An Energy Efficient and Spectrum Efficient Wireless Heterogeneous Network Framework for 5G Systems

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ABSTRACT

In this article we explore a system framework of cooperative green heterogeneous networks for 5G wireless communication systems. We first survey the state-of-the-art on spectrum efficiency (SE), energy efficiency (EE), and quality of service (QoS) based mobile association, multi-layer interference management and power control, network wide cooperation and dynamic resource allocation for heterogeneous wireless networks. We also present the system framework of cooperative green heterogeneous networks, which aims at balancing and optimizing SE, EE, and QoS in heterogeneous wireless networks. We discuss the design principles and show some preliminary performance results on the tradeoffs among SE, EE, and QoS. Finally, we identify the technical challenges that remain in the cooperative green heterogeneous network design. The presented wireless system framework is expected to advance the understandings of the critical technical issues toward energy and spectrum efficient 5G wireless communication systems.

INTRODUCTION

Global mobile traffic increased 66 times with an annual growth rate of 131 percent between 2009 and 2014 [1]. On the contrary, the peak data rate from third generation (3G) wireless technology to fourth generation (4G) wireless technology only increased 55 percent annually. With the 4G wireless communication systems being deployed in the world most recently, the fifth generation (5G) mobile and wireless communication technologies are emerging into research fields. Clearly there is a huge gap between the capacity growth rates of new wireless access technologies and the growth of wireless data traffic demand. As the wireless link efficiency is approaching its fundamental limit, future improvements on the wireless capacity can be alternatively achieved by infrastructure technologies such as node density increase, cooperative and collaborative radio technologies [2]. Furthermore, the fast growing data traffic volume and dramatic expansion of network infrastructures will inevitably trigger tremendous escalation of energy consumption in wireless networks, which will directly result in the increase of greenhouse gas emission and pose ever increasing urgency on the environmental protection and sustainable network development. The growing energy consumption becomes one of the major challenges in meeting the cost reduction and green environment targets [3]. To meet those goals, green networking has become another primary trend for 5G wireless technology evolution. The research on 5G mobile and wireless communication systems should meet all the challenges raised by both wireless traffic explosion and energy consumption escalation.

In the recent years, heterogeneous network deployment has emerged as a new trend to enhance the capacity/coverage and to save energy consumption for the next generation wireless networks. A heterogeneous network, or HetNet, is a wireless network consisting of nodes with different transmission powers and coverage sizes. High power nodes (HPNs) with large coverage areas are deployed in a planned way for blanket coverage of urban, suburban, or rural areas. Low power nodes (LPNs) with small coverage areas aim to complement the HPNs for coverage extension and throughput enhancement. Furthermore, the infrastructure featuring a high density deployment of LPNs can also greatly improve energy efficiency compared to the one with a low density deployment of fewer HPNs, owing to the higher than linear path loss exponent in a wireless environment [4].

There have been many research activities in HetNets, including node cooperation, optimal load balancing, and enhanced inter-cell interference coordination [4]. A HetNet features with a large number of cell splitting, transmission power disparity between HPNs and LPNs, and the individualistic nature of user-deployed LPNs. The resource usage of HPNs and LPNs should be tightly coordinated to realize the maximum capacity and coverage benefits of the HetNet deployment. In order to significantly increase capacity and coverage, advanced inter-cell inter-

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layer cooperation and coordination will be needed in HetNets. This is usually addressed by various centralized optimization techniques, which normally need excessive data exchanges and a high signaling overhead on the air interface as well as on the backhaul links. In a distributed HetNet architecture, each access node connects to a fixed set of antennas, handles transmission/reception signals in their own coverage area, and possesses a dedicated baseband unit (BB) that is co-located with a radio front (RF), as shown in Fig. 1. As such, the distributed architecture may lack the capability to support the centralized coordination and optimization schemes that are essential in a HetNet. Furthermore, energy consumption increases almost linearly with the increase of isolated radio access nodes. Based on the studies from [3], 57 percent of total energy consumption from the wireless network operation comes from radio access nodes. Among the energy consumed by radio access nodes, 15 percent comes from transmission while 33 percent comes from air-conditioners for each isolated access node site. So a very effective way to save energy and to decrease carbon-dioxide emissions is to decrease the number of access nodes. However, for a traditional distributed architecture shown in Fig. 1, decreasing the number of access nodes will inevitably result in lower network capacity and may also lead to worse network coverage.

The limitations discussed above have seriously hampered the development and deployment of HetNet technology. There is an urgent need to exploit and establish the technology foundations that can facilitate HetNet development and deployment and also instill solid understanding of the performance gains and tradeoffs in HetNets. In this article, we explore a new framework of cooperative green heterogeneous networks for 5G wireless communication systems, which supports centralized baseband processing, cooperative radio and energy saving in HetNets. Centralized baseband processing greatly reduces the energy consumption and enables processing power aggregation and dynamic resource allocation. Cooperative radios largely improve system SE and EE for the cell edge users. Both will be the key technologies that can help cultivate the ultimate capacity and coverage gains and energy savings expected in HetNets.

The rest of this article is organized as follows. In the next section, we survey the current state-of-the-art on SE, EE, and QoS based mobile wireless techniques for heterogeneous wireless networks. After that we present the cooperative green heterogeneous wireless network design framework, with discussions on the technical challenges of the cooperative green 5G wireless communication systems. We also show some preliminary performance results under the presented 5G design framework. We conclude the paper in the last section.

Current State-of-the-Art on Spectrum and Energy Efficient HetNets

In this section we survey the existing wireless research activities pertaining to SE and EE, and discuss the significance of the new heterogeneous network framework in achieving the revolutionary advances on SE, EE, and QoS. Many studies have been done in the areas of SE, EE, and QoS in the traditional wireless networks. Optimal radio resource usage is normally critical in achieving high SE in most wireless communication systems [5]. To achieve optimal radio resource usage, it is crucial for a mobile station (MS) to attach to the access node that provides the best and most efficient radio services. In a traditional homogeneous wireless network, which is composed of only HPNs, mobile association has been well investigated. Typically, a MS is associated with the node that provides the strongest downlink received signal power or signal quality, i.e. signal-to-interference-plus-noise ratio (SINR), in order to receive the best radio service. This works very well in the traditional homogeneous wireless network and has been widely adopted in the earlier generation wireless networks such as GSM and UMTS. However, the conventional mobile association schemes may not work efficiently in a HetNet, where, due to different transmission power levels of HPNs and LPNs, MSs tend to select HPNs as their serving nodes while ignoring the LPNs. This will result in an unnecessarily small coverage and poor resource utilization of the LPNs. Therefore, the resources provided by the LPNs may not be efficiently utilized. Furthermore, if considering low power relay node in a HetNet, both downlink and uplink signals have to traverse multiple wireless hops. How to do mobile association by considering the composite multihop signal quality in mobile association should also be considered. In [6], a heuristic algorithm is provided for suboptimal resource allocation in a multihop cellular network with fixed RN deployment. In the mobile associations in HetNets, if the loading conditions on various network nodes are not carefully considered when making mobile association decisions, the system wide resource utilization may not be optimized. As most of the existing mobile association studies in HetNets have focused on SE, limited study on EE and QoS related mobile association in a HetNet has been found. In the

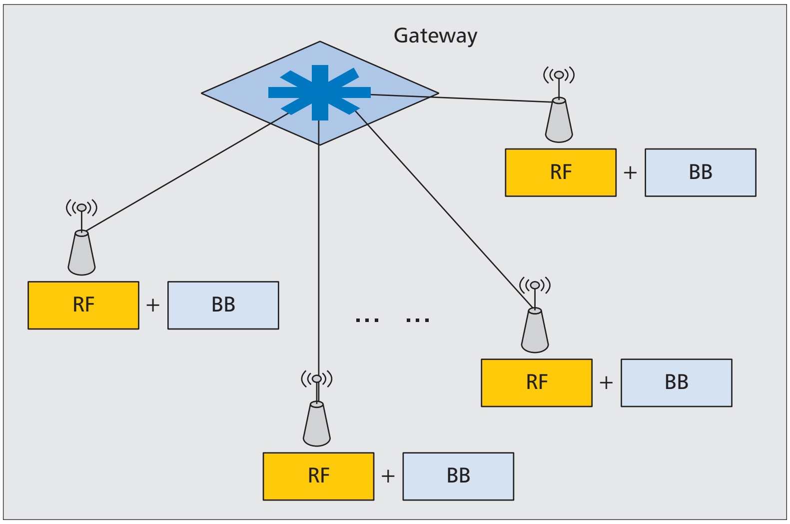

Figure 1. A traditional radio access node architecture.

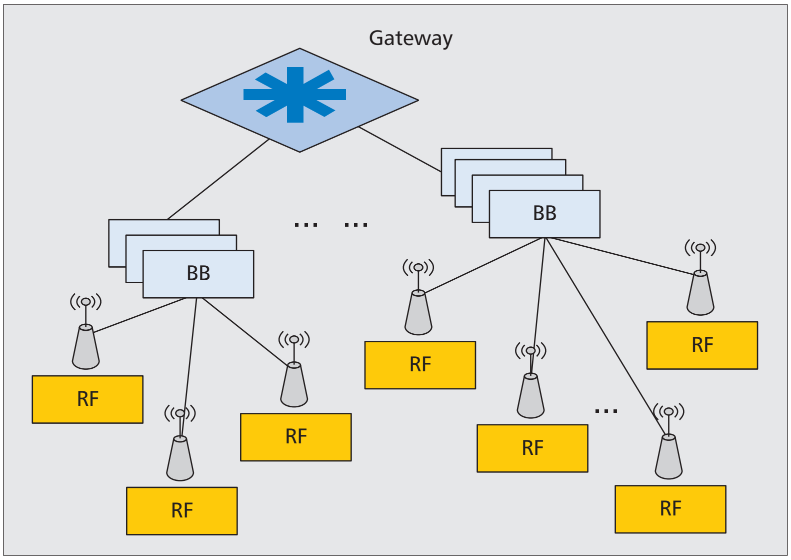

Figure 2. New radio access node architecture.

wireless systems, another primary issue impacting SE and limiting the system capacity is the interference problem. Due to the use of Orthogonal Frequency Division Multiple Access (OFDMA) in most of the new wireless systems, the intra-cell MSs are assumed to use orthogonal resources and thus the primary source of interference comes from inter-cell co-channel users. ICIC in traditional homogeneous wireless networks has been well studied and can be effectively achieved via different static or pseudo-dynamic frequency reuse schemes based on long-term channel statistics and user distribution information [7].

On the EE side, significant results already exist to conserve MS battery power as well as Base Station (BS) transmission power. In [8], the authors investigated the impact of cell size on energy saving and on system capacity and then demonstrated the EE of using small cell based future mobile communication systems. If the path-loss exponent increases and cell radius becomes smaller, the EE becomes even higher. It is concluded in [8] that small cell based mobile communication systems can be a very effective solution to accommodate high data rates with low energy consumption in a future green radio environment. In [9] the authors evaluated the impact of power reduction on the coverage and on the capacity of wireless access networks. They established close form formulas of outage probability by taking into account shadowing, thermal noise, and BS transmission power impacts. They quantified the transmission power needed for different environments (urban, rural) and frequency bands and showed that the transmission power can be optimized according to the network characteristics without sacrificing QoS. They also showed that increasing the BS density results in a reduction of the global power density in the network. In [10] the authors described energy consumption demographic data in operating a real mobile network for a wireless service provider. It identified the radio access node as the most power consuming component of the entire wireless network. It also investigated MS power consumption and found that although the terminal power consumption is relatively not harmful to the environment, the battery life is crucial in portable wireless devices, especially in cellular systems, and thus it is significantly important to save the power consumption at the MS side. While most of the traditional EE researches have focused on mobile battery consumption and cell size perspectives, more recent efforts have been focused on studying EE from the network architecture and cross-layer design perspectives [15].

Cooperative Green HetNet Framework and Technical Challenges

As an effective way to address the future needs on high SE, EE, and QoS, a new radio access architecture that consists of remote radio heads (RRHs) and centralized baseband units, as shown in Fig. 2, has been proposed recently [11]. A traditional radio access node normally uses passive antennas connected via thick and noisy feeder cables to the cabinet containing the RF modules and baseband processing. A RRH places the RF module next to the passive antenna to reduce cable losses. Further different from the traditional architecture, the new architecture allows the dynamic coupling between RRHs and baseband units so that the baseband unit pool can be shared among a large number of cells. As such, a much higher utilization rate of processing resources can be achieved and centralized resource coordination is made possible. The new architecture also greatly reduces the number of sites and equipment rooms to host baseband units so that the power consumption from air conditioners can be largely cut back [11]. Furthermore, the distance from RRHs to the end users can be decreased since the cooperative radio technology can reduce the interference among RRHs and allow a higher density deployment of smaller cells. The energy used for signal transmission will be reduced, which is especially helpful to prolong the mobile battery life and to reduce the power consumption at the radio access nodes. The new architecture enables centralized baseband processing, cooperative radio and energy savings, which greatly facilitates SE and EE HetNet technology development and deployment.

In this work the new radio access node architecture in Fig. 2 is applied to HetNets, and a new design framework of centralized, cooperative, and green HetNets is studied. More specifically, we present a multi-layer cooperative green HetNet framework, with each layer comprising nodes with a similar level of transmission power and serving a similar coverage need. This multi-layer cooperative green HetNet framework provides a promising solution to meet the future capacity and green needs and it opens a large number of new research avenues, ranging from the silicon design to the applications. In this arti-

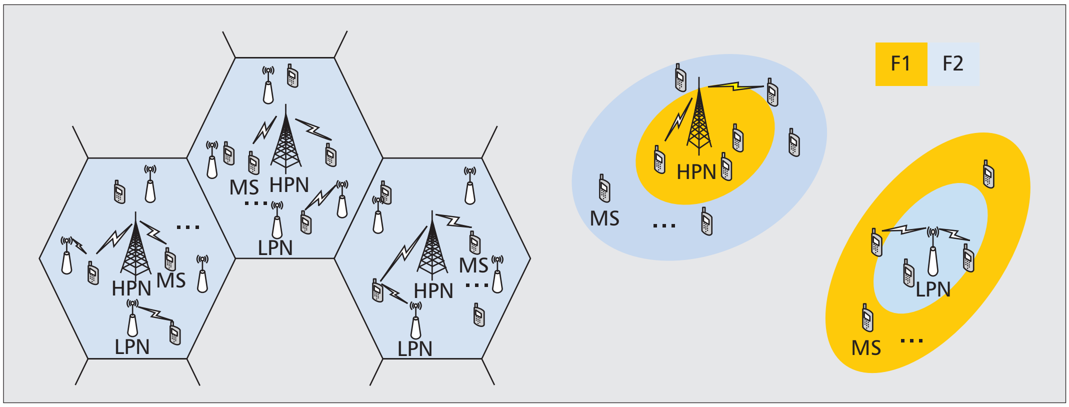

Figure 3. A 2-layer HetNet model with interference coordination and power control.

Due to the ubiquitous applications of real-time services such as video streaming, online gaming, mobile computing, etc., which are all delay sensitive and power consuming, spectrum/energy efficient transmission under QoS constraints over wireless channels is becoming increasingly important.

cle we mainly focus on the radio resource management schemes for heterogeneous networks that can address the ever-increasing SE, EE, and QoS demands for 5G wireless communication systems.

We address the technical challenges of the cooperative green HetNets in the following:
- Mobile association with SE, EE, and QoS in cooperative green HetNets.
- Multi-layer interference management and power control in cooperative green HetNets.
- Cooperative dynamic resource allocation in cooperative green HetNets.

Mobile association and interference coordination mainly address radio resource management in the wireless environment with large scale channel conditions and pseudo static user distribution information, while cooperative dynamic resource allocation achieves efficient radio resource management by considering fast fading and multiuser diversity.

Mobile Association with SE, EE, and QoS

Supporting QoS and SE/EE in 5G wireless communication systems is a key performance promise to real-time applications. Due to the ubiquitous applications of real-time services such as video streaming, online gaming, mobile computing, etc., which are all delay sensitive and power consuming, spectrum/energy efficient transmission under QoS constraints over wireless channels is becoming increasingly important. How to address these three performance metrics at the mobile association stage is the first defense line provided by the wireless networks.

• **Mobile association with SE and QoS**: Our preliminary mobile association study [12] mainly addressed SE but did not consider the QoS requirements. Effective capacity was proposed as a metric to measure the wireless fading channel performance in the presence of statistical QoS needs [13]. Effective capacity can be considered as the maximum link layer data rate that can be served by the wireless fading channel subject to the link layer buffer violation probability. Effective capacity models the physical layer wireless channel with three QoS parameters related to mobile association: source data rate, delay bound, and delay-violation probability. The new mobile association scheme can consider all these related parameters, besides the SE, when making a decision on the best node to attach to, in order to better accommodate QoS needs before the connection is physically set up.

• **Mobile association with EE**: Most of the existing mobile association schemes in the traditional homogeneous wireless network have been developed either based only on the downlink information or only on the uplink information, but not both. In cooperative green HetNets, due to the transmission power difference among various nodes, there will be a large coverage difference among nodes belonging to different layers. If only downlink information is used for association decision, most of the MSs may associate themselves to the HPNs due to the larger coverage areas of the HPNs. As a result, MSs may not associate with the nodes that are the closest. Thus, excessive MS uplink transmission power will be needed in order to maintain the target received uplink signal level, which will cause a higher uplink interference floor and consequently lead to a shorter MS battery life. On the other hand, if mobile association is done based only on the uplink information, MSs will be able to attach to the closer nodes and save their battery life. But MSs associated with LPNs may receive a strong interference from the neighboring HPNs on the downlink, especially for MSs at the coverage edge of LPNs. To make the most EE association decision, a new mobile association scheme that will consider both downlink and uplink channel information is desirable.

Multi-Layer Interference Management and Power Control

Due to multi-layer deployment in the cooperative green HetNet design framework, more advanced interference coordination and radio resource management schemes are required than in the traditional wireless network in order to achieve high SE, EE, and QoS. In a cooperative green HetNet, in addition to inter-cell interference, nodes from different layers, i.e. macro, micro, and pico layers, have different transmission powers and are overlaid on each other, resulting in new and complicated interference scenarios [7]. Interference coordination involves intelligent coordination of physical resources

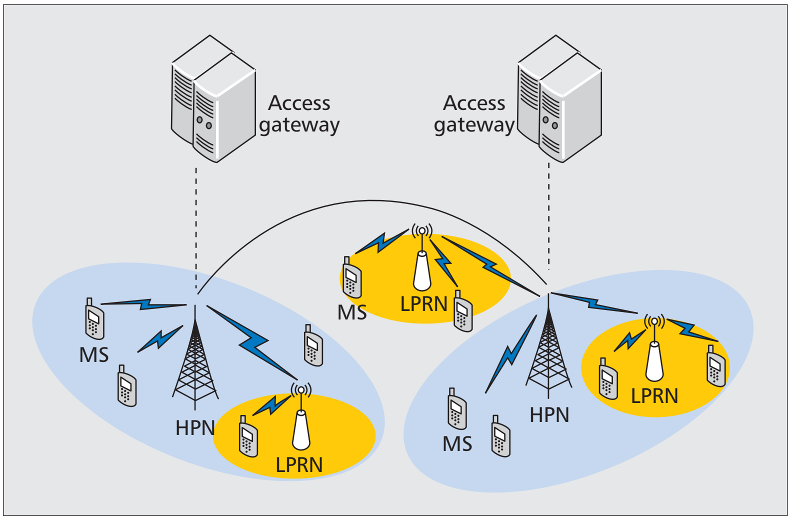

Figure 4. A HetNet model: HPNs+LPRNs.

among nodes belonging to different layers and/or to different cells. Each layer and/or each cell may need to give up some resources, in a coordinated fashion, to improve performance, especially for cell-edge users who experience the highest impact from multi-layer interference. Different cells and different layers usually also need to coordinate transmission powers across various resource blocks. We start the design on multi-layer interference management and power control with a two-layer cooperative green HetNet, as shown in Fig. 3. Due to the high power of the HPNs and the lower power of the LPNs, the MSs located at the edge of the LPN cells are most vulnerable to interference, which in turn leads to the low coverage range of the LPNs. To mitigate the inter-layer interference while still achieving high spectrum efficiency, the entire frequency band F can be divided into two parts, denoted as F_1 and F_2, denoting β as the portion of the frequency band assigned to the F_1 part, i.e. $F_1 = \beta F$ and $F_2 = (1 - \beta)F$. In F_1, HPNs transmit at a reduced power αP_H ($0 < \alpha < 1$) to the cell center MSs, while LPNs transmit at its full power to the MSs located at their cell edge. In F_2, both HPNs and LPNs transmit at their respective full powers, with the HPNs transmitting to the cell edge MSs and the LPNs transmitting to the MSs located at their cell center. In order to optimize the performance of the proposed scheme, the values of α and β need to be chosen properly. Upon achieving the requested minimum rate requirement, MS k can be assigned with more resources to get a better QoS. A good frequency resource allocation scheme should achieve a high spectrum efficiency and fair resource allocation among the MSs. We want to design an optimal scheme that can maximize the long-term system throughput as well as ensure a good user experience. The optimization of the scheme is closely related to the mobile association scheme. We can either jointly optimize the interference control scheme and the mobile association or optimize the interference control scheme separately from the mobile association scheme. In both cases, we need to decide

1 The optimal partition of the frequency sub-bands F_1 and F_2, i.e. the value of β;
2 The optimal transmit power of the HPNs in the F1 sub-band, i.e. the value of α.

- **Joint interference management and mobile association**: Most of the existing works on interference management and power control optimization are based on a pre-determined mobile association scheme. The system performance can be further improved by jointly optimizing mobile association and the dynamic fractional frequency reuse (FFR) scheme. Such extension is not straightforward due to the high dependence of the FFR and resource allocation outcome on the mobile association scheme.
- **Interference management and mobile association in an L-Layer cooperative green HetNet**: It is a challenging task to extend the studies to a general L-layer ($L \geq 2$) cooperative green HetNet with each layer having a distinct transmission power level and/or coverage/capacity need. We assume nodes from layer 1 have the highest transmission power while nodes from layer L have the lowest transmission power. We need to develop the similar interference management scheme but with coordination from all L layers. Each layer l, except the last one, will have its corresponding α_l and β_l, so the general interference coordination rules by giving the mathematical relationship among all α_l and β_l should be established. The optimization formulation can be used to solve the optimal α_l's and β_l's.

Cooperative Dynamic Resource Allocation

We further study dynamic radio resource allocation in cooperative green HetNets. Dynamic cooperative transmission has been considered as a promising technique to increase cell average SE and cell-edge user SE. It can also reduce the energy consumption in cell-edge communications. The cooperation is more effective if the feasible groups of nodes to cooperate are carefully selected in advance and information from the cooperative set can be timely exchanged with a low overhead. Cooperative transmission naturally increases the system complexity in a distributed architecture. With multiple RRHs attached to the centralized baseband unit pool, it is easier to implement coordinated beamforming and cooperative processing in the baseband unit pool. Multiple baseband units can coordinate with each other to share the scheduling information, channel status and user data efficiently to improve the spectrum efficiency and energy efficiency. In a cooperative green HetNet, different RRHs could transmit at different power levels, forming a general L-layer cooperative green HetNet. Cooperative transmission is particularly useful among nodes from different layers. For example, for a cell edge user of a node belonging to layer l, the cooperative transmission from a node belonging to layer l' with $l' < l$ could help greatly to eliminate the dominant interference. Each node is assumed to have only one antenna. N cooperative nodes and N cooperative MSs form an $N \times N$ network MIMO. In order to maximize the total throughput in a network MIMO system, we can select N MSs to simultaneously receive from the N nodes by applying a precoding algorithm [14], which can alleviate inter-user interference among these N MSs that receive from the same cooperative nodes on the same radio resources. In order to apply the precoding scheme, the channel information and user data need to be shared among these N nodes, which can be greatly facilitated by cooperative green HetNets.

- **Optimal cooperative size N and cooperation overhead study**: With cooperative green HetNets, the size of cooperation set N is closely related to the performance of the dynamic resource coordination schemes. We expect both spectrum efficiency and energy efficiency will improve as N increases. However, when N reaches a certain threshold, the performance gain may saturate while coordination complexity and the backhaul capacity requirement will go up tremendously. An optimal cooperation approach needs to be determined to balance the complexity and performance gain.

Performance Studies

In this section, we summarize our preliminary studies on mobile association and dynamic resource allocation in a HetNet consisting of HPNs and LPRNs [12]. The unique multi-hop feature and cooperative capability of RNs impose great complexities on the mobile association and dynamic resource allocation schemes. The work can be conveniently expanded to include other LPNs such as femto node, pico node, RRHs, etc. Relaying technique has been widely considered as one of the promising solutions to cost-efficient delivery of high data rates in the next-generation wireless systems [6]. Figure 4 outlines a cooperative relay network topology for the use of two-hop RN in a HetNet. The link between a MS and a RN is called an access link and the link between a RN and a HPN is called a backhaul. RNs are positioned around the cell edge of HPNs, where the MSs can access the RNs at a much higher data rate with a much lower transmission power. In [12] we formulated an optimal mobile association scheme in HetNets with RNs. The design goal of the mobile association scheme is to maximize the total number of MSs being accepted in the network while minimize the usage of the radio resources. The optimization problem is a 0-1 knapsack problem, which has been proved to be NP-hard. A real-time optimal solution is difficult to obtain, especially given a large number of MSs and a large number of HPNs and RNs in the network. We have developed a pseudo-optimal solution based on a gradient descent search method. For a linear optimization problem, the pseudo-optimal solution approaches the global optimal solution that is located at the boundary of the constraint region. In Fig. 5a, the network capacity or the maximum number of MSs accepted per cell is simulated for different association schemes. All the capacity numbers are expressed as the relative percentage of the capacity number in a network consisting of only HPNs. It can be seen that the proposed association scheme yields the highest network capacity.

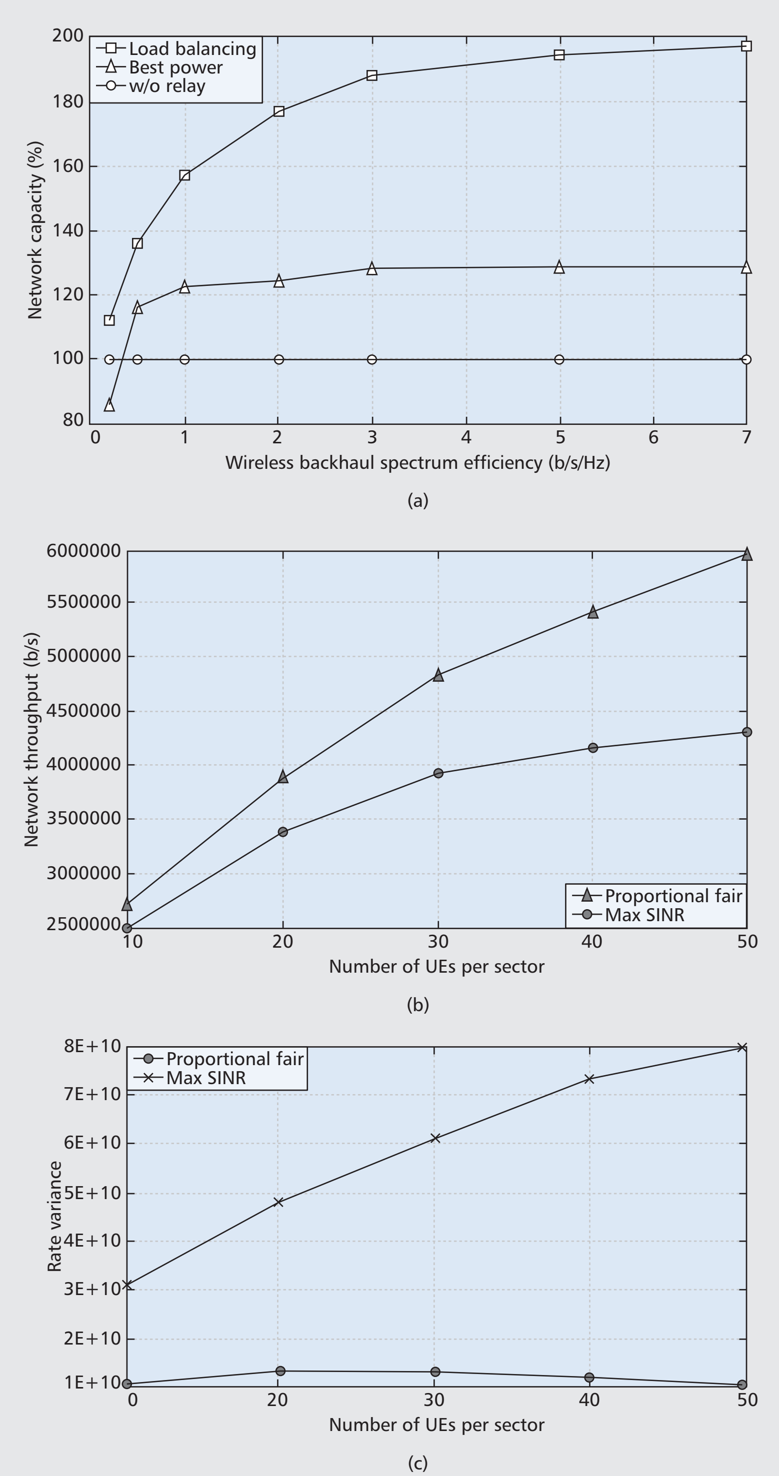

Figure 5. Comparison on network capacity, network throughput, and rate variance: a) network capacity; b) network throughput; and c) rate variance.

For all the MSs that are admitted into the network through mobile association, network resources will be dynamically allocated at each scheduling cycle. During mobile association, the decisions are made based on long-term channel information, i.e. pathloss and shadowing. The scheduling decision, on the other hand, will be made based on both long-term and short-term

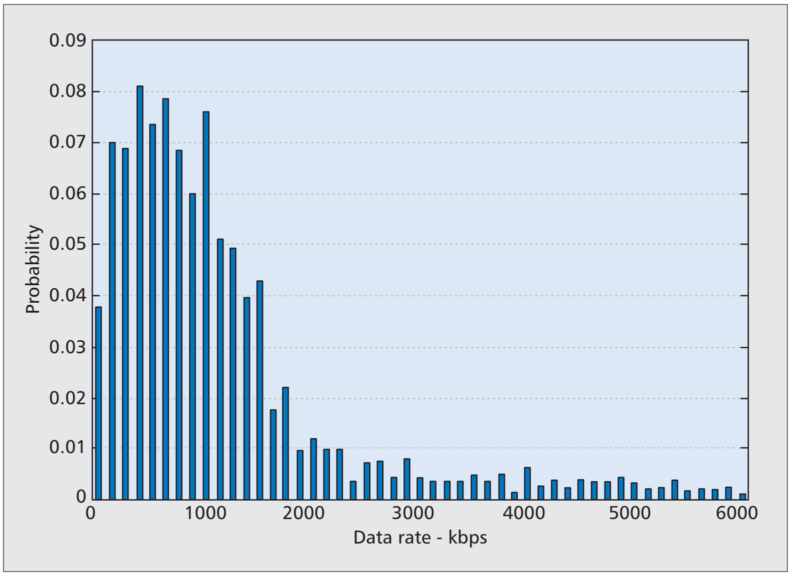

Figure 6. Mobile rate distribution.

channel fading so that time selectivity and frequency selectivity can be exploited to achieve multi-user diversity. In [12] the scheduling algorithm uses proportional fairness as the performance metric to ensure a good tradeoff between SE and user fairness. The optimization problem with a long-term proportional fair resource allocation has thus been formulated in [12], which, instead of directly maximizing the total throughput, maximizes the sum log-scaled throughput to achieve the proportional fairness. With sum log-scaled throughput as the performance metric, further throughput increase for users that already possess a high throughput will lead to only a marginal increase in the total log-scaled throughput. To maximize the total log-scaled throughput, it is more beneficial to help users with a low throughput. In Fig. 5b, we compared the proposed scheduling scheme with a max SINR-based scheme. Since max SINR-based scheduling scheme fully exploits the multiuser diversity with no fairness, it yields a better network throughput than the proportional fair-based scheme. However, this throughput gain comes at the cost of fairness among the MSs, as can be observed from Fig. 5c, where the variance of the mobile rates is plotted. The rate distribution of the MSs for the proportional fair-based scheme is shown in Fig. 6, which demonstrates a well-achieved fair resource allocation among MSs. Leveraging our preliminary work, we can further explore more advanced dynamic radio resource management schemes for energy and spectrum efficient wireless heterogeneous networks with the cooperative green HetNet design.

Conclusions

In this article we proposed a new design framework of cooperative green heterogeneous networks, which aims at balancing and optimizing spectrum efficiency, energy efficiency, and QoS in 5G wireless communication systems. We presented a survey of current literature on spectrum efficiency, energy efficiency, and QoS based mobile association, multi-layer interference management and power control, network wide cooperation and dynamic resource allocation for heterogeneous wireless networks. The critical issues and technical challenges of the framework are discussed, followed by the preliminary performance studies. The promoted new heterogeneous network framework is expected to significantly improve the energy and spectrum efficiencies for the wireless technology evolution to 5G communication systems.

Acknowledgment

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