BACKHAULING 5G SMALL CELLS: A RADIO RESOURCE MANAGEMENT PERSPECTIVE

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ABSTRACT

Developing efficient backhauling solutions for small cells is considered as one of the most significant challenges in the rollout of the upcoming 5G cellular systems where massive numbers of small cells will be deployed. In this article, we first review small cell evolutions and the consequent radio access network architecture evolution toward heterogeneity and centralized baseband processing. The backhaul solution, which is mainly determined by the availability of existing backhaul infrastructures and service demand, will lead to a heterogeneous backhaul network architecture. Radio resource management issues including cell association, and interference management and scheduling with inter-node coordination, as well as how they are related to backhaul solutions are discussed. Based on the existing RRM solutions and their limitations in multi-tier 5G systems with heterogeneous backhaul network architecture, backhaul-aware RRM strategies are envisioned. Results from a simple case study of joint cell association and bandwidth allocation with a massive MIMO-based in-band wireless backhauling framework are presented to demonstrate the performance gain with backhaul-aware RRM in a multi-tier cellular RAN. Several related open research issues are highlighted, and possible solution approaches are briefly discussed.

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INTRODUCTION

The upcoming fifth generation (5G) cellular technology, which is expected to be rolled out by 2020, is going to be a paradigm shift of mobile networking offering native support to more diverse service types with quality of service (QoS) provisioning. Even though there is no global consensus on the definition of 5G, it is widely accepted that compared to the current cellular systems, the key performance indicators (KPIs) of 5G cellular should include 1000 times higher data traffic, 10–100 times more connections, 10 times longer battery lifetime, sub-millisecond latency, 1 Gb/s rate with mobility, and 10 Gb/s stationary access rate [1]. In order to achieve these goals in a cellular system accommodating highly diverse user and service types, the solution must involve a tiered heterogeneous network (HetNet) architecture of different radio access technologies (RATs). For improved spectral and energy efficiency, network densification by implementing small cell networks (SCNs) and distributed antenna systems (DASs) is an inevitable technological choice [2]. With extreme network densification, the design of high-performance backhauling systems for the radio access network (RAN), as well as how backhaul impacts radio resource management (RRM), become significant challenges that must be addressed. Also, from the operators' standpoint, the backhauling system, which is predicted to contribute to over 50 percent of the small cells' total cost of ownership (TCO) [3], should be neither the performance bottleneck nor the cost bottleneck in the deployment of 5G cellular networks.

In this article, we first review the evolutions of small cells and the cellular RAN architecture, which lead to an evolved heterogeneous architecture of the backhaul network. Design issues and challenges for RRM with backhaul considerations are outlined, and limitations of the existing schemes are discussed. We then briefly introduce an in-band small cell wireless backhauling scheme based on massive multiple-input-multiple-output (MIMO) antenna technology. Through numerical results, we illustrate how the proposed scheme impacts the cell association design in a two-tier macrocell–small cell network. To this end, several open research issues on backhaul-aware RRM are highlighted, and possible solutions are briefly discussed.

EVOLUTION OF SMALL CELLS IN CELLULAR RAN

EVOLUTION OF SMALL CELLS

Early Forms of Small Cells: Microcell base stations (BSs) and repeaters are the early forms of small cells, which have been used as complements to tower-mounted macrocell base station (MBS) deployments at hotspots, indoor coverage systems, remote locations, and so forth. With much lower transmit power than their MBS counter-

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There are practical limitations that make C-RAN solutions not viable in many scenarios. Backhaul is the most critical factor that impacts the RAN architecture and topology in reality, and consequently impacts RRM of 5G cellular networks.

parts (~2 W vs. ~20 W), a *microcell* has smaller footprint, lower capacity, and also economic but less protective backhaul. A *repeater* is a relay-type equipment that amplifies-and-forwards the (analog) RF signals from a donor BS to achieve extended RF footprint to a remote/blocked location. Based on the backhauling mechanism (i.e. how the repeater is connected to the donor BS), different types of repeaters (e.g., RF and fiber-connected) have been introduced. As cellular standards have evolved, more diverse small cell solutions have been introduced, which pose different requirements to the backhaul system.

Evolution of Microcells: Base station densification was proposed to improve spectral and energy efficiency through enhanced control over coverage and interference. Picocell and femtocell have evolved from the microcell concept in this context by lowering the transmit power of the BS. A picocell's coverage radius is reduced to about 30 percent that of a microcell. Improved capacity and coverage within a hotspot area, such as an office building or a dense urban canyon, can thus be achieved with reduced per-cell footprint and increased total number of cells. Driven by the continuously increasing communication demand in high-capacity indoor hotspots and emerging personalized coverage scenarios (e.g., home and in-vehicle), femtocells with further reduced transmit power (on the same level as Wi-Fi access point, AP) were introduced by the Third Generation Partnership Project (3GPP). Femtocells can be deployed by either operators or subscribers. This allows more flexibility in network deployment and support to more diverse and complex service scenarios. To facilitate this change, the backhaul requirement for femtocells is relaxed to any type of broadband connection that satisfies certain bandwidth and QoS specifications.

Evolution of Repeaters: A direct development of a repeater is the relay station, which adopts more "intelligent" signal processing of cooperation. Three layers of relays with different complexity and performance levels are defined by Long Term Evolution (LTE)-Advanced [4]. Due to the temporal separation of transmitting and receiving on the air interface, it is considered that wireless backhaul is employed by relays. On the other hand, by transmitting digitized baseband I/Q signals over a fiber optical link to the donor BS, digital optical repeater completely separates baseband processing and RF subsystems. The most widely used digital radio over fiber (RoF) standard for digital fiber optical donor connections is the common public radio interface (CPRI) [5]. Originally standardized as an onboard interface, the CPRI requires very high bandwidth of the backhaul. For example, a 20 MHz bandwidth on the air interface corresponds to about 10 Gb/s on the CPRI. This idea was later developed in the separated baseband unit (BBU)-remote radio unit (RRU) structure of BS design to provide more flexible coverage and capacity solutions with improved processing resource utilization. Further development of this BBU-RRU structure contributes to the emergence of cloud-RAN (C-RAN) [6], where a BBU pool is shared by a large number of RRUs.

RAN Architecture Evolution: Multi-Tier RAN and C-RAN

Evolution toward Multi-Tier RAN: With evolutions of small cells, the cell-centric legacy cellular RAN is migrating into a new user-centric RAN architecture in 5G. By implementing small cells at hotpots, dead spots, and personalized coverage locations within the MBS range, the RAN is evolving into a multi-tier architecture where nodes with different power levels, capabilities, and/or backhaul conditions are attributed to different network tiers. Radio resource and interference management in this new cellular RAN architecture is the key to optimizing and balancing utilizations of different tiers.

Evolution toward C-RAN: Another key idea of RAN evolution for 5G is C-RAN, which is due to the BBU-RRU design that separates baseband processing and RF parts in RAN equipments. The term remote radio head (RRH) is used instead of RRU in the C-RAN context. In a C-RAN, digital baseband processing is realized at BBU pools located at BS hotels. The remote sites, where the antennas are located, only have RRHs. The RRHs at tens or hundreds of BS sites are connected to the BBU pool through the CPRI via high-capacity, preferably fiber optic, backhaul. The CPRI-based BBU-RRH backhaul is also known as fronthaul in the C-RAN context. Network functions virtualization (NFV) is achieved by accomplishing all-digital signal processing with general-purpose computing facilities in cloud servers.

As discussed above, heterogeneity and centralized baseband processing are the two major trends in the evolution of 5G RAN architecture, which are demonstrated in Fig. 1. The tiered structure of a HetNet allows user-centric deployment of the RAN. This improves availability of cellular services of different levels provided by a ubiquitous 5G network, and consequently enhances quality of experience (QoE). With a centralized baseband processing of the C-RAN architecture, improved resource utilization and inter-cell/inter-tier coordination/cooperation are achieved. Consequently, advanced features like enhanced inter-cell interference cancellation (eICIC), coordinated multi-point (CoMP) transmission, and carrier aggregation (CA) that provide significant performance gains to cell-edge users can be better supported [7]. However, there are practical limitations that make C-RAN solutions not viable in many scenarios. Backhaul is the most critical factor that impacts the RAN architecture and topology in reality, and consequently impacts RRM of 5G cellular networks.

Backhauling 5G Small Cells: Radio Resource Management Issues

Backhauling Solutions for 5G Small Cells

A number of wired and wireless backhaul solutions, as a "toolbox," have been proposed to address the backhaul needs in highly diverse communication scenarios of 5G RAN.

Wired Backhaul: Fiber optic backhaul is the most preferable solution in terms of both capacity and delay, especially for C-RAN where multi-gigabit-per-second digital radio signals are transmitted over the CPRI interface. In relatively long distance (>10 km) backhaul/fronthaul scenarios, optical transport network (OTN) with wavelength-division multiplexing (WDM), which adopts a ring topology to provide full protection and operations, administration and maintenance (OAM), is considered. For shorter links (<10 km), a point-to-muiltipoint (PtMP) unified passive optical network (Uni-PON) which uses an optical splitter to aggregate WDM signals from backhaul/fronthaul links of multiple cells is suggested. As a complementary solution, point-to-point (PtP) fiber, which yields low fiber resource utilization and weak protection, are also used. However, it is worth noticing that ubiquitous fiber connectivity is very limited in existing backhaul infrastructures. In particular, the resource inefficient PtP fiber is rare in most countries. This situation will not change in the near future due to many practical limitations. It is therefore important to consider alternative viable backhaul solutions in different application scenarios.

In small cell backhaul scenarios, where bandwidth requirement is looser, e.g. in an indoor femtocell which serves a small number of users, existing wired infrastructures such as digital subscriber loop (DSL) over copper can be used. More sophisticated copper wire technologies such as G.fast, developed based on the DSL, will be capable of providing up to 1 Gb/s bandwidth for short-range backhaul links in the near future. If such a small cell location has fiber optic backhaul in proximity (e.g., in the same building), the small cell traffic can also be multiplexed into the main fiber optic backhaul.

Wireless Backhaul: Wireless backhaul has been attracting increasing interests due to its implementation flexibility and cost efficiency. With line-of-sight (LOS) communication path, up to several gigabits per second highly directional wireless links are supported by PtP microwave or free space optical (FSO) communications. Such solutions can be used for backhaul/fronthaul connections requiring very high bandwidth (e.g., C-RAN fronthaul) as alternatives to fiber optic backhaul/fronthaul. By assigning different operating frequency bands and bandwidths, PtP microwave can be configured to offer different link capacities for various small cell backhaul scenarios. Non-line-of-sight (NLOS) wireless backhaul solutions mainly occupy sub-6 GHz licensed/unlicensed bands and provide both PtP and PtMP connections. The NLOS solutions typically offer several hundreds of megabits per second link capacity and flexible deployment.

Different from the above solutions which require additional bandwidth and hardware, in-band small cell wireless backhaul uses the same frequency bands where the cellular system operates. Although mainly used for relays, in-band wireless backhaul solutions can also be adopted by standalone small cell BSs through proper protocol design [8] to offer higher flexibility in personalized communication scenarios such as mobile femtocell. The in-band wireless backhauled small cell equipments are integrated plug-and-play devices that can be easily installed and maintained by subscribers. Via wireless backhaul, traffic of the hard-to-reach small cells is routed to a hub location where high-capacity wired backhaul is available. The easy-to-install features and the high flexibility of the wireless backhaul solutions greatly reduce the time to market as well as the cost at the large-scale roll-out of 5G SCNs.

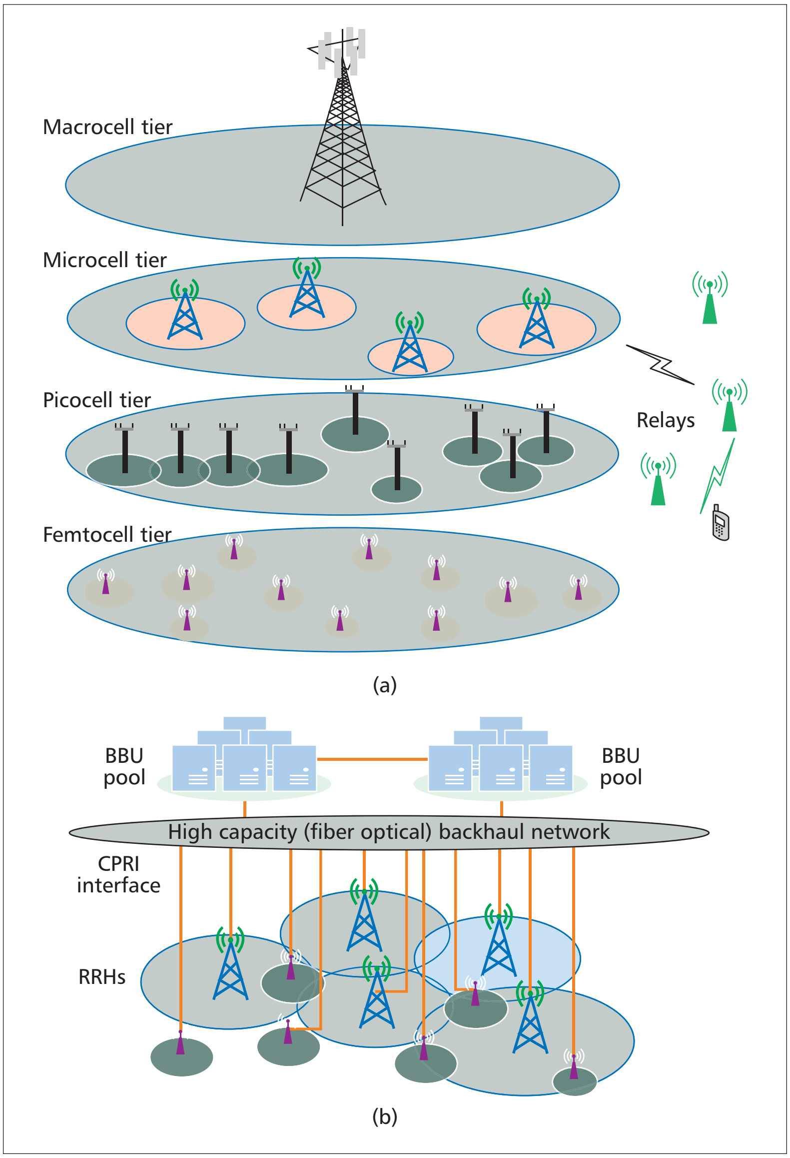

Figure 1. Cellular RAN architecture evolution trends toward: a) multi-tier RAN; and b) cloud-RAN.

Technologies for High-Speed Wireless Backhaul: More sophisticated wireless technologies are being studied for backhaul solutions that enhance both capacity and implementation flexibility. Massive MIMO is an emerging multi-user MIMO technology. By using a large excess of (typically over 100) very low power (mW) antennas at a backhaul hub, the radiating power is focused into the ever smaller terminal spots by beamforming [9]. Significant improvement in spectral and energy efficiency is achieved via spatial-division multiple

Backhaul solutions			Frequency band	Link capacity	Typical link distance
Wired solutions	Fiber	OTN/WDM	1.31 µm laser, WDM	Up to 100 Gb/s	>10 km
		Uni-PON	1.31 µm laser, WDM	10 Gb/s/wavelength	<10 km
		PtP fiber	1.31 µm laser	10 Gb/s	~20 km
	Copper	xDSL (ITU G.99x)	Up to 30 MHz	Up to 100 Mb/s	<3 km
		G.fast	Up to 212 MHz	Up to 1 Gb/s DL + UL	~0.1 km
	Main backhaul multiplexing		Varies	Varies	<1 km
Wireless solutions	LOS	FSO	1.31 um laser	Up to 10 Gb/s	<5 km
		Microwave	6–42 GHz, 60 MHz, 70/80 GHz	Up to 5 Gb/s	<5 km
	NLOS	PtMP	Sub 6 GHz	Up to ~500 Mb/s	<1 km
	Massive MIMO + mmWave		mmWave band	Up to 10 Gb/s	<1 km

Table 1. Major backhauling solutions for small cells.

access (SDMA) and spatial-division multiplexing (SDM). Millimeter-wave (mmWave), which refers to the 30–300 GHz bands, provides abundant bandwidth for wireless communications compared to the currently oversubscribed sub-3 GHz spectrum. Up to 100 GHz bandwidth mmWave spectra can be released or refarmed for cellular uses [9]. Even though radio signals in the mmWave bands experience high propagation and penetration losses, high-gain antennas can be realized with much smaller element sizes, which is desirable for massive MIMO implementations. Combining the two disruptive technologies in wireless backhaul significantly boosts the backhaul performance with adequate equipment (antenna array) size, and consequently improves the overall performance of the cellular system. It is therefore considered as a candidate technology for small cell backhauling.

We summarize the major backhauling solutions for small cells and their main features in Table 1. The backhaul network (BN) for 5G will have a heterogeneous architecture with a mixture of a variety of wired and wireless solutions. From the operators' perspective, the choice of the backhaul solution in specific scenarios often comes down to what is available and what is affordable, leveraging between cost and QoE. The rollout of the 5G cellular network then involves implementations of two HetNets, one in the RAN plane and the other in the BN plane, which is illustrated in Fig. 2.

5G RAN RRM Considerations with Backhauling

Introduction of a multi-tier RAN along with more sophisticated technologies such as massive MIMO, eICIC, CoMP, and CA for improved user rates and system capacity add significantly to the RRM of 5G systems. In particular, the problems of cell association/RAT selection, bandwidth allocation, interference management, multi-cell coordination, and so on are considered and will be fundamentally different from the mechanisms used in legacy cellular systems. The addition of the new network features including cognitive spectrum access, network-assisted device-to-device (D2D) communications and the associated energy-efficient requirements, also puts forward more RRM functionalities. The heterogeneous backhaul network of 5G, which poses highly diverse constraints to different nodes in the cellular RAN and couples tightly with many RRM functionalities, further complicates the RRM design. For example, how limitations set by backhaul conditions complicate cell selection in HetNets was studied in [10].

The RRM in the heterogeneous multi-tier cellular RAN primarily deals with two issues, interference and load/traffic management, based on which we optimize utilization of the radio resources across the system such that the overall performance is improved, or certain design objectives (e.g., energy efficiency) are achieved under QoS constraints. The coupling between the backhaul constraints and RRM in the multi-tier RAN are mainly considered in the following aspects.

Cell Association and RAT Selection: In order to alleviate congestion at the high-power MBSs in a multi-tier RAN, it is widely accepted that user traffic can be offloaded to the low-power cellular small cells or carrier Wi-Fi APs which tend to be underloaded. Offloading (of fixed and mobile users) and load balancing are achieved by cell association and RAT selection strategies which use some admission control methods. However, whether admitting a user by a small cell is beneficial or not is determined by many factors among which the backhaul support for the small cell is an important one. Admission of too many users in a small cell with non-ideal backhaul may overwhelm the small cell backhaul, which can result in poor spectral and energy efficiency. It is therefore important to consider backhaul limitation in the cell/RAT selection scheme. Novel

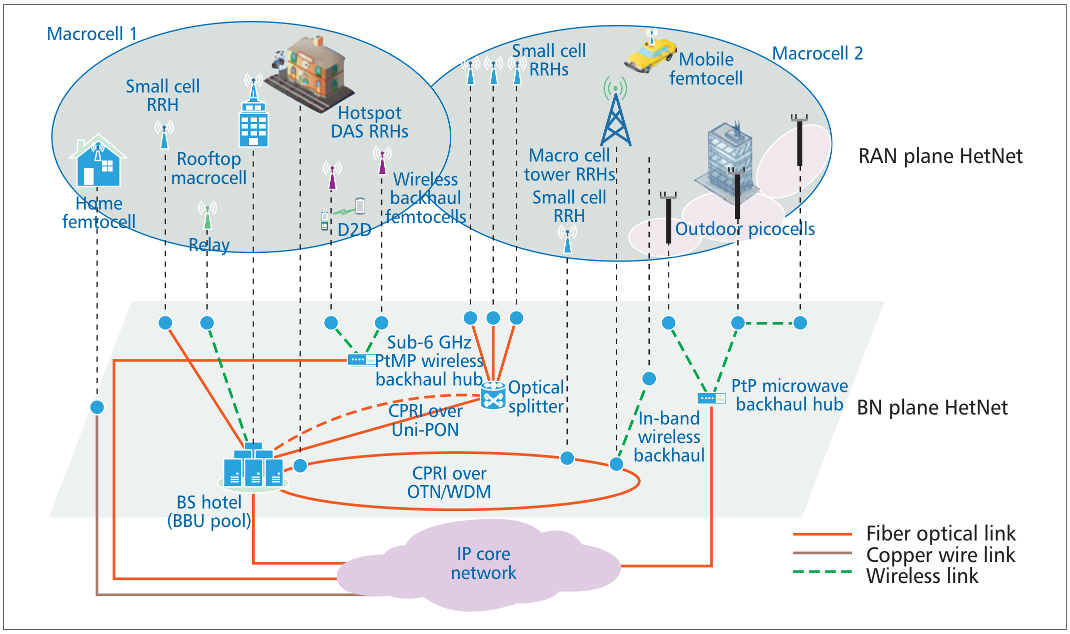

Figure 2. RAN plane and backhaul network plane for 5G cellular networks.

Management of the radio resources for the access links and backhaul links is critical to optimize the network resource utilization. In particular, when in-band wireless backhauling is employed at the small cells, management of the backhaul resources is tightly coupled with the resource allocation and interference management for the access links.

backhaul-aware routing algorithms in the network layer can also be investigated to optimally balance loads among cells.

Resource/Interference Management: Management of the radio resources for the access links (i.e., links bteween users and small cell BSs) and backhaul links is critical to optimize the network resource utilization. In particular, when in-band wireless backhauling is employed at the small cells, management of the backhaul resources is tightly coupled with the resource allocation and interference management for the access links.

Cell Coordination: Coordination among cells in the dense multi-tier RAN can significantly mitigate interference and improve link quality, and consequently boost the overall system capacity. It is critical for advanced RAN features such as eICIC and CoMP. However, it is noted that cell coordination poses extra burdens to the already scarce small cell backhaul resource. Availability of cell coordination features and performance gain due to coordination depend on the backhaul support for small cells.

Spectrum Sharing: By considering known traffic demands at each connected small cell, RRM for PtMP wireless backhaul systems can be designed to achieve improved spectral and energy efficiency. Particularly in cellular networks with cognitive spectrum access (e.g., cognitive D2D communications), minimizing the power and spectrum usage of the backhaul system will leave more white/grey spaces in the spectrum for opportunistic access.

Energy-Efficient Backhauling: For energy-efficient design of RRM in 5G networks, energy consumption for backhauling needs to be taken into consideration. Small cell clustering for wireless backhaul multiplexing/resource sharing and joint energy- and backhaul-aware cell zooming are promising energy-efficient backhaul-aware RRM solutions.

The above aspects are not completely independent and are often jointly considered in the RRM designs for HetNets, e.g. joint cell association and power control for interference management, coordinated interference mitigation via eICIC, joint energy-efficient RRM of wireless backhaul and RAN, and so on. The backhaul constraint often appears as a bottleneck rate. This may impose a limit on the access rate over the air interface, or on admission of new users or services. According to the type of the backhaul connection, the following backhaul considerations may apply to RRM problems.

- In C-RAN deployments, the fronthaul, which adopts the CPRI interface, is capable of conveying digital radio signals for all the radio resources at the remote site. Therefore, it may not be required to consider backhaul constraint in C-RAN.
- Backhauling using the existing wired infrastructure, such as digital subscriber line (DSL), introduces a constant backhaul capacity constraint. Similarly, the PtP LOS microwave backhaul with slow link variation can also be considered as fixed rate link that poses a constant backhaul constraint.
- PtMP NLOS wireless backhaul solutions, which are often based on IEEE 802.11 and IEEE 802.16 standards, or emerging technologies such as mmWave and massive MIMO, are designed to handle fast channel dynamics and to provide RRM functionalities in themselves. As a consequence, dynamically changing backhaul constraint can be considered for standalone PtMP wireless backhaul.
- In-band wireless backhauling is part of the RRM of the multi-tier RAN because it shares the radio resources with the service functionalities of the BSs. More involved backhaul constraints must be introduced to reflect the coupling relationship.

The heterogeneous multi-tier RAN of 5G is evolving into a user-centric architecture. The ultra dense small cell deployment will have to abandon the cell planning and optimization approach for interference management and adopt denser spectrum reuse patterns to further boost capacity.

Existing Resource Management Solutions and Their Limitations

RAT Selection and Cell Association

SINR-Based Association and CRE: The signal-to-interference-plus-noise ratio (SINR) has been used as the cell association criterion in legacy homogeneous cellular networks. However, in multi-tier heterogeneous cellular RAN where different tiers have different transmit powers, the high-power MBSs tend to attract more users with SINR-based cell association; severe load imbalance between BS tiers will occur. The high-power MBS users then perceive very low rate because the radio resources are shared by a large number of users. Distance-based cell association can alleviate load imbalance, but is still incapable of adequately addressing the problem due to diverse transmit powers among tiers. Cell range expansion (CRE) [11] based on an SINR biasing mechanism has been proposed to better deal with this issue. The CRE mechanism helps to offload users from high-power MBSs to low-power small cells or other RATs like carrier Wi-Fi. The overall service level in terms of user perceived rate is significantly improved because of better utilization of radio resources across the network. A quantitative way to consider the system load in cell/RAT selection is to use the cell accessibility, which accounts for both the cell load and the scheduling mechanism as the association criterion [12]. A more balanced load across the system is achieved with this resource-aware scheme.

Cell Association by Optimization: The cell association problem can be formulated as mixed-integer optimization, subject to resource constraints. Although such problems are in general NP-hard, they can be transformed into continuous optimization by relaxing the binary association indices, which makes it mathematically more tractable [13]. Other schemes based on Markov decision process (MDP) and game theory have also been reported. However, due to the overhead and convergence issues, they may not be suitable for online applications.

RAT selection and cell association problems essentially deal with admission control and mobility management of the cellular network. Backhaul considerations, in particular small cell backhaul, are the missing pieces in existing cell association schemes. An aggressive MBS offloading scheme may lead to overload of small cell backhaul, and therefore degraded QoE. Integrating the backhaul constraints in the cell association mechanisms, e.g. in the relaxed optimization or in the determination of accessibility in resource-aware schemes, will jointly consider both the air interface and backhaul resources in cell association design such that the overall resource utilization can be improved.

Interference Management

Network Planning and Optimization: The cellular structure has been the core of the cell-centric architecture. By RAN planning and optimization, the coverage of each cell is controlled to certain geographic area, and adjacent cells use orthogonal radio resources to avoid inter-cell interference. Radio resources can thus be reused at a sufficiently far away location to improve system capacity. The heterogeneous multi-tier RAN of 5G is evolving into a user-centric architecture. The ultra dense small cell deployment will have to abandon the cell planning and optimization approach for interference management and adopt denser spectrum reuse patterns to further boost capacity.

Combining OFDMA and MIMO: The orthogonal frequency division multiple access (OFDMA) offers high flexibility in dynamic bandwidth allocation of sub-carriers. The MIMO technology adds spatial degrees of freedom to RRM and scheduling; the beamforming feature improves the cell's control over interference. Combining the OFDMA and MIMO technologies give even finer resource blocks for scheduling. It is therefore a promising solution to interference management, especially cross-tier interference management, for the user-centric architecture of the multi-tier RAN.

Resource Partitioning and Interference Avoidance: With CRE-based cell association, cell edge users of small cells are vulnerable to interference from MBSs. MBSs employing the almost blank subframe (ABS) scheme intentionally leave a specific subframe blank to avoid interference to offloaded users in the CRE region of small cells [14]. Alternatively, the MBSs can also reduce interference to small cells via open-loop or closed-loop power control. Resource partitioning and fractional frequency reuse (FFR) mitigates co-channel interference with less dense frequency reuse. It divides the frequency band into non-overlapping sub-bands that are assigned to different cells or areas. The small cells sense the pilot signals and determine which sub-bands are not occupied. Dynamic partitioning and allocation of the radio resources in both the frequency and time domains yield better utilization of the spectrum, and consequently improve system capacity.

The above interference management schemes in general combine interference management with cell coordination. However, they fail to capture the heterogeneous backhaul constraints, which are inherent in 5G cellular networks. Some recent studies have shown increasing interests in incorporating the backhaul considerations in resource allocation and interference management solutions for HetNets, particularly for those with in-band wireless backhaul where backhaul and service functionalities are tightly coupled. Much work has to be done to gain more insights into the interactions of backhaul and interference management in HetNets.

Scheduling and Inter-Cell Coordination

Localized Resource Allocation: In cellular systems up to 3G, scheduling and radio resource allocation are mostly conducted locally at the BS. Inter-cell coordination is mainly for mobility management and is realized at the aggregation nodes, for example, the radio network controller (RNC) and the associated Iur interface between RNCs in 3G. LTE adopts a flatter architecture which merges most RNC functionalities to BSs (eNBs). The X2 interface between neighboring eNBs is introduced for inter-cell coordination. As the cellular RAN evolves toward the tiered architecture, scheduling and resource allocation are often jointly considered with cell association (admission control and mobility management), interference management, and energy-efficient designs. Advanced features such as eICIC, CoMP, and CA require intense interactions on the inter-cell interfaces, which poses heavy burdens to the backhaul.

C-RAN for Centralized Resource Management: Centralized baseband processing and control of C-RAN, which fully exploits the channel state information (CSI) from all RRHs, is ideal for inter-cell coordination for admission control, mobility management, interference management, and so on. However, benefits of C-RAN come at the expense of increased complexity and overhead. Due to the high bandwidth demand and stringent delay requirement of the CPRI interface, whether a BS can be incorporated into the C-RAN largely depends on its backhaul. The bottleneck for C-RAN-based inter-cell coordination in multi-tier RAN thus mainly lies in small cell backhaul. Even though much work on C-RAN-based inter-cell coordination has been done, there lacks an effective method to deal with the limited CSI feedback due to the backhaul constraints. Also for the ultra dense large-scale 5G multi-tier RAN, scalability is another important issue that has not been adequately addressed.

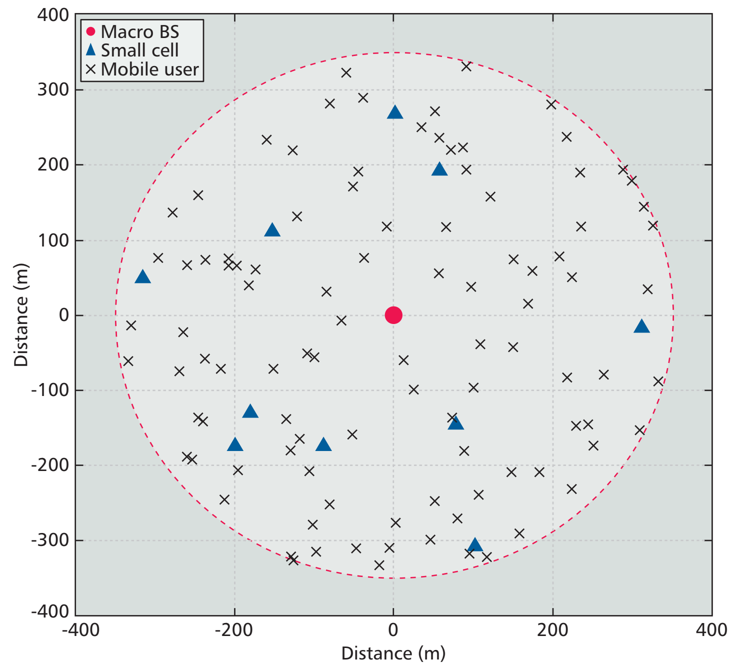

Figure 3. An example of the network geometry of a two-tier cellular RAN.

Massive-MIMO-Based In-Band Wireless Backhauling for Dense Small Cells: A Case Study

In this section, we consider a simple two-tier cellular RAN consisting of one MBS and a number of small cells nested within the footprint of the macrocell to gain a general idea of how small cell wireless backhauling impacts RRM in a tiered cellular network. An example of the network geometry is shown in Fig. 3. Large-scale antenna array is implemented at the macro BS to serve both the macrocell users and the small cell wireless backhaul; all the small cells rely on the over-the-air links to the massive MIMO MBS for backhauling.

In order to share the RF components by both the service and backhaul functionalities of the small cells to reduce hardware complexity, a small cell cannot transmit and receive at the same time over the same frequency band. A co-channel reverse time-division duplex (R-TDD) and soft frequency reuse (SFR) framework is considered for interference management [8]. Specifically, the downlink time slots designated by the MBS are uplink time slots of the underlaying small cells, and vice versa. Simultaneous service and backhaul communications of the small cells are scheduled in orthogonal frequency bands.

Because the small cell traffic has to be routed to the MBS via the massive MIMO wireless backhaul and then to the core network, optimal cell association is tightly coupled with the varying backhaul constraint in the bandwidth allocation mechanism. Consider the same bandwidth allocation is adopted throughout the macrocell range, which simplifies scheduling and gives less complex interference pattern, a unified wireless backhaul bandwidth allocation (u-WBBA) factor needs to be determined to designate the fraction of total bandwidth allocated for wireless backhaul. The u-WBBA factor takes into account the backhaul and load conditions at all small cell locations within the macrocell range. Overloading the backhaul of any small cell will significantly deteriorate the overall system capacity. The bandwidth allocation is updated every cell association period for dynamic SFR.

We evaluate SINR-based cell association, small cell CRE with 5 dB SINR bias, and backhaul-aware cell association with u-WBBA in the two-tier HetNet by computer simulations. The physical layer system model parameters for the simulation, following path loss models for urban macro- and microcells suggested by 3GPP TR 36.814 V9.0.0, are summarized in Table 2. Different numbers of small cells (N_S) and mobile users (N_U) are examined. The empirical cumulative distribution functions (CDFs) of the user rates are plotted in Fig. 4.

By conducting cell association and bandwidth allocation with the in-band u-WBBA constraint taken into consideration, significant gains in perceived user rates are achieved. For example, with 10 small cells and 100 mobile users uniformly distributed within the macrocell range, the median user rate is 1.33 b/channel use with SINR-based cell association. This number is increased to 2.33 b/channel use with the backhaul-aware cell association and bandwidth allocation, which achieves over 75 percent gain. In contrast, the gain due to CRE is negligible. Also, with in-band wireless backhauling, the small cell density has much lower impact on the perceived user rates compared to the impact of the density of users. This is because of another bottleneck in the massive MIMO air interface that is shared by all the small cells for backhauling. The observation is in agreement with the findings about the invariant offloading effect of in-band wireless backhauling at different small cell densities as revealed in [15].

Open Research Issues

In the following, we highlight several open research issues and challenges of RRM with backhaul considerations for 5G multi-tier heterogeneous RAN. Directions toward possible solutions are also briefly discussed.

Distributed Backhaul-Aware Cell Association: With highly diverse backhaul/fronthaul supporting different cells in the multi-tier RAN, it is in general difficult to collect CSI, cell load information, and backhaul status of a large number of cells at a central scheduler for centralized optimization. Distributed cell association algorithms are therefore more desirable in practice. The idea of channel accessibility for resource-aware cell association [12] can be extended to include backhaul status in this metric to achieve load balancing in both the air interface and the backhaul.

Dynamic Cell Load-Based Backhaul RRM: NLOS PtMP wireless backhaul with MIMO capability can be configured to support small cells with dynamic backhaul requirements through beamforming and power and bandwidth allocation. Based on the cell load information, joint optimization which minimizes the service outage probability subject to power and bandwidth constraints can be conducted. More complex cases with massive MIMO hub can also be considered.

Wireless Backhaul for Buffer-Aided Relaying: With buffer aided relaying capabilities, the instantaneous relay backhaul capacity is not necessarily always greater than the first hop source-to-relay link capacity. The backhaul constraint therefore needs to be modified to reflect certain statistical delay constraints such that the end-to-end latency of the cooperative communication link can be guaranteed.

Inter-Cell Coordination with Heterogeneous Backhaul and Limited Feedback: Coordination and joint scheduling of C-RAN cells and non-C-RAN cells employing non-ideal backhaul is a challenging problem. Due to the wireless backhaul limitations, the non-C-RAN cells may only provide limited feedback. Appropriate techniques have to be investigated to effectively exploit both the full CSI from the C-RAN cells and the limited feedback from the non-C-RAN cells. Schemes that achieve different degrees of coordination/cooperation among C-RAN and non-C-RAN cells with partially centralized processing can also be investigated.

Parameter	Value
Carrier frequency	3.5 GHz
System bandwidth	5 MHz
Macro BS height	25 m
Small cell BS height	3 m
Average building height	20 m
Road width	8 m
Noise power spectral density	–174 dBm/Hz
dB-spread of the log-normal shadowing for macro BS σ_{BS} for small cells σ_{SC}	 6 dB 4 dB
Macro BS large-scale antenna array size	100
Massive MIMO beamforming group size	20

Table 2. Parameter values in the radio propagation model.

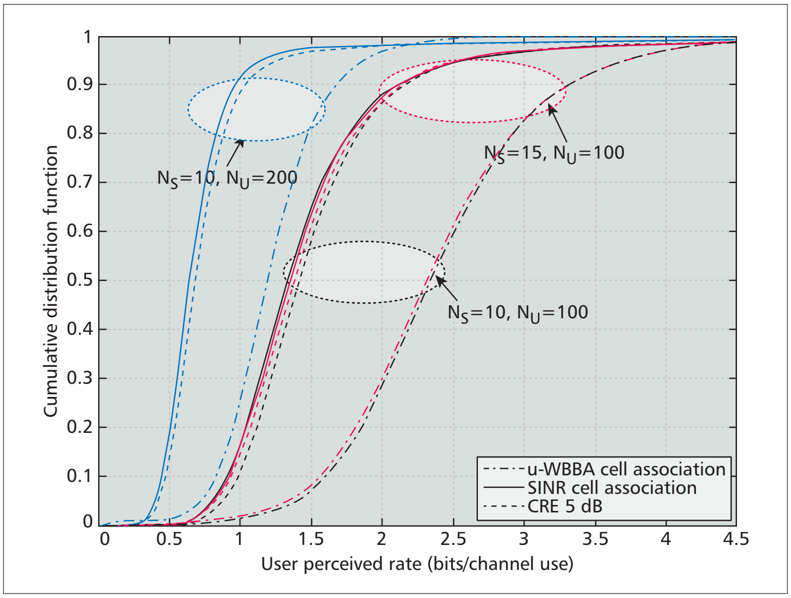

Figure 4. Empirical CDFs of the user rate in a two-tier macrocell-small cell network employing massive MIMO in-band wireless backhaul for small cells with different cell association schemes.

Conclusion

We have first surveyed the evolution of small cells and its impact on the RAN architecture evolution toward heterogeneity and centralized baseband processing in 5G. The backhauling system for small cell will significantly impact the RAN performance in 5G systems. Existing wired and wireless backhauling/fronthauling solutions that can be used to support 5G multi-tier RAN and C-RAN have been briefly discussed. The impact of backhauling mechanism and system architecture on the radio resource management in 5G RAN have been discussed in the context of cell association, interference management, and inter-cell coordination. Existing RRM solutions and their limitations in 5G RAN with heterogenous backhaul constraints have been discussed, and possible solutions which take backhaul considerations into account have been envisioned. We have demonstrated the performance gain of backhaul-aware RRM design when compared to existing RRM solutions ignoring the backhaul constraints through a simple case study. This study considers joint cell association, interference management, and bandwidth allocation in a two-tier macrocell-small cell network where in-band massive MIMO wireless backhaul is adopted. To this end, several open research issues on RRM for heterogeneous multi-tier RAN with backhaul considerations have been outlined.

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Appropriate techniques have to be investigated to effectively exploit both the full CSI from the C-RAN cells and the limited feedback from the non-C-RAN cells. Schemes that achieve different degrees of coordination/coorperation among C-RAN and non-C-RAN cells with partially centralized processing can also be investigated.