that users may handoff frequently. It is very critical to provide smooth handoff to the moving users for seamless connectivity.

References

[1] Cisco, "Cisco Visual Networking Index: Global Mobile Data Traffic Forecast," White Paper, 2014.

[2] N. Lu *et al.*, "Vehicles Meet Infrastructure: Toward Capacity-Cost Tradeoffs for Vehicular Access Networks," *IEEE Trans. Intelligent Transportation Systems*, vol. 14, 2013, pp. 1266–77.

[3] X. Zhang, W. Cheng, and H. Zhang, "Heterogeneous Statistical QoS Provisioning over 5G Mobile Wireless Networks," *IEEE Network*, vol. 28, 2014, pp. 46–53.

[4] N. Zhang *et al.*, "Risk aware Cooperative Spectrum Access for Multi-Channel Cognitive Radio Networks," *IEEE JSAC*, vol. 32, no. 3, 2014, pp. 516–27.

[5] N. Zhang *et al.*, "Cooperative Heterogeneous Framework for Spectrum Harvesting in Cognitive Cellular Network," *IEEE Commun. Mag.*, to apprear.

[6] A. T. Gamage *et al.*, "Device-to-Device Communication Underlaying Converged Heterogeneous Networks," *IEEE Wireless Commun.*, vol. 21, 2014, pp. 98–107.

[7] L. Lei *et al.*, "Operator Controlled Device-to-Device Communications in LTE-Advanced Networks," *IEEE Wireless Commun.*, vol. 19, no. 3, 2012, p. 96.

[8] J. Liu *et al.*, "Device-to-Device Communications Achieve Efficient Load Balancing in LTE-Advanced Networks," *IEEE Wireless Commun.*, vol. 21, no. 2, 2014, pp. 57–65.

[9] Z. Zhang *et al.*, "Coalitional Games with Overlapping Coalitions for Interference Management in Small Cell Networks," *IEEE Trans. Wireless Commun.*, vol. 13, no. 5, 2014, pp. 2659–69.

[10] F. Boccardi *et al.*, "Five Disruptive Technology Directions for 5G," *IEEE Commun. Mag.*, vol. 52, 2014, pp. 74–80.

[11] X. Zhou *et al.*, "Towards 5G: When Explosive Bursts Meet Soft Cloud," *IEEE Network*, vol. 28, 2014, pp. 12–17.

[12] Cisco Meraki, https://meraki.cisco.com/.

[13] T. Taleb, "Toward Carrier Cloud: Potential, Challenges, and Solutions," *IEEE Wireless Commun.*, vol. 21, no. 3, 2014, pp. 80–91.

[14] S. Zhang, Y. Wu, and Z. Niu, "Traffic-Aware Network Planning and Green Operation with BS Sleeping and Cell Zooming," *IEICE Trans. Commun.*, vol. 97, no. 11, 2014, pp. 2337–46.

[15] D. Lopez-Perez, I. Guvenc, and X. Chu, "Mobility Management Challenges in 3GPP Heterogeneous Networks," *IEEE Commun. Mag.*, vol. 50, no. 12, 2012, pp. 70–78.

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