WIRELESS BACKHAULING OF 5G SMALL CELLS: CHALLENGES AND SOLUTION APPROACHES

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ABSTRACT

Dense deployment of small cells over traditional macrocells is considered as a key enabling technique for the emerging 5G cellular networks. However, a fundamental challenge is to provide an economical and ubiquitous backhaul connectivity to these small cells. There is a wide range of backhaul solutions that together can address the backhaul challenges of 5G networks. In this context, this article provides an overview of the different backhaul solutions and highlights the perceived challenges in backhauling small cells. A qualitative overview of the existing research studies and their critical assumptions are then discussed. Next, for backhauling downlink traffic of a small cell user, we characterize the cellular region in which the downlink transmission capacity for a user served by a given half-duplex small cell becomes limited by the backhaul link capacity. We then illustrate solution techniques such as full-duplex backhauling to improve the performance of wireless backhauling for small cells.

INTRODUCTION

To enable efficient spectral reuse, massive deployment of small cells will be a key technique for fifth generation (5G) cellular networks [1]. However, provisioning of efficient and economical backhauling solutions for these small cells is a challenging problem. By definition, small cell backhaul connections are used to:

- Forward/receive the end-user (small cell user) data to/from the core network.
- Exchange mutual information among different small cells over X2 interface.

The backhaul evolution for 5G small cells will include wired and wireless backhauling to and from core network aggregators (e.g., macro base stations (MBSs)), cooperation through anchor base stations (A-BSs),[1] multi-hopping at short-range links, and cloud-based architecture as illustrated in Fig. 1. Since the backhaul requirements can significantly vary depending on the locations of small cells, the cost of implementing backhaul connections, traffic load intensity of small cells, latency, and target quality of service requirement of small cell users, there is no single optimal approach for the backhauling of small cells.

Although wired backhaul solutions ensure reliability with high data rates, the cost of wired connections is highly dependent on the offered capacity as well as the distance. Moreover, highly reliable wired backhaul connectivity may not be necessary for small cells, which typically serve a relatively reduced traffic load compared to a macrocell.

Nevertheless, the five-nines reliability[2] and capacity of wired backhauling cannot be completely overlooked. As such, the backhaul transmission of 5G small cell networks will certainly leverage the combination of wired and wireless backauling solutions. However, since the reliability, challenges, and performance of wired backhaul solutions have been quite well investigated and the associated cost-complexity trade-offs are well-known, this article focuses mainly on the investigation and performance analysis of wireless backhaul networks.

Wireless backhauling has recently been considered as a viable and cost-effective approach that allows operators to obtain end-to-end control of their network rather than leasing third party wired backhaul connections. The key wireless backhaul solutions leverage exploiting the millimeter wave (mmWave) spectrum in 60 GHz and 70–80 GHz bands, microwave spectrum between 6 GHz and 60 GHz bands, sub-6 GHz band, TV white spaces, and satellite technologies. However, an optimal selection of the wireless backhaul solution depends on the propagation environment as well as a number of system parameters such as locations and deployment density of small cells, desired backhaul capacity, interference conditions, cost, coverage, hardware requirements, and spectrum availability.

In this context, this article focuses on a multi-tier radio access network (RAN) where the small cells communicate with the MBSs instead of communicating with a cloud for backhauling.[3] The contributions of the article are listed herein:

- We provide a comprehensive overview of the existing wireless backhaul solutions and list their fundamental features, benefits, drawbacks, application scenarios, and the imple-

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[1] These refer to the BSs with wired connectivity to MBSs and forward backhaul data from MBSs to small cells wirelessly in downlink.

[2] This means that the backhaul link remains reliable for 99.999 percent of the time.

[3] In a cloud-based architecture, several small cells are connected to a pool of baseband units (i.e., cloud) using fronthaul links. Similar to backhaul, fronthaul can be realized using wired/wireless solutions, such as optical fiber, microwave, or even mmWave communication [3].

 1536-1284/15/$25.00

mentation challenges. A qualitative overview of the existing research studies and their critical assumptions are then discussed.

• Next, we focus on the wireless backhaul solutions and mathematically characterize the cellular region in which the downlink transmission capacity of a half-duplex (HD) small cell base station (SBS) becomes limited by its backhaul capacity. To overcome this limitation, we propose enabling the in-band full-duplex (FD) mode of operation and mathematically analyze the interference scenarios in which FD is a potential solution. We further investigate the performance enhancements offered by deploying A-BSs in the presence of either HD or FD SBSs.

• The performance gains of the aforementioned solution techniques are quantitatively analyzed through simulations, and insights are extracted related to the scenarios in which the FD mode and deployment of A-BSs are advantageous. In the HD mode, an SBS operates on the access link (between an SBS and its user) and the backhaul link (link between an SBS and an MBS) in different time slots, while in the FD mode, an SBS operates (i.e., receives and transmits) on both the access and backhaul link simultaneously.

• Finally, we point out other design considerations that can potentially tackle the challenges of sub-6 GHz wireless backhauling in small cell networks.

The application of FD communication for wireless backhauling of small cells is novel and has not been investigated yet. Wireless backhauling of small cells using FD communication results in new types of interference such as self-interference and backhaul interference. As such, in the context of wireless backhauling, the benefits of in-band FD communication over traditional HD communication are not evident. It is therefore crucial to understand the fundamental performance limits of FD communication and analyze the scenarios in which the FD mode of operation is advantageous.

Overview of Existing Wireless Backhaul Solutions and Their Key Challenges

This section first provides an overview of existing wireless backhaul solutions. Challenges related to different backhaul solutions are then discussed, and a brief summary of their fundamental features, benefits, and drawbacks is listed in Table 1.

Overview of Wireless Backhaul Solutions

Sub-6 GHz spectrum: Sub-6 GHz frequencies support non-line-of-sight (NLOS) propagation and provide ubiquitous coverage through obstacles. Due to the NLOS feature, point-to-multipoint (P2MP) backhaul connectivity is possible at the cost of interference. For licensed sub-6 GHz spectrum, the licensee is responsible for managing the interference within this spectrum. Moreover, no new hardware is required to manage the access and backhaul links. Nonetheless, the wireless backhaul solution using sub-6 GHz frequencies is highly vulnerable to interference and traffic congestion, and has a high licensing cost.

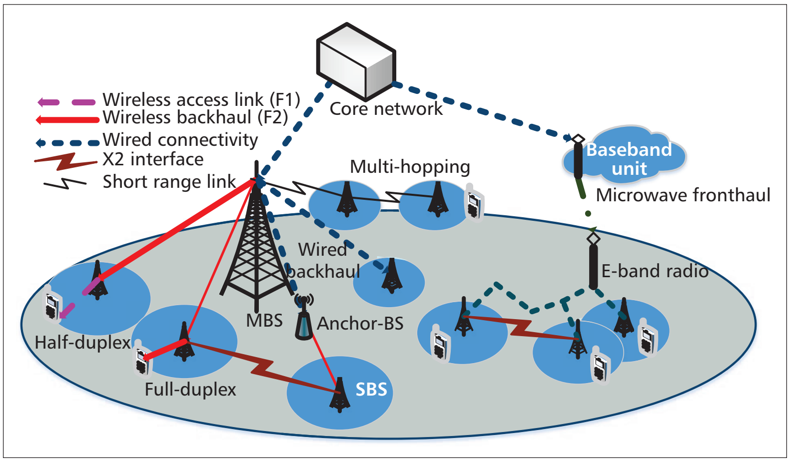

Figure 1. Graphical illustration of backhaul evolution of 5G small cell networks with wireless backhauls and cloud-RAN architecture [2].

Microwave spectrum: The microwave frequency range has been mentioned as 6–60 GHz [4]. The frequencies of microwave links are typically reported as 10.5, 13, 15, 18, 23, 26, and 32 GHz [5]. However, in a number of countries, these bands (e.g., 13, 15, and 23 GHz) are becoming congested. As a result, the exploitation of higher frequencies are currently under consideration. For instance, in the United Kingdom, an auction of spectrum in the 10, 28, 32, and 40 GHz bands was conducted in 2008 to meet the demand for microwave frequencies [5]. Due to shorter wavelengths, microwave spectrum is suitable for LOS scenarios with fixed antenna alignments on both the transmitting and receiving ends.

Since the signal attenuation is high in microwave frequencies, they are favorable for short-range communications (e.g., neighborhood backhauling in ultra-dense small cell deployment scenarios).

Millimeter-wave spectrum: The propagation properties of mmWave (60 GHz and 70–80 GHz) are attractive for high-capacity short-range links. This mmWave spectrum is spacious and can potentially minimize interference with highly directive narrow beamwidth antennas. Nevertheless, mmWaves are affected by atmospheric attenuation to a greater degree than lower frequencies. The power attenuation at 60 GHz is basically due to the oxygen or dry air, whereas 70–80 GHz is more similar to conventional microwave, where attenuation is mainly caused by water molecules in the air. As a result, 60 GHz is more heavily attenuated. However, the license-exempt nature of 60 GHz makes it more cost effective from the operators' perspective.

TV white spaces (TVWS): The TV band is divided into two bands: VHF band (54–60 MHz, 76–88 MHz, 174–216 MHz) and UHF band (470–698 MHz) [6]. With the emerging digital TV (DTV) transmission, a large amount of TV spectrum has become vacant and is referred to as TV white spaces (TVWS). While TVWS are licensed for TV transmissions, they can be exploited for backhaul provisioning to small cells in a cognitive (unlicensed) manner. That is, the backhaul interference caused to primary TV transmissions should not exceed a prescribed threshold. TVWS have larger footprint due to their longer wavelengths and unlicensed nature, which help to minimize the cost. The channels in the TVWS offer much better propagation characteristics compared to low-frequency cellular bands. Nonetheless, the usefulness of TVWS for small cell backhauling would be strictly limited by the transmit power and location of primary TV transmitters.

Satellite frequency bands: In a satellite backhaul link, the degree of attenuation due to weather or rain fade would depend on the frequency band selected. Lower frequency bands, that is, 4–6 GHz (also known as C band), are practically unaffected by weather, while the Ku-band (10–12 GHz) is slightly more affected. However, the highest currently used band, Ka-band (20–30 GHz), could expect up to 24 dB of rain fade. The main benefit of satellite-based backhauling is that it becomes possible at any location from where a suitable satellite is visible and also in high mobility scenarios. By high mobility scenarios, we refer to those scenarios where the small cells are located on airplanes (business or large-bodied jets), ships (ranging from large yachts to commercial vessels and cruise ships), and land deployed "cells on wheels" to provide extra coverage. In such a case, the wireless backhaul solutions should be selected such that they are capable of providing continuous backhaul coverage to these mobile small cells. Typically, a satellite backhaul for a small cell requires a small parabolic dish and a

Backhaul spectrum features [4]	Benefits	Limitations	Applications
Sub-6 GHz • 800 MHz–6 GHz • Licensed • NLOS • 70 Mb/s @ 20 MHz • Urban: 1.5–2.5 km • Rural: 10 km @ 3.5 GHz	• No additional spectrum • No new hardware required • Easy O & M • Wider coverage • Antenna alignment not required • Low attenuation	• Limited spectrum • High cost spectrum • Interference issues	• Low mobility scenarios • Rural and urban areas • Conversational voice and video (live streaming), real-time gaming
Microwave • 6–60 GHz • Licensed • LOS • 1 Gb/s+ • 2~4 km	• High capacity • Medium coverage • High directivity	• Additional spectrum cost[4] • Hardware cost • Require antenna alignment • High attenuation	• Urban and rural areas • Real-time as well as non-real-time services
Millimeter-wave • 60 GHz • Unlicensed • LOS • 1 Gb/s+ • ~1 km	• Bulk of unused spectrum • High capacity • Low coverage • High directivity • Small form factor[5] • Zero spectrum cost • Noise limited	• Hardware cost • Multi-hopping required • High attenuation • Multiple antennas required • Require antenna alignment	• Dense urban areas • Real-time as well as non-real-time services
Millimeter wave • 70–80 GHz • Light licensed • LOS • 1 Gb/s • ~ 3 km	• Bulk of unused spectrum • High capacity • Low coverage • High directivity • Small form factor • Noise limited	• Hardware cost • Multi-hopping required • High attenuation • Multiple antennas required • Require antenna alignment	• Dense urban areas • Real-time as well as non-real-time services
TV white space • 600–800 MHz • Unlicensed • NLOS • 18 Mb/s • 1~5 km urban	• Antenna alignment not required • Wider coverage • Low attenuation	• Primary user constraints • Hardware cost • Opportunistic availability • Interference issues	• Sparsely populated areas • Conversational voice and video (live streaming), real-time gaming
Satellite • 4–6, 10–12, 20–30 GHz • Licensed • LOS • 2–10 Mb/s downlink • 1–2 Mb/s uplink	• Wider coverage • Supports high mobility • Ubiquitous coverage	• Additional spectrum cost • Hardware cost • Antenna alignment issues • Jitter, time delay	• Rural and remote areas • Mobile situations • Buffered streaming

[4] Spectrum cost also includes the licensing cost.
[5] The term form factor refers to the length of the antenna array.

Table 1. Summary of the fundamental backhaul solutions for 5G small cells.

remote satellite modem to be installed. For ships and airplanes, stabilized antenna systems can be used to point at the satellite and to switch between different satellites when moving from one coverage area to another.

Key Challenges

Outdoor propagation impairments of mmWave signals: While the LOS nature of mmWaves tends to limit the interference between small cells, poor penetration (blocking) through obstacles is a critical problem [7]. For example, a 100 m mmWave outdoor link requires an additional 32 dB or more gain to ensure reliable communication compared to an indoor mmWave link. To overcome this, large-sized phased-array antennas can be used. However, larger antenna arrays are more sensitive to wind induced misalignments. Furthermore, due to short links and narrow beams, minor variations of propagation geometry could result in severe pointing errors that can degrade the backhaul performance.

Multi-hopping in microwave and mmWave bands: For both microwave and mmWave links, a physically clear and unobstructed radio path is required between the SBS and its backhaul gateway. This may require multiple hops to overcome obstacles in the propagation path. Multi-hop routing can significantly increase the overall capital expenditure and the end-to-end delay. Furthermore, the LOS requirements lead to more complex installation, precise alignment, and commissioning of equipment compared to NLOS transmitters and receivers.

Spectral mask requirements in TVWS: While the TVWS can be a potential candidate for wireless backhauling, the radio design and interference threshold at a primary user can be a performance limiting factor. For instance, the spectral mask requirements, that is, adjacent channel leakage ratio (ACLR) and adjacent channel selectivity (ACS), may result in costly filter designs with increased power consumption [4]. ACLR requirements impact the dynamic range of the digital-to-analog converter. On the other hand, the ACS requirements impact receiver linearity, power consumption, and analog-to-digital converter design. Thus, the coexistence issue needs to be efficiently resolved to enable robust as well as reliable backhaul operation.

Backhaul interference: Wireless backhauling can be in-band or out-of-band. With the former, the same channel is used for access and backhaul links. With out-of-band backhauling, there is no interference between access and backhaul links due to the transmissions on different bands/spectrum or wired connectivity. With in-band wireless backhauling, network operators can upgrade their existing networks in a short time and at low cost. However, this gives rise to additional sources of interference, which may severely degrade the benefits of resource reuse in both transmission and backhaul links. As such, intelligent cell association and resource allocation strategies are required that can potentially mitigate backhaul interference.

Backhaul signaling overhead: In dense small cell deployments, the information exchange between small cells and macrocells, as well as between neighboring small cells would be much more frequent. This can be a direct consequence of frequent handovers [8], the execution of interference management, load balancing, and energy saving solutions, or other collaborative communications methods. Moreover, if joint processing techniques like coordinated multipoint (CoMP) are applied, the user data needs to be shared among multiple BSs [9]. This data exchange can lead to a huge backhaul signaling overhead. Consequently, small cells should be able to dynamically manage and activate/deactivate different connections, and adapt according to favorable conditions such that backhaul signaling overhead can be minimized.

Backhaul delay: Transmission through a wireless medium incurs a delay when retransmissions are required due to transmission failures. This can happen, for example, due to interference from concurrent transmissions and due to channel fading. This delay, referred to as backhaul delay, can significantly degrade system reliability and end-user performance. Therefore, characterizing the wireless backhaul delay will be crucial while analyzing the performance of different backhaul solutions [10].

Jitter and time delays in satellite backhauling: Satellite backhauling leads to large time delays due to:
- Signal propagation delay between the ground station to the satellite and that between the satellite and the ground station. This delay can range from 240 to 260 ms.
- Delays due to packetization and processing. These can be in the range of 35–50 ms, yielding a typical one-way trip time of 275–310 ms.

Moreover, the expected variations in delay (jitter) in the uplink and downlink would be in the range of 5–25 ms and 10–50 ms, respectively [4].

Non-uniform user traffic: A direct consequence of small cell densification could be non-uniformity of user traffic. Due to reduced coverage, the number of users in a small cell would typically not be very large, and the traffic load per small cell can be highly time varying (e.g., due to user mobility). Therefore, backhaul resource allocation solutions need to be developed that can adapt to the traffic load conditions in the small cells.

Downlink (DL)/uplink (UL) traffic asymmetry: The mobile traffic in the uplink and downlink can be highly asymmetric. The ratio of downlink to uplink traffic varies in the range of 4:1 to 8:1. The backhaul resource allocation solutions should be able to exploit this traffic asymmetry to utilize the backhaul resources efficiently.

Overview of Existing Approaches to Wireless Backhauling of Small Cells

The major deployment techniques that have been considered recently to ensure reliable wireless backhauling include the deployment of aggregator nodes [11], wireless backhaul hubs with multiple antennas [12], deployment of Type-A relay systems [13], and so on. Several recent studies have focused on developing efficient backhaul interference management and

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delay minimization solutions or performance characterization of integrated backhaul systems where wired and wireless backhauls for SBSs can coexist. A qualitative overview of some of the existing approaches proposed in the state-of-the-art literature to tackle the key challenges as discussed earlier is given in Table 2.

Deployment-Based Backhauling Solutions

In [11], a two-tier network is considered where MBSs are connected to the core network and small cells can access the MBSs wirelessly. Small cells that are unable to access the MBSs using single-hop wireless links utilize aggregator nodes (ANs) to ensure backhaul connectivity. A joint cost function of placing the aggregator nodes, power control, channel scheduling, and routing is formulated and minimized to optimize the locations of the ANs. Another two-tier network underlaid with single-antenna small cells is considered in [12]. The small cells are connected to the core network via wireless backhaul links. A wireless backhaul hub (WBH) with multiple antennas is deployed to provide backhauling for the SBSs. To maximize the deployment benefits, it is desirable for the WBH to support as many SBSs as possible. As such, given the service constraints at the SBSs and power constraints at the WBH, the number of SBSs that can be admitted into the network is optimized.

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Flexible Wireless Backhaul (Challenges 8 and 9)

In [13], deployment of Type-A relay is proposed where the MBS transports backhaul data wirelessly to SBSs. From a functional perspective, a Type-A relay resembles a user equipment with relaying capability. However, Type-A relays differ in terms of deployment (e.g., Type-A relays are operator-deployed), protocol stack, scheduling strategy, transmission power, and so on. A Type-A relay communicates simultaneously with two BSs by leveraging the downlink resources of MBS as well as the uplink resources of SBS to effectively increase the spectral efficiency while addressing the issue of DL/UL traffic asymmetry. The position of a Type-A relay is optimized to maximize the backhaul capacity.

Backhaul Delay Management Solutions (Challenge 6)

In [10], a tractable analytical model is developed to characterize the average network backhaul delay and the delay experienced by a typical user in the downlink considering both wired and wireless backhaul scenarios. The network delay is further investigated for both the in-band and out-of-band wireless backhaul scenarios. It is shown that the total aggregate wired backhaul delay can be minimized for an optimal density of small cells. On the other hand, for wireless backhauling, it is not cost effective to increase the density of SBSs beyond a certain point. It is thus concluded that deploying dense small cell networks may not be as effective without comparable investment in the backhaul network.

Cooperation among small cells requires efficient exchange of channel state information (CSI). However, real-time CSI sharing is a crucial challenge since a user feeds back CSI directly to its serving BS only, while any further inter-cell CSI exchange takes place over backhaul links. In practice, information exchange over the backhaul links introduces additional delays, which further degrade CSI reliability. Any CSI at a transmitter pertaining to an interfering user is subject to a larger delay than that of the served user. In this context, the authors of [14] devise an efficient modified zero forcing beamforming technique to overcome the CSI discrepancy created by the backhaul delay.

Interference Management (Challenge 4)

In [15], large-scale multiple-input multiple-output (MIMO) is considered at the MBS to mitigate intra-cell and inter-cell interference. However, the small cell tier relies on large-scale MIMO links to the MBS for backhauling. A duplex and spectrum sharing scheme, which is based on co-channel reverse time-division duplex (TDD) and dynamic soft frequency reuse (SFR), is proposed for backhaul interference management. A joint optimization problem is formulated to optimize backhaul bandwidth allocation and user association such that the sum log-rate of the network is maximized.

In [16], an interference management strategy is proposed for self-organized small cells considering the wired and wireless backhaul (called heterogeneous backhaul) constraints. The SBSs operate like decode-and-forward relays for the macrocell users and forward their uplink traffic to the MBS over heterogeneous backhauls. Specifically, the users split their uplink traffic into two parts. The first part is a coarse message, which can only be decoded at the MBS, and the second part is a fine message, which can be decoded by neighboring SBSs as well as the MBS. The users select the best SBS and optimize their transmission strategy while accounting for the underlying backhaul conditions at the same time. The problem is formulated as a noncooperative game, and a reinforcement learning approach is used to find an equilibrium. Using the proposed approach, the users self-organize and implicitly coordinate their transmission strategies in a fully distributed manner while optimizing their utility function, which captures the trade-off between throughput and delay.

Millimeter-Wave Backhauling (Challenge 1)

A self-backhauled mmWave small cell network is considered in [7] where a fraction of SBSs, referred to as A-BSs, have wired backhaul, and the rest of SBSs backhaul wirelessly to A-BSs. The A-BSs serve the rest of the SBSs in the network, resulting in two-hop links to the users associated with the SBSs. The uplink and downlink coverage and rate distribution are characterized. MmWave networks in dense urban scenarios employing high-gain narrow-beam antennas have been shown to be noise-limited for practical BS densities. Consequently, densification of the network improves the signal-to-interference-plus-noise ratio (SINR) coverage. It is concluded that increasing the fraction of A-BSs improves the peak rates in the network, whereas increasing the density of BSs while

	Assumptions	Benefits	Limitations
Deployment-based backhauling solutions	[11] • Out-of-band • µwave backhaul, sub-6 GHz backhaul • Uplink, single cell • Single antenna AN and small cells • Two hop network	• Minimized network operational cost • Optimal placement of AN	• Computational complexity • Co-tier and cross-tier interferences ignored
	[12] • Out-of-band • Single antenna SBSs and multiple antenna MBSs	• Fast convergence • Minimized cost of small cell backhauls • Small cell SINR and backhaul power constraints	• CSI is required • MBS intercell interference ignored • Computational complexity
Flexible backhauling (Challenges 8 and 9)	[13] • In-band, • Sub-6 GHz backhau • Downlink • Single antenna small cell and relay • Single antenna macrocell	• Low operational cost • Reduced interference at user • Improved backhaul capacity • Optimized location of relays	• Increased interference at SBS • Co-tier and cross-tier interferences ignored • Effect of backhaul delay ignored
Backhaul delay management solutions (Challenge 6)	[10] • Both sub-6 GHz backhaul and wired backhaul • Downlink • Single antenna MBS and SBSs	• Improved delay performance • Flexible choice of SBS density • Minimize expected delay and deployment cost	• MBS intercell interference is ignored
	[14] • Out-of-band • Wired backhaul • Two macrocell, each with single antenna MBS	• Overcome the CSI delay • Optimal beamforming scheme	• Perfect CSI is required
Interference management (Challenge 4)	[15] • In-band • Sub-6 GHz backhaul • Downlink • Massive MIMO at MBS • Single antenna SBSs	• Maximize network sum log-rate • Optimized bandwidth allocation for backhauling • Optimized user association	• Computational complexity • MBS intercell interference is ignored
	[16] • In-band • Sub-6 GHz backhaul • Uplink • Single antenna MBS and SBSs	• Slow convergence • MBS inter-cell interference is ignored • Interference is managed under backhaul constraint	• Optimum uplink macrouser performance
Backhaul signaling overhead (Challenge 5)	[9]• In-band • Sub-6 GHz backhaul • Downlink • Multicell • Multi-antenna BSs	• Reduced signaling overhead • Minimize backhaul user data • Given QoS and per-BS power constraint	• Computational complexity • Backhaul delay is ignored

Table 2. Qualitative overview of existing wireless backhaul solutions for 5G small cells.

keeping the density of A-BSs constant in the network leads to saturation of user rate coverage.

Backhaul Signaling Overhead (Challenge 5)

When the joint processing technique is applied in CoMP downlink transmissions, the data for each user needs to be shared among multiple BSs. This data exchange can lead to a tremendous backhaul signaling overhead if the number of users is large. To address this backhaul signaling overhead, a multi-cell CoMP network with multi-antenna BSs and single-antenna users is assumed. The objective is to distribute the user data only to the minimum number of cooperating BSs, while satisfying the SINR constraint of each user. The problem of minimizing backhaul user data transfer is formulated, which jointly determines the optimal BS clustering and the transmit beamformers [9].

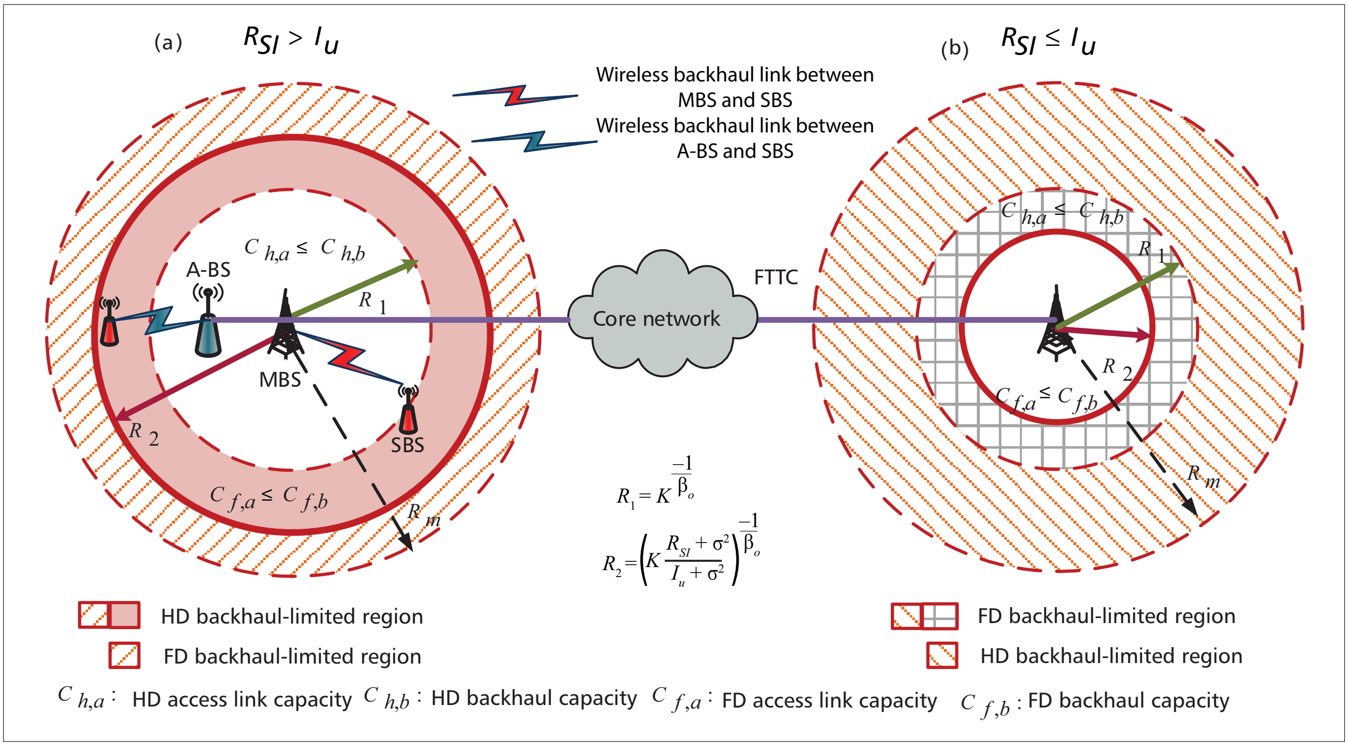

Figure 2. Graphical illustration of the backhaul-limited regions with HD and FD small cells. A demonstration of different backhauling options for SBSs deployed in the backhaul-limited region, that is, direct sub-6 GHz backhauling with MBS and sub-6 GHz backhauling via A-BS. MBSs are connected to the core network via fiber to the curb (FTTC).

Use of TV White Spaces (Challenge 3)

In [6] use of TV white spaces is proposed to provide a backhaul network for rural areas and areas with no preexisting wired infrastructure. To quantify white space availability in the considered region, the area is divided into a grid of 5 mi × 5 mi square cells. Each cell has a radio tower in (or near) the middle. Each radio tower has four sector antennas covering all directions instead of one isotropic antenna. The distance between transmitter and receiver is 5 miles. This model allows more concentrated line-of-sight (LOS) transmission and less interference. Achievable capacity is derived using FCC power limits and widely accepted propagation models. Traffic demand per cell is derived using a Cisco data traffic survey.

In the rest of the article we focus on RAN spectrum[6] (sub-6 GHz)-based wireless backhauling for small cells, identify the limitation of traditional HD wireless backhauling, and introduce the idea of wireless in-band FD backhauling for small cells.

Design Guidelines to Overcome the Limitations of Wireless-Backhauled Small Cells

In this section, considering traditional HD SBS, we first theoretically characterize the cellular region boundary beyond which the downlink transmission capacity of a user served by a given small cell becomes limited due to the backhaul link capacity. This region is referred to as the "backhaul-limited region" in which the transmission link capacity cannot be improved any further. As the distance between MBS and SBS increases, the received signal power at the SBS decreases due to path loss, which limits the backhaul link capacity and in turn the transmission capacity for a user in the downlink. For a clear exposition, we do not consider the shadowing and fading effects in the propagation model. Note that the distance between the MBS and the SBS is the root cause of this backhaul limitation. We demonstrate the usefulness of FD transmission in reducing the backhaul-limited areas under certain interference conditions (as shown in Fig. 2). We then quantitatively analyze the benefits of FD transmission and deployment of A-BSs to enhance the backhaul experience of a typical HD small cell. A-BSs are connected to an MBS through wired connection while providing wireless backhauling for the HD or FD SBSs. The transmission power of an A-BS is considered to be same as that of an SBS (i.e., $P_a = P_s$).

Backhaul-Limited Region for HD SBS

Let us define the HD *backhaul and access link capacities* as

$$C_{h,b} = \alpha \log_2\left(1 + \frac{D^{-\beta_o} P_m}{\sigma^2}\right)$$

and

$$C_{h,a} = (1-\alpha)\log_2\left(1 + \frac{d^{-\beta_i} P_s}{\sigma^2}\right),$$

respectively, where P_m represents the transmit power of MBS, β_o and β_i are path-loss exponents corresponding to macrocell and small cell propa-

[6] The spectrum for cellular RANs is a part of the sub-6 GHz band. For instance, bands including 450–470 MHz, 698–960 MHz, and 1.710–2.025 GHz have been identified for the International Mobile Telecommunications-Advanced (IMT-Advanced) system in the Radio Regulations (RR) 2008 [17].

gation environments, respectively, D represents the distance between the MBS and the SBS, $\alpha = 0.5$ represents the fraction of time allocated for backhaul transmission, d is the distance between SBS and its user, P_s is the transmit power of SBS, and σ^2 is the noise power.

The *achieved downlink transmission capacity of a small cell user* can then be given as

$$\mathcal{C}_{h,u} = \min\left\{ \begin{aligned} &\mathcal{O}\times(1-\alpha)\log_2\left(1+\frac{d^{-\beta_i}P_s}{\sigma^2}\right), \\ &\mathcal{O}\times\alpha\log_2\left(1+\frac{D^{-\beta_o}P_m}{\sigma^2}\right) \end{aligned} \right\},$$

where $\mathcal{O}$ represents the overhead of the backhaul traffic, which is typically generated at S1 interface.

Given the definitions of backhaul and access link capacities, the distance boundary R_1 at which $\mathcal{C}_{h,a} = \mathcal{C}_{h,b}$ can be derived as $R_1 = (d^{-\beta_i}P_s/P_m)^{-1/\beta_o}$. Beyond R_1, the user capacity becomes limited by the backhaul capacity.

Backhaul-Limited Region for FD SBS

Similarly, for FD SBS, the *backhaul and access link capacities* can be defined as

$$\mathcal{C}_{f,b} = \log_2(1 + D^{-\beta_o}P_m / (R_{\mathrm{SI}} + \sigma^2))$$

and

$$\mathcal{C}_{f,a} = \log_2\left(1+\frac{d^{-\beta_i}P_s}{I_u+\sigma^2}\right).$$

respectively, where $R_{SI} = P_s/C_{SI}$ [18], and C_{SI} represents the self-interference cancellation value, and I_u is the backhaul interference received at a user from the MBS.

The *achieved capacity of a small cell user* can then be given as

$$\mathcal{C}_{f,u} = \min\left\{ \begin{aligned} &\mathcal{O}\times\log_2\left(1+\frac{d^{-\beta_i}P_s}{I_u+\sigma^2}\right), \\ &\mathcal{O}\times\log_2(1+D^{-\beta_o}P_m/(R_{\mathrm{SI}}+\sigma^2)) \end{aligned} \right\}.$$

Given the definitions of backhaul and access link capacities, the distance R_2 at which $\mathcal{C}_{f,a} = \mathcal{C}_{f,b}$ can be derived as $R_2 = (d^{-\beta_i}P_sA/P_m)^{-1/\beta_o}$, where $A = (R_{SI} + \sigma^2)/(I_u + \sigma^2)$. Beyond R_2, the user capacity becomes limited by the backhaul link capacity.

Remark: It can be observed that the boundary point R_2 depends on the value of A, that is, if $A \leq 1$ (self-interference is less than the backhaul interference I_u, i.e., $R_{SI} \leq I_u$), $R_2 < R_1$; otherwise, $R_2 \geq R_1$, as illustrated in Fig. 2.

Quantitative Analysis

HD vs. FD SBS: Figure 3 demonstrates the backhaul-limited regions for HD and FD SBSs for a scenario when $A \leq 1$. As expected, due to increased path-loss, the capacity of the backhaul link decreases with increasing distance D between the MBS and the SBS. This trend remains valid for both FD and HD SBS. However, the backhaul link capacity of HD SBS turns out to be relatively limited compared to FD SBS due to the orthogonal phases for backhauling and information transfer.

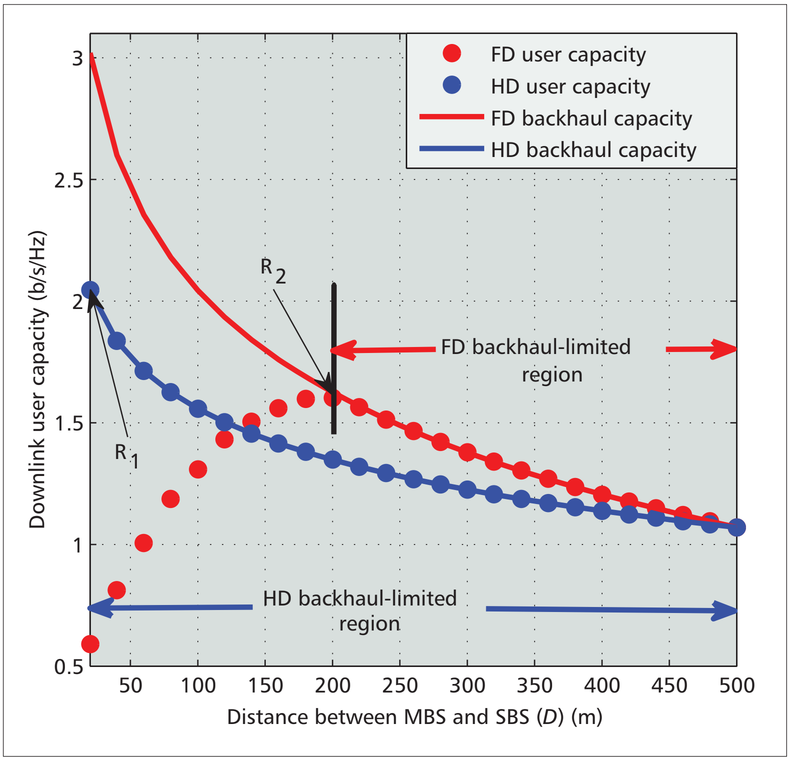

Figure 3. Graphical illustration of the backhaul-limited regions and user capacity as a function of D (for R_m = 500 m, R_s = 40m, $\beta_i = 2$, $\beta_o = 3$, P_m = 5 W, P_s = 2 W, $\sigma^2 = 1 \times 10^{-12}$W/Hz, d = 30m, $\mathcal{O} = 0.14$).

Conversely, in FD SBS, the attained user capacity is significantly reduced compared to backhaul capacity at small values of D. This is due to the backhaul interference, which does not allow a user to enjoy higher backhaul capacity at small values of D. Note that in the case of HD SBS, the attained user capacity is quite close to HD backhaul capacity, and it monotonically decreases with increasing D, which is the converse of FD SBS. The reason is the absence of backhaul interference and the dominating effect of path loss.

Interestingly, for small values of D, the user capacity in HD SBS turns out to be higher than that in FD SBS. However, as D increases the user capacity with FD SBS tends to increase due to reduced backhaul interference and becomes limited by the backhaul capacity at a certain point. This is the point beyond which an increase in the access link capacity will not bring any further benefit to user capacity.

Remark: These facts motivate the need for adaptive FD in sub 6 GHz-backhauled small cells that allow SBSs to decide their mode of operation in an opportunistic manner. Moreover, the need for other assisting deployments (e.g., anchor SBSs, relays) or backhaul interference management solutions (e.g., power control) becomes evident. As such, we now numerically investigate the performance gains in the backhaul-limited regions by employing A-BSs.

Deployment of anchor base stations: The deployment of A-BSs can potentially reduce the backhaul-limited regions. Figure 4 demonstrates

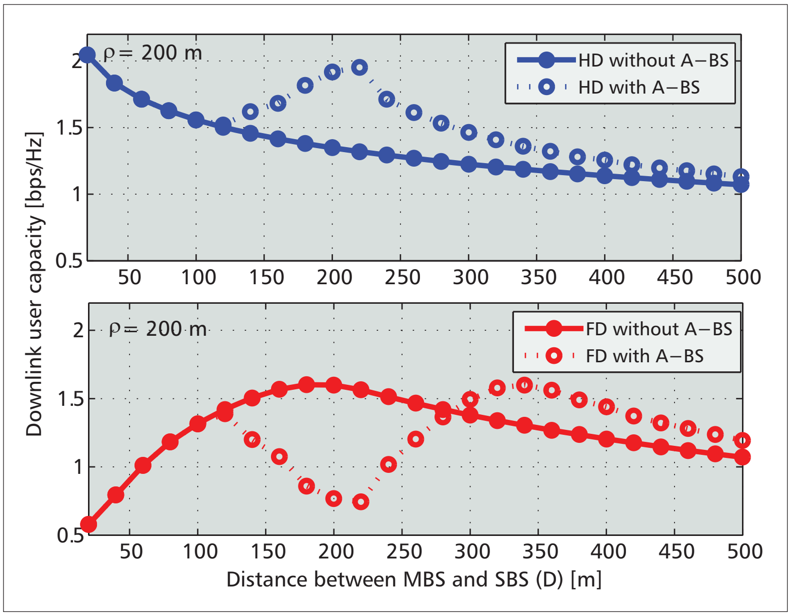

Figure 4. Downlink user capacity as a function of distance between MBS and SBS considering symmetric deployment of A-BSs (for R_m = 500 m, R_s = 40 m, β_i = 2, β_o = 3, P_m = 5 W, P_s = 2 W, P_a = 2 W, $\sigma^2 = 1 \times 10^{-12}$ W/Hz, d = 30m, $\mathcal{O}$ = 0.14).

the impact of deploying A-BSs on the user capacity considering that A-BSs are placed around the MBS at a fixed distance ρ. A given SBS selects the nearest A-BS or MBS for backhauling. The gains of HD SBS with A-BSs in the backhaul-limited region, especially in the vicinity of A-BSs, are observed to be significantly high compared to all other schemes. This is due to the strong received signal power at an HD SBS from an A-BS due to short distance and absence of backhaul interference due to orthogonal backhauling and transmission time slots. Hence, the optimal capacity can be achieved at point ρ (i.e., the point where the A-BSs are deployed). However, as the distance between the HD SBS and A-BS increases, the user capacity degrades.

Conversely, the gains of FD SBS with A-BSs in the backhaul-limited region, especially in the area far away from A-BSs, are observed to be high compared to all other schemes. The worst-case capacity can be achieved at ρ, which is due to backhaul interference from the nearest A-BS. In this case, backhauling through MBS is more feasible. However, as the distance between FD SBS and A-BSs starts increasing, the user capacity tends to increase. This is due to reduction in backhaul interference and gain due to simultaneous backhaul and information transfer.

It has been observed that the optimal user capacity gains with HD SBS depend directly on the location of A-BSs. On the other hand, FD gains are mostly achieved at locations far from A-BSs. *It can thus be concluded that deploying A-BSs helps to improve the user capacity with HD SBS in the same region and enhances the user capacity with FD SBS in distant areas. Thus, the use of HD mode can be recommended for SBSs located near A-BSs, and FD mode can be recommended for SBSs located far from A-BSs.*

Other Design Considerations for Wireless Backhauling

User association schemes: With the emerging non-ideal wireless backhaul solutions, the existing user association schemes such as channel-aware, traffic-load-aware, and channel-access-aware schemes may be highly suboptimal. New user association criteria are therefore required that perform cell selection based on the backhaul capacity limitation, backhaul delays, and backhaul interference in addition to traffic load and channel conditions. Note that the traffic load conditions need to be considered now for both the transmission link of an SBS as well as its backhaul link.

Resource allocation: Efficient solutions for backhaul resource allocation need be developed that can adapt according to the locations, channel conditions, and traffic load of different SBSs. Moreover, the backhaul transmissions from SBSs or MBS should be power adaptive depending on the required backhaul capacity per small cell. This will minimize interference while achieving the required backhaul capacity. In dynamic TDD systems, the spectral efficiency of the small cell user can be maximized by optimizing the time allocated for backhaul and transmission given a total time constraint.

Massive MIMO for wireless backhauling: To serve multiple SBSs at a certain time in the downlink backhauling, the use of multiple antennas or multiple channels is inevitable. From the operators' perspective, deploying large antenna arrays at the MBS to serve massive small cell deployments using the same time-frequency resource could be more attractive than using multiple sets of channels. With such a deployment, the use of efficient beam-forming techniques can completely cancel the intra-cell backhaul interference. However, the limitations of pilot training sequences per coherent time interval restricts the total number of SBSs served per time-frequency resource.

FD SBS with satellite backhaul: The satellite backhaul is a competitive solution to bring small cell services to remote and rural areas. FD backhauling can be implemented at satellite bands by an SBS to serve simultaneously small-cell users and backhaul data to/from a core network via satellite gateways and, in turn, satellites. Specifically, in the uplink, very small transmit power of the user would not have any impact on the performance of a satellite gateway receiver. In the downlink, the directive feeder antennas at a satellite gateway with possibly additional isolation and processing would cause negligible interference to the small cell user.

Conclusion

We have highlighted the primary challenges of wireless backhauling of small cells in a multi-tier cellular network where several types of backhaul solutions can coexist. Different wireless backhauling options have been compared qualitatively. To this end, for a two-tier macrocell–small cell network, we have characterized the backhaul-limited regions where the downlink transmission capacity of a small cell user is constrained by the transmission capacity of a half-duplex system. In this system the access link and the backhaul link operate in different time slots. Solution approaches such as a full-duplex approach, where access link and backhaul link operate in the same time slots, and anchor-BS deployment have then been considered, and their performance gains have been illustrated quantitatively.

Finally, other possible solution techniques have been discussed that can potentially improve the performance of wireless backhauling of small cells.

Acknowledgments

This work was supported in part by the Natural Sciences and Engineering Research Council of Canada (NSERC) and in part by the National Research Foundation of Korea (NRF) grant funded by the Korean government (MSIP) (2014R1A5A1011478)).

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Efficient solutions for backhaul resource allocation need be developed that can adapt according to the locations, channel conditions, and traffic load of different SBSs. Moreover, the backhaul transmissions from SBSs or MBS should be power adaptive depending on the required backhaul capacity per small cell.