Radio Resource Management Considerations for 5G Millimeter Wave Backhaul / Access Networks

Yilin Li, Emmanouil Pateromichelakis, Nikola Vučić, Jian Luo, Wen Xu, Giuseppe Caire

Abstract

Millimeter wave (mm-Wave) frequencies between 6 and 100 GHz provide orders of magnitude larger spectrum than current cellular allocations and allow usage of large numbers of antennas for exploiting beamforming and spatial multiplexing gains. In this paper, we elaborate the main design concepts when integrating mm-Wave radio access networks (RANs) into the fifth generation (5G) system, considering aspects like spectrum, architecture, and backhauling/fronthauling. The corresponding radio resource management (RRM) challenges, extended RRM functionalities for 5G mm-Wave RAN, and RRM splits, are addressed, as well. Finally, based on the previous discussions, a framework is proposed which allows joint backhaul and access operation for 5G mm-Wave RAN, which we envisage as one of the key innovative technologies in 5G. The proposed framework consists of a joint scheduling and resource allocation algorithm to improve resource utilization efficiency with low computational complexity and to fully exploit spatial multiplexing gain for fulfilling user demands.

INTRODUCTION

Success of cellular communication technologies has resulted in explosive demand of mobile data traffic, which is expected to have an eight fold growth within five years [1]. Correspondingly, the fifth generation (5G) of cellular networks aims to deliver as much as 1000 times the capacity relative to current levels [2]. To fulfill such requirements, cell densification, more bandwidth and higher spectral efficiency are required.

Considering spectrum shortage situation in the favorite 300 MHz to 3 GHz frequencies used by most of today's wireless communication systems, the limited potential for spectral efficiency enhancement, the utilization of a large amount of bandwidth in millimeter wave (mm-Wave) bands seems to be indispensable. [3]. The available bandwidths in these bands, e.g. in the Ka band (26.5-40 GHz), the V-Band, (57-71 GHz) and or the E-band (71-76 GHz and 81-86GHz), can significantly exceed all allocations in contemporary cellular networks. Moreover, the very small wavelengths of mm-Wave signals combined with advanced low power CMOS RF circuits enable deploying large numbers of miniaturized antennas and exploitation of beamforming and spatial multiplexing gain [4].

However, mm-Wave signals suffer from increase in isotropic free space loss, higher penetration loss, and propagation attenuation due to atmosphere absorption of oxygen molecules and water vapor [5], resulting in outages and intermittent channel quality. Therefore, higher antenna gain is required at both transceiver sides, where directional transmissions have impact on radio resource usage, multiple access, and interference characteristics, and thus impact radio access networks (RANs) and radio resource management (RRM) design. Furthermore, heterogeneous networks (HetNets), with small cells densely deployed

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underlying the conventional homogeneous macro cell, have been treated as one promising candidate of mm-Wave RAN architecture to cope with the adverse propagation conditions [6]. In particular, close interworking between small cells and macro cells enables users to have simultaneous connection to both macro cell base stations (BSs) and small cell access points (APs) thus improving coverage and augmenting overall capacity. The challenge of having large numbers of small cells is that it may be too expensive or impractical to equip every cell with fiber connectivity. As an attractive cost efficient alternative, namely wireless backhauling, provides technology- and topology-dependent coverage extension and capacity expansion to fully exploit heterogeneity of the networks. A further step in this paradigm is wireless self-backhauling, which use same frequency band for both backhaul (BH) and access links, leading to challenges in RRM between BH and access links. Thus, joint BH and access RRM is desired for 5G mm-Wave RAN to optimize system efficiency.

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The rest of the paper is organized as follows. We start by explaining the fundamental principles of the mmWave RAN design in 5G, and discuss spectrum and architecture options, backhauling aspects, and the new notion of resource. We continue by providing details regarding the RRM challenges in the mmWave RAN. Finally, we elaborate our illustrative application scenario of interest, namely the joint backhaul and access operation, and address the corresponding RRM challenges by a proposed system optimization framework.

5G MM-WAVE RAN DESIGN CONSIDERATIONS

In 5G mm-Wave RAN, the architectural design is expected to be different from the conventional RAN to cope with special propagation characteristics of such high frequencies. The architecture plays an important role in order to meet tight 5G key performance indicators (KPIs) [7] and notion of resource will be different from the traditional RAN and also impact the RRM. In this section, key features of mm-Wave RAN design are elaborated, which affect the way of handling the RRM.

Spectrum Considerations

At the World Radiocommunication Conference (WRC) 2015, a list of candidate frequency bands has been selected for future IMT usage, including bands where mobile service has been allocated to be primary service (24.25-27.5 GHz, 37-40.5 GHz, 42.5-43.5 GHz, 45.5-47 GHz, 47.2-50.2 GHz, 50.4-52.6 GHz, 66-76 GHz, and 81-86 GHz) and those without allocation for mobile service (31.8-33.4 GHz, 40.5-42.5 GHz, and 47-47.2 GHz). In the coming WRC 2019, it is expected that one to two global bands within the range of 24.25-86 GHz will be identified to fulfill 5G high capacity demand. It should be noted that although 28 GHz band is not included in the candidate list of WRC 2015, it would still probably be used in some countries.

Generally, the higher the frequency, the more bandwidth becomes available. On the one hand, higher frequency allows accommodation of more antennas within a certain area, thus achieving higher antenna gains; on the other hand, power efficiency of the electronics, especially power amplifiers, decreases when operating on higher frequencies. Another, license free mm-Wave band of interest is the V-band, which experiences high attenuation due to absorption of oxygen molecules, water vapor, and rain drops, respectively. However, for small cells with intersite distance of 100-200 meters, such impact is not significant. In addition to bandwidth, propagation, and coverage, co-existence with other services is a further issue, for example with satellite and/or fixed link services.

Mm-Wave RAN Architecture

Deployment characterizes network layout including physical and logical locations. A typical deployment needs to consider network elements including BS, AP and user equipment (UE), propagation characteristics, and cell parameters [8]. Moreover, it also covers RAN configurations like carrier frequency band, bandwidth, antenna pattern, transmitter (Tx) and receiver (Rx) configuration, and other system features as well as the supporting architectural solution.

The current mm-Wave RAN considers two basic modes of operation:

- *Standalone* operation where the mm-Wave RAN operates without support of any network in the lower frequency bands.
- *Non-standalone* or *overlay* operation where network elements have simultaneous connections to the mm-Wave RAN and the lower frequency band network, such as LTE or 5G sub-6 GHz system.

One example with a standalone and non-standalone deployment is illustrated in Fig. 1.

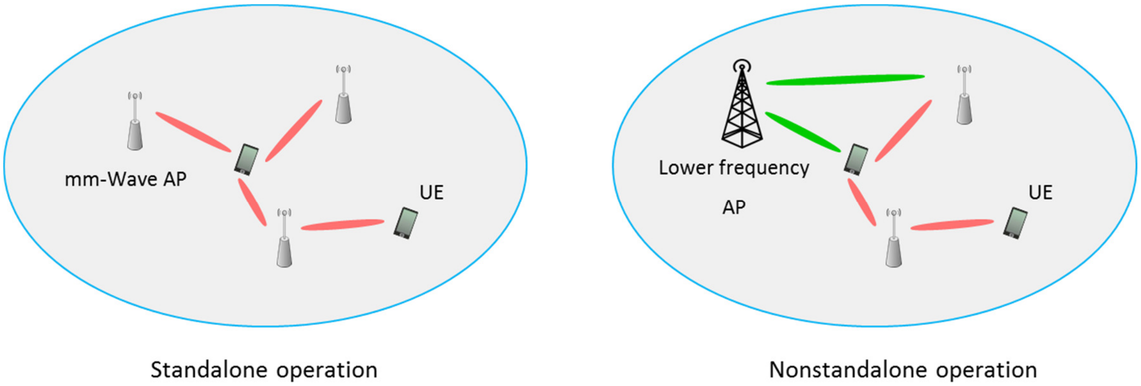

Figure 1 Exemplary standalone vs. non-standalone deployments.

A standalone mm-Wave system is assumed to be deployed and operated without fundamental support from another radio access technology (RAT) system. It should have full control plane capability. Non-standalone mm-Wave can use lower frequency bands as a control plane anchor. Preferably, the system would even work without necessarily having awareness on cositing or noncositing of the cooperating RATs. If a mm-Wave network is deployed as a non-standalone RAN, it should be able to operate in a standalone mode without architecture redesign. Specifically, non-standalone RATs should allow fast, seamless, and reliable mobility and aggregation handling among RATs, with efficient management and pooling of resources for optimum performance.

One of the key architectural considerations in mm-Wave RAN nonstandalone operation is the split between control plane (C-plane) and user plane (U-plane) functionalities [8]. This logical split of functions will be essential to provide fine grained and service tailored optimization assuming different types of resources, multiple air interface variants and 5G services with diverse KPIs. The level of split between C-U

Plane might strongly depend on some factors like the BH technologies/topologies and the deployment, for example, one key challenge of having complete functional separation is the requirement of very low latency BH.

Backhauling in mm-Wave RAN

The new level of densification in 5G will require innovative approaches in radio resource, mobility, or interference management. Mm-Wave BH can enable direct, low latency connections among BSs and hence provide them with a possibility for enhanced cooperation to achieve better performance, in addition to providing high data rate throughput to small cells. Another RAN paradigm of interest for the future is fronthauling (FH). FH or cloud RAN (C-RAN) systems assume a centralized pool of baseband processing units which communicate to distributed remote radio units, with the latter having a significantly reduced functionality compared to classical BSs with the full protocol stack. Such a concept renders significant advantages in terms of hardware centralization benefits, improved RRM and interference management, and simplified onsite equipment. FH requires, however, a significant increase in transport network capacity, and compliance with requirements on very low latency and jitter.

Regarding mm-Wave BH/FH, one can notice that mm-Wave RAN will rely, among other technologies, on large antenna arrays for both sub 6 GHz and mm-Wave solutions. As current FH and common public radio Interface (CPRI) link data rates grow proportionally with the number of antennas [9], it is obvious that the existing solutions do not scale for the future and that new approaches are required, as discussed recently in the eCPRI initiative for 5G FH support [10].

Finally, coexistence of both BH/FH and access links in the same mm-Wave frequency band is likely to be a key design issue in all considered bands. For the license free V-band, an ongoing study in ETSI is to evaluate street level interference levels. Handling interference and corresponding ability to guarantee certain performance targets for BH links is one of the key questions of interest for operators here. Note that in the V-band, there are different worldwide regulations in terms of maximum EIRP, minimum antenna gain, and maximum output power, which greatly affect BH deployment possibilities. On the other hand, the Ka- or the E-Band, are already used for BH/FH purposes. However, there is a significant interest to allocate some portions of spectrum in these bands to access applications, too. In contrast to passive coexistence management, more active coordination of BH and access is beneficial for further increasing resource usage efficiency. One promising way, which will be tackled in the sequel, is the joint BH and access operation.

Notion of Resource in 5G

Prior to 5G, a radio resource is typically considered as a part of the conventional notion of resource. It is characterized by time (duration of the transmission), frequency (carrier frequency and bandwidth), transmit power, and other system parameters including antenna configuration and modulation/coding schemes. In 5G [7], the notion of resource can be extended to cover different aspects such as, hard resources (e.g., number/type/configuration of antennas, existence of nomadic / unplanned access nodes or mobile terminals that can be used as relays) and soft resources (software capabilities of network nodes and UEs). One particular extension which is relevant to this study is the operation of access nodes in high frequencies (which can operate in both licensed and unlicensed spectrum) with much larger bandwidth and different challenges regarding the management and control, compared to low frequencies.

RRM CONSIDERATIONS FOR MM-WAVE RAN

This section provides an overview of challenges and some considerations on RRM functions and their split. In particular, the RRM functions are grouped in three main categories (fast, slow and topology) and different functional elements are discussed as key enablers for 5G mm-Wave RAN.

RRM Challenges in mm-Wave RAN

In the mm-Wave radio, the main challenges regarding resource management are the following:

- High penetration loss of mm-Wave frequencies can severely deteriorate the performance and hence, maintaining reliable connectivity is a challenge especially for delay critical services.
- Wireless channel conditions and link quality can change significantly during movement of users, calling for fast RRM decisions and multi-connectivity support. User mobility also cause significant and rapid load changes and handovers due to small coverage areas of access nodes. Therefore, connection management and load balancing in conventional RRM functionalities need to be revisited to cope with the aforementioned challenges.
- Due to highly directional transmissions, crosslink interference characteristics become much different from sub-6 GHz systems. For example, there can be flashlight effects (an interfering beam hits a user). Advanced interference management is thus required.

Extended RRM Functionalities for mm-Wave RAN

In LTE and beyond systems, RRM functions can be categorized in three main groups given their output, their in-between interactions, and the time scale they operate:

- *Fast RRM*: change resource utilization/restrictions
- *Slow RRM*: trigger cell selection/reselection
- *Topology RRM*: beam steering in BH.

Fast RRM: set of functions which require channel state information (CSI) measurements as input and have tight timing constraints (per TTI). The modified functions for mm-Wave could be:

- Dynamic Resource Allocation (DRA): similar functionality as in LTE, however, the TTI size in mm-Wave radio will be much smaller (around 100 μs) and adaptation of the DRA operation will be necessary.
- Beam management (BM): dynamic beam alignment and corresponding resource allocation, and maintain connectivity between an UE and a serving access node during mobility or radio environment change.
- Inter-node Coordinated Multipoint (Inter-node CoMP): due to high density of access nodes, coordination between access nodes should consider large and dynamically changing clusters of cooperative nodes.

Slow RRM: set of functions which require RRM measurements (e.g. RSRP) as input and have less tight timing constraints. The modified functions in this case could be:

- Load balancing (LB): An existing function which will be modified to cope with fast load fluctuations due to short mm-Wave range.
- Connection mobility control (CMC): another function related to handover management among access nodes, which could be strongly coupled with BM.
- Interference management (IM): in addition to employing inter-cell interference coordination/avoidance in time, frequency and power domain as in LTE, in mm-Wave this should be also handled in spatial domain.

Topology / BH RRM: set of functions which require BH CSI/RRM measurements as input and have variable timing constraints. In this category, depending on BH technology and topology, BH link scheduling and path selection is highly required. In the case of multi-hop mm-Wave self backhauling, proper path selection and switch on/off of access nodes in a way that target KPIs are met, is a key RRM process to avoid BH bottleneck.

RRM Split Considerations

In dense mm-Wave RANs, multiple limitations for BH/access might require a certain handling of RRM. In particular, non-ideal wireless BH among RAN nodes can be a limiting factor and will require extra RRM for BH part. To this end, joint BH and access optimization can be used to meet high throughput requirements for throughput demanding services. Another important factor is the extensive signaling which will be required in HetNets for wireless BH and access measurements. In Figure 2, three possible splits of the aforementioned RRM categories and their possible interactions are illustrated.

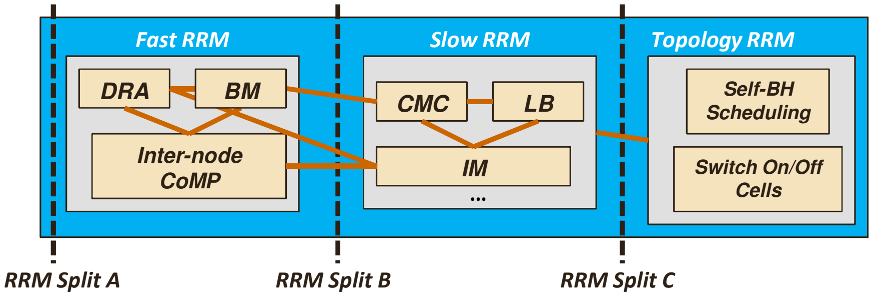

Figure 2 Different RRM splits with exemplary functionalities for mm-Wave RAN.

The pros / cons of these splits are presented in Table 1, as candidate RRM placement options for different mm-Wave RAN scenarios.

	RRM split A (centralized)	RRM split B (semi-centralized)	RRM split C (semi-centralized)
Description	All RRM centralized	Slow and Topology RRM centralized	Topology RRM centralized
Advantages	➢ Provides resource pooling gains (per TTI scheduling) ➢ Allow multi-connectivity	➢ Relaxed BH requirement (non-ideal) ➢ Ideal for low mobility and low/medium load scenarios	➢ Good for no mobility scenarios ➢ Support flexible multi-hop backhauling
Limitations	➢ Centralized Fast RM will require ideal BH/FH	➢ Require fully functional small cells ➢ Require extra signaling for interaction between fast and slow RRM	➢ Require fully functional small cells ➢ For joint BH/access need extra signaling among access nodes

Table 1 Pros and cons for different RRM splits.

As can be seen in Table 1, the key factors which strongly affect the level of split of the RRM functions can be:

- BH is an important factor, since strict timing requirements for certain dynamic RRM functions can be a strong limitation towards centralization for particular cases (e.g. non-ideal BH).
- Deployment is another key factor, as deployment of multiple air interfaces for non-standalone scenario will require centralization of certain slow functions (e.g. mobility control) to allow for multi-connectivity among different air interfaces.
- User mobility and cell density will also impact on required centralization, since no/low mobility requires more distributed RM splits and more dense deployment needs higher centralization to exploit the gain of multi-connectivity.

JOINT BH AND ACCESS OPTIMIZATION FRAMEWORK FOR 5G MM-WAVE RAN

A challenging 5G mm-Wave RAN architecture is HetNet that requires joint BH and access optimization to achieve high capacity and resource utilization. The optimization problem is mathematically decomposed into transmission link scheduling, transmission time and power allocation governed by a set constraints. The scheduling and resource allocation algorithm is further proposed to exploit space division multiple access (SDMA) that allows non-conflicting (see details in subsection "concurrent transmission scheduling") links to be transmitted simultaneously. The proposed solution exploits the aforementioned fast, slow and topology RRM functionalities within a unified BH/access optimization framework. In the following, we describe the framework assuming non-standalone deployment. However this can be also applicable to a standalone network with internode coordination. Compared to sub-6 GHz, the spatial dimension can be exploited more efficiently to manage interference. Further, due to strong directional links, the interference in mm-wave network becomes sparse, allowing the application of simplified schemes.

System Model

Here, we assume BH and access links share the same air interface, and all network elements (including BS, AP and UE) are equipped with directional steerable antennas and can direct their beams in specific directions. The BS processes transmission link scheduling and adjusts transmission duration and power on both BH and access links. Figure 3 shows an example of considered HetNet.

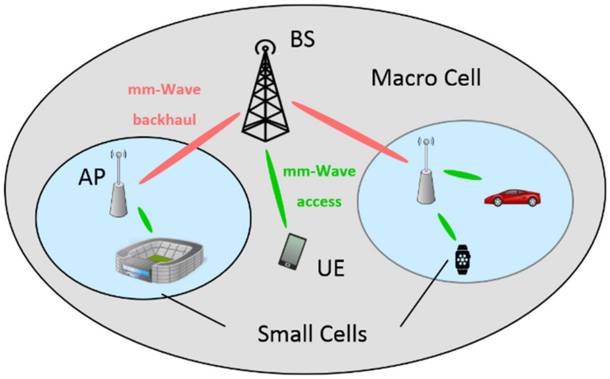

Figure 3 Illustration of a HetNet with mm-Wave wireless BH and access.

In the context of maximizing network throughput of the considered mm-Wave HetNet, how to schedule transmission links and allocate radio resource to both BH and access links for both downlink and uplink transmissions becomes quite challenging, when same radio resource and air interface are shared between mm-Wave BH and access links and TDD mode is assumed. We consider scheduling as many concurrent transmission links simultaneously as possible to fully exploit spatial multiplexing, and time/power resource allocation on the simultaneous scheduling links relies on the result of concurrent transmission scheduling.

Problem Formulation

We formulate the joint scheduling and resource (transmission duration and power) allocation problem mathematically as a constrained optimization problem. We assume that M transmission links are scheduled in a given frame consisting of N slots as illustrated in Figure 4a). These slots are allocated to K SDMA groups, and number of slots in each group is denoted as n^k. Here, an SDMA group is defined as a transmission interval that consists of consecutive slots. It is worth noting that SDMA groups are mutually orthogonal in time-frequency, but inside each group multiple links can be scheduled simultaneously on the same time-frequency slots. The achievable data rate of link i in SDMA group k is denoted as r_i^k, and can be calculated according to Shannon channel capacity equation as follows:

$$r_i^k = B \cdot \log_2(1 + \frac{\delta_i^k g_i p_i}{\eta + \sum_{I_i} g_{I_i} p_{I_i}})$$

Here, B represents the available bandwidth and η models white Gaussian noise power over the indicated link. The term $g_i p_i$ calculates the received power of link i where g_i and p_i describe the channel gain and transmission power of link i, respectively. The sum $\sum_{I_i} g_{I_i} p_{I_i}$ models the resulting interference on link i from other links. δ_i^k is defined as the scheduling indicator of link i in SDMA group k, where $\delta_i^k = 1$ indicates link i is scheduled in SDMA group k.

Based on the above description, the generic representation of maximizing network throughput problem can be described as follows

$$\max_{\boldsymbol{\delta},\boldsymbol{n},\boldsymbol{p}} \sum_{i=1}^{M} \sum_{k=1}^{K} \frac{r_i^k}{N} \cdot n^k$$

subject to the following constraints:

- Scheduling constraints: each link can be scheduled only once in each frame (i.e., each link can be scheduled in one SDMA group), however it can occupy all slots within the group.
- Half duplex constraint of TDD: BS/AP/UE can only either transmit or receive for a given time slot, instead of simultaneous transmission and reception.
- Time resource constraint: The total number allocated slots to all groups is equal to N.
- Power constraint: Total transmission power of all simultaneously active links from the same Tx should not exceed the available transmission power of the Tx.

Note that $\boldsymbol{\delta}$, $\boldsymbol{n}$, and $\boldsymbol{p}$ represent the sets of δ_i^k, n^k, and p_i, respectively.

Scheduling and Resource Allocation Algorithm

To solve the optimization problem efficiently with low complexity, we propose a heuristic scheduling, time and power allocation algorithm, which is described in the following.

Concurrent Transmission Scheduling

Main idea of this algorithm is to determine which link(s) to be transmitted in each SDMA group according to UE transmission request and interference information acquired by for example initial access and interference sensing procedure. To simplify analysis of considered HetNet, we abstract the network to a directed graph, referred to as "link graph" in Fig. 4b), where nodes represent network elements (BS, APs and UEs), and edges represent transmission links among the elements. With the interference information, the link graph can be transferred to a new graph referred to as "conflict graph". In this graph, the nodes now represent the transmission links (edges in link graph), and the edges depict the "conflicts" among links. To be more specific, links that are "connected" by an edge either cannot be scheduled simultaneously due to half duplex constraint, or will result in interference above threshold if simultaneous transmitted. An example of conflict graph construction is illustrated in Fig .4b).

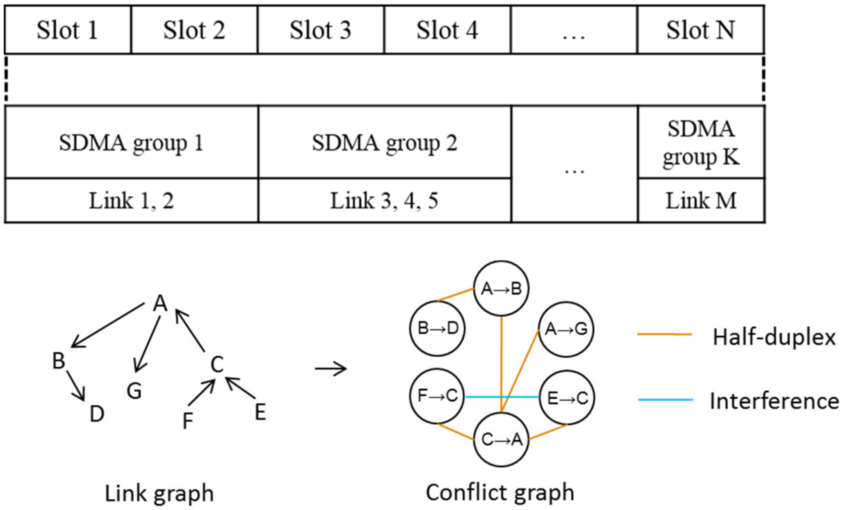

Figure 4 a) considered frame structure; b) conflict graph construction.

Having the conflict graph, a maximum independent set (MIS) based scheduling algorithm is proposed to distribute links into different SDMA groups, where the maximum number of nodes in the conflict graph will be found where no edge exists between any chosen nodes. In other words, the MIS based scheduling algorithm finds maximum number of links that can be transmitted simultaneously without violating half duplex constraints and without strong interference. The algorithm iteratively schedules concurrent transmission links for each SDMA group by obtaining MIS of the conflict graph until all links are scheduled.

Transmission Duration Allocation

With the concurrent transmission scheduling results, a proportional time resource allocation algorithm is proposed to determine the transmission duration for each SDMA group. We denote the number of slots that can be allocated to flow i in the benchmark scheme (i.e., TDMA) as n^i. Then the maximum number of slots among all links in the SDMA group k (denoted as V_k) can be obtained by $n_{max}^k = \max_{i\in V_k} n^i$. Based on this, the total number of N slots in the frame are allocated to each SDMA group proportionally to its maximum number of slots n_{max}^{k}, and the number of slots distributed to SDMA group k, denoted as n^{k}, can be calculated as

$$n^{k} = \left\lfloor \frac{n_{max}^{k}}{\sum_{k} n_{max}^{k}} \cdot N \right\rfloor$$

where $\lfloor x \rfloor$ is the floor function.

Transmission Power Allocation

Because of spatial multiplexing, a given Tx may be transmitting simultaneously multiple links. Therefore, power allocation across such links is required in order to meet the Tx sum power constraint. In the algorithm, we apply the waterfilling power allocation algorithm for concurrent links transmitted from BS and APs in the distributed manner, and keep maximum transmission power for those links without sum power constraints, that is to say, only one transmission link from the network node simultaneously. The waterfilling power allocation algorithm gives more power to the links with higher SNRs and vice versa. For other links, maximum transmission power can be allocated. Note that the SNR based power allocation, neglecting interference, is valid since interference suppression has been performed in the scheduling layer.

Numerical Results

Monte Carlo simulations are used to evaluate the efficiency of proposed algorithms in enhancing user throughputs. For the evaluation, we consider a HetNet deployed under a single Manhattan Grid, where square blocks are surrounded by streets that are 200 meters long and 30 meters wide. One BS and four APs are located at the crossroads. 100 UEs are uniformly dropped in the streets. Channel model is consistent with [11].

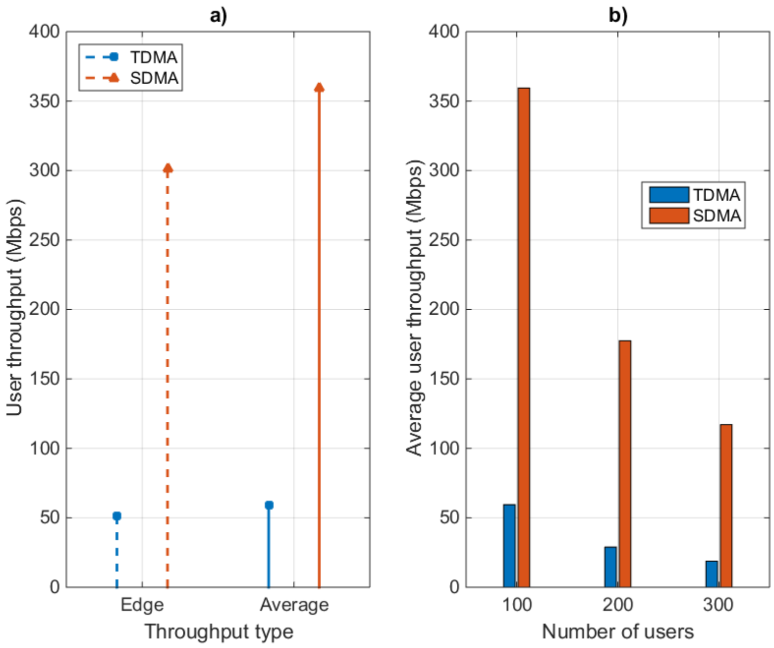

Figure 5 Comparison of user throughputs for carrier frequency of 28GHz and bandwidth of 1GHz: a) edge and average user throughputs for 100 users; b) average user throughputs for different number of users.

Figure 5a) shows the simulation results of user throughputs at carrier frequency of 28 GHz and bandwidth of 1 GHz. Here, cell edge user throughput is defined as 5th percentile point of the cumulative distribution function of user throughputs. Compared to the benchmark TDMA scheme, our proposed algorithm provides considerable improvement in both edge user throughput and average user throughput due to exploiting spatial multiplexing that allocates more time resources to each link in the network by allowing multiple links to transmit concurrently.

Figure 5b) shows the simulation results of average user throughputs for different numbers of users in the network. On the one hand, as expected, increasing the number of users reduces average user throughput due to limited bandwidth. However, enabling space dimension still achieves high user throughput in the case of 300 users, and provides significant improvement compared to the benchmark scheme. On the other hand, as user density increases, gain of proposed scheme to TDMA scheme also grows (604 percent, 614 percent and 623 percent of proposed algorithm against TDMA for 100, 200 and 300 users, respectively). This is mainly because with the increasing number of users, allocable slots for each link in TDMA scheme is limited and becomes dominant factor in determining user throughputs, consequently user throughputs benefit more from the spatial multiplexing gain.

CONCLUSIONS

In this paper, an overview of RAN aspects and resource management of 5G mm-Wave radio communication systems was presented, including RAN design, RRM and a framework of joint BH and access optimization. A 5G mm-Wave cellular network has been characterized to have large amount of available bandwidth at higher frequency bands, dense deployed small cells that closely interwork with macro cells, and large antenna arrays with directional antennas at both transceiver sides to enable high beamforming gains. Wireless backhauling and its extension, self-backhauling, has been considered as a key enabler for providing technology- and topology-dependent coverage extension and capacity expansion and supporting heterogeneous network deployment of the 5G. One key challenge for wireless backhauling and self-backhauling is the RRM.. This was addressed in this paper with joint BH and access optimization, which supports multiple simultaneous transmissions to exploit spatial multiplexing gain and allows flexible adaptation of resource usage including transmission duration and power allocation of different links. With the proposed joint BH and access optimization framework, the network throughput can be dramatically increased.

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