

# Optimized and low-complexity power allocation and beamforming with full duplex in massive MIMO and small-cell networks

Selvam Paranche Damodaran<sup>1</sup> ·  
Vishvaksenan Kuttathati Srinivasan<sup>1</sup> ·  
Kalidoss Rajakani<sup>1</sup>

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**Abstract** By combining massive multiple-input and multiple-output (Ma-MIMO) and small-cell approaches, it is possible to improve the capacity of the network, with the features like energy efficiency and high coverage. Ma-MIMO helps in advancing the wireless communication, to incorporate it in the wireless broadband standards such as Wi-Fi and LTE. The use of Ma-MIMO is expected to increase the spectral efficiency for the mobile networks. In this paper, these two different technologies are incorporated for improving the 5G wireless communication. The concern of the whole paper is to satisfy the user with high quality of service. The effective technologies like Ma-MIMO and small cell are analyzed by employing beamforming and power allocation while operated in full-duplex transmission mode. The simulation is conducted to prove the optimal as well as low-complexity beamforming and power allocation, which is required for improving the total power consumption.

**Keywords** Massive MIMO · Small cell · Full duplex · Beamforming · Power allocation

## 1 Introduction

The traditional radio coverage network is also known as macro-cell topology. This network is used to provide the large area coverage for mobile network. But it could not manage the drastically surging mobile users and quality of service (QoS) which includes energy efficiency, capacity of the network. Nowadays, the network efficiency is poor and the coverage area is weak. Densification of network is a process of attach-

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✉ Selvam Paranche Damodaran  
paranche@eurecom.fr

<sup>1</sup> SSN College of Engineering, Chennai, Tamil Nadu, India

ing new access point into the already existing access points in a network. This is used to allow maximum spatial reuse. This paper investigates on two methods such as massive MIMO (Ma-MIMO) and small-cell network (SCN) [1–3]. Ma-MIMO wireless communication technology supports to improve the wireless communication [3] and incorporates it with the wireless broadband standards like the Wi-Fi and LTE. The small cell is another wireless communication technology that plays a vital role in providing 5G communication. Generally, the Ma-MIMO increases the spectral efficiency for the cellular networks by using array of antennas at the presented macro base stations (MBSs). These MBSs contain large number of active elements to perform the process of coherent transceiver. The array of antennas ensures to provide better signal paths, which increases the performance by increasing the rate of data transmission and reliability of link. This method allows specific focusing on producing energy for anticipated users, and its result provides maximum range of energy efficiency. Without the MIMO technology, 4G or the LTE was not possible at all. The network realization is important for Ma-MIMO setup, which desires the management of network interchange by time-division duplex (TDD). For making network estimation range, this approach limits the network users, but it does not limit the range of base station (BS) antennas. The small cell or the femtocell is used to organize a top layer of small-cell antennas (SCAs) control points to relieve the traffic from the MBSs. Therefore, by utilizing the reality the majority of data traffic is restricted and demanded by small portable users on a network. This method decreases the usual gap between the mobile users and the antenna transmitters. Antenna transmitters are used to translate the less propagation failure and advanced energy efficiency of the network. This method comes under the heterogeneous network which is not easy to monitor and manages inter-user border. Each of the network industries and Universities has to face this challenge by focusing on operator-deployed small-cell antennas, and not by user-deployed SCAs. Finally, it will meet the trustworthy backhaul connections and access control of the base stations and small-cell antennas. By using the proposed method of soft cell, the reality of SCA can be visible to the mobile users. This soft cell method is used for long-term evolution (LTE). The entire power consumption of network can be formed with two different parts such as static and dynamic parts. The static part is based on the hardware of the transceiver, and the dynamic part is related to producing the power signals from the network. Combination of Ma-MIMO and small-cell network assures to provide improved power signal in the field of dynamic part. But it needs additional hardware for increasing the capacity of transceiver in the static part. Otherwise, the compact network system is supposed to be accurately deployed and developed to essentially better the entire energy efficiency. This report evaluates the feasible way of expanding the network's energy efficiency when the traditional macro-cell topology is used by the customized or utilized Ma-MIMO approach at the base station and covers with the small-cell antennas. The concern of this paper is to provide a clear and rationally achievable method by the models used in this paper. It is observed that the optimization problem contains an unseen convex construction which permits to find the best possible result in the polynomial instant. This solution is verified for repeatedly or animatedly assigning each network users to the most selective transmitter (SCA/BS). A least difficult algorithm is working based on the typical regularized zero-forcing (RZF). An antenna beamforming is papered and associated with the greatest solution.

The probable benefits of several densified network topologies and their results are evaluated by MATLAB simulation tool.

Small cell comprises of various technologies. It is a less powered, cellular radio access node that can control with licensed as well as unlicensed spectrum. It contains a range between 10m to less than a kilometer. It looks tiny, so collectively they can maximize their radio of surface area to volume. It can provide improved cellular coverage, capacity as well as the applications for the homes, organizations and the rural areas. They can include different types of technologies in it. Small-cell base stations are a collection of group, which plays a very important role in expanding the capacity of the wireless networks. It can provide flexibility and has the capacity to increase the quality of service at a highly attractive price. Implementing a small-cell infrastructure is very good for the users. It will also decrease the number of small-cell towers. As well as, it provides a perfect and cleaner signal with less power [1, 2].

According to [4], the author states the concept of channel estimation and backhaul which requires quality of service (QoS) in ultra-dense network (UDN), for 5G technique. Here, when a macro base station offers the control service or access service through minimum frequency bandwidth, the small base station makes use of Ma-MIMO access and backhaul services. Here, the author recommends the structured compressive sensing (SCS) method of channel estimation model. Whenever the pointed sparsity of mm-wave channel is demoralized, it decreases the mandatory channel overhead and the channel loss is also high. Particularly, even as the non-line-of-sight path is bigger than its path loss in line-of-sight paths. By using sparsity, the necessary pilot angular channel depends on minimum number of conquered multipath. Non-line-of-sight (NLOS) propagation method for short elevation antennas is presented in the device-to-device communication for the enterprise network. In this network, the structure NLOS path loss is increased for reducing the path loss in the transmitter side non-orthogonal model, which is used along with SCS-based valuation in the receiver side of the antenna. The proposed method of this network design calculates the networks connected in the multiple small-cell base station and pilot overhead works based on the less amount of multipaths. By using this study, channel estimation of the network will increase the efficiency of the networks.

As stated by [5], the author states about the backhaul characteristics of wireless communication solutions like TV white space, microwave, mm-wave, satellites and radio waves. The latest problems such as beamforming, backhaul model, pre-coding, large area antenna arrays and energy efficiency of the dense small-cell backhaul with the mm-wave method are studied in the fifth-generation network communication. The wireless backhaul method consumes less cost when compared to the wired backhaul method in the small-cell technology. In the small-cell backhaul system, white-spectrum (WS) method is used for managing the traffic. The satellite offers more than 340Mbps which is just allocated for the remote area in some situations. The mm-wave system is perfect for the small-cell base station, because the size of the system is very small and the maintenance cost is less.

According to [6], the authors discuss the beamforming in the backhaul and access in a mm-wave wireless network technologies. It is observed that the extended communication channel's distance is collective with more path loss at mm-wave; frequencies, build in a line transmit/receive beams, are by default the main problem. In this paper,

the notified new problem is subspace sampling which gives data required for the beam alignment algorithm (BAA). The subspace sampling problem is done in a method of adaptive and non-adaptive manner. An adaptive sampling method can control the already received data for improving the system's performance. The performance analysis of beamforming and subspace sampling is reviewed using the simulation tool. For increasing the beamforming gain, signal-to-noise ratio (SNR) is involved in this paper. By using this research, we can reduce the beamforming.

As per [7], the authors review the performance analysis of random spatial network (RSN) along with multiantenna transmission. In this paper, the effects of base stations (BSs) density and range of antennas used on the wireless system network throughput and energy efficiency are examined. By adding asymmetrical base station to the network, the quality of the throughput and the energy efficiency will be affected. For improving the quality of throughput and energy efficiency, the logical structure of the downlink implementation and estimation of the SC network is developed. The development process depends on the small-cell base station and the network user, when they are demonstrated as a separate three-dimensional Poisson random measures. Base station density and base station antenna, respectively, are used to measure the network throughput. By increasing the base station density or increasing the base station antennas, the energy efficiency of the network increases when the power consumption of base station convinces certain situation. The simple demonstration of the outage probability is a systematic resultant for multiantenna transmission. The network model and its outage properties are evaluated in the simulation part of this development.

As said by [8], the research paper discusses improving the energy efficiency in Ma-MIMO and the small-cell control point. If multiple transmitters are used by a user, there is a soft cell access point that is applied by the network designer. Efficient solution technique is used for solving the power consumption of the network. For better high power consumption in a network, the authors in this research paper use grouping of Ma-MIMO and small-cell method. The numerical analysis is done using MATLAB simulation tool. By combining both techniques, the network will be more optimal and less beamforming. This development offers less power feeding though assuring quality of service (QoS) of each network user.

The exponential growth of wireless communication systems demands the more spectrum to deliver high data rates to large number of users. Most of the present wireless systems are working in half-duplex (HD) mode of transmission. The FD mode of transmission can reduce the spectrum demand by half in theoretically. But the FD faces the real challenge of eliminating the self-interference of the nodes [9, 10].

In the half-duplex or out-of-band FD systems, the transmission and reception of the nodes at the same time/ frequency band are not possible. But, with in-band FD communication, the nodes can be able to transmit and receive concurrently over the same frequency band with increase in the spectral efficiency [10–14]. The interference mitigation in the network between the backhaul link and the access link can be efficiently handled by employing proper power allocation mechanism [15, 16]. Two types of interference may occur. The first one is cross-tier interference caused due to the transmission of the backhaul station and the small-cell base stations (SBSs), and the second one is self-interference caused by the FD. Using the proposed power allocation under the in-band FD scheme, the backhaul and the access networks inter-

ference is improved resulting in the overall improvement in the throughput. This letter is organized as follows. In Sect. 2, the system model and proposed low-complexity beamforming and power allocation are discussed and optimization problem is given. Numerical evaluations are discussed in Sect. 3. The research work conclusion is summarized in Sect. 4.

## 2 System model

Ma-MIMO network with small-cell comprising one MBS enabled with  $M$  antennas and  $N$  number of SBSs with single antenna is considered in this paper. Spectrum resource is shared between MBS and SBSs to completely utilize the spectrum. Here it is assumed that the MBS delivers  $K$  single-antenna users (MUs) and each SBS delivers to one single-antenna user (SU).  $M$  is very large such that  $K + N \ll M$  (e.g., 100, 1000, or even more ). It is defined the MU set as  $\mathcal{U}^m$  with  $k$ th elements  $u_k^{md}$  and SU set  $\mathcal{U}^s$  with  $n$ th small-cell BS elements  $u_n^{sd}$ . TDD protocol is implemented in this paper to utilize the channel reciprocity and to estimate the channel state information (CSI) present in the MBS transmitter. The CSI is initially estimated from the pilots sent from the users to MBS, and the same is assumed at the MBS transmitter because of the reciprocity [17–22]. In this paper, flat fading channel is assumed between the base stations (BSs) and users. The notations used in this paper is given in Table 1. The channel matrix between the transmission node and reception node is given as

$$\mathbf{G} = \mathbf{T}^{1/2}\mathbf{B}; \quad \mathbf{T} = \text{diag}\{\Psi_1, \Psi_2, \dots, \Psi_I\} \tag{1}$$

The path loss and shadow fading are given by the term  $\Psi_i$ , and it consists of the following terms: a constant related to carrier frequency and antenna gain denoted by  $\varphi$ , distance between the two nodes denoted by  $d_i$ , path loss exponent denoted by  $\alpha$ , shadow

**Table 1** Notations

Notation	Definition
$K$	The number of MUs
$M$	The number of the MBS' antennas
$N$	The number of SBSs
$F$	Transmission power
$\Psi$	Large-scale fading
$\mathbf{b}$	Small-scale fading
$\mathbf{d}$	Pre-coding matrix
$s$	Transmission symbol
$k$	$k$ th MU index
$n$	$n$ th SBS and its user index
$(*)^{md}$	Downlink variable related to MBS
$(*)^{bd}$	Downlink variable related to backhaul
$(*)^{sd}$	Downlink variable related to SBS

fading denoted by  $\zeta$ , and it follows the log-normal distribution  $10 \log \zeta \sim N(0, \sigma^2)$  and based on this  $\Psi_i$  is written as  $\Psi_i = \varphi \zeta / d_i^\alpha$ . The fast fading channel matrix is written as  $\mathbf{B} = [\mathbf{b}_1^T, \mathbf{b}_2^T, \dots, \mathbf{b}_I^T]^T \in C^{I \times J}$  where  $I$  and  $J$  denote the number of antennas of transmission node,

$$I = \begin{cases} 1, & \text{for SBSs DL,} \\ K + N, & \text{for MBSs DL} \end{cases} \quad J = \begin{cases} 1, & \text{for SBSs DL,} \\ M, & \text{for MBSs DL} \end{cases} \tag{2}$$

$b \sim N(0, 1)$  are Rayleigh flat fading random variables.

In this paper, multiflow regularized zero-forcing (MRZF) beamforming is adopted for MBS DL. By employing MRZF, the multiuser interference can be perfectly eradicated. The message symbols from the BS and the  $n$ th SCA to user  $k$  are represented  $s_k^{md}$  and  $s_n^{sd}$ , respectively, having unit power (in mW), and derived from independent Gaussian codebooks, that is,  $s_n^{sd} \sim \mathcal{CN}(0, 1)$  for  $s = 0, \dots, S$ . These symbols are multiplied with the beamforming vectors  $\mathbf{d}_k^{md} \in^{N_{MBS} \times 1}$  and  $\mathbf{d}_n^{sd} \in^{N_{SCA} \times 1}$  to obtain the transmitted signals

$$\mathbf{s}_n = \sum_{n=1}^N \mathbf{d}_n^{sd} s_n^{sd}, \quad s = 0, \dots, S. \tag{3}$$

where  $\mathbf{d}_n^{sd} \neq \mathbf{0}$  for transmitters  $n$  that serve user  $k$  and is the one of the optimization variables in this paper.

The received signal at  $k$ th MU is given as below which is suffering the inter-tier interference from SBSs,

$$y_k^{md}(t) = \sqrt{F_k^{md} \Psi_k^{md}} \mathbf{b}_k^{md} \mathbf{d}_k^{md} s_k^{md} + \sum_{n=1}^N \sqrt{F_n^{sd} \Psi_{nk}^{sd}} b_{nk}^{sd} s_n^{sd} + n_k^{md}, \tag{4}$$

The signal-to-interference and noise ratio (SINR) at  $k$ th MU can be formulated from the above equation as

$$\lambda_k^{md} = \frac{F_k^{md} \Psi_k^{md} \|\mathbf{b}_k^{md} \mathbf{d}_k^{md}\|^2}{\sum_{n=1}^N F_n^{sd} \Psi_n^{sd} b_{kn}^{sd} s_n^{sd} + \sigma^2}. \tag{5}$$

The interference at the SBSs is caused by (a) self-interference from themselves, (b) intra-tier interference from other SBSs due to the in-band operation for both uplink and downlink. The signal received at  $n$ th SBS is expressed as

$$y_n^{bd}(t) = \sqrt{F_n^{bd} \Psi_n^{bd}} \mathbf{b}_n^{bd} \mathbf{d}_n^{bd} s_n^{bd} + \sum_{n'=1, \neq n}^N \sqrt{F_{n'}^{sd}, \Psi_{n'n}^{bd}} b_{n'n}^{bd} s_{n'}^{sd}, \tag{6}$$

$$+ \sqrt{\Theta F_n^{sd}} s_n^{sd} + n_n^{bd},$$

where the third term in R.H.S denotes the self-interference and the  $\Theta$  value finds out at the SBSs by self-interference cancellation methods. Then, at the  $n$ th SBS SINR received is written as

$$\lambda_n^{bd} = \frac{F_n^{bd} \Psi_n^{bd} \|\mathbf{b}_n^{bd} \mathbf{d}_n^{bd}\|^2}{\sum_{n'=1, \neq n}^N F_{n'}^{sd} \Psi_{n'}^{bd} b_{n'n}^{bd 2} + \Theta F_n^{sd} + \sigma^2}. \tag{7}$$

The SUs suffer two types of interference (a) inter-tier interference, (b) intra-tier interference. The former is caused MBS, and later is caused by SBS. At the  $n$ th SBS' user, the received signal can be expressed mathematically as

$$\begin{aligned} y_n^{sd}(t) = & \sqrt{F_n^{sd} \Psi_n^{sd}} b_n^{sd} s_n^{sd} + \sum_{n'=1, \neq n}^N \sqrt{F_{n'}^{sd}, \Psi_{n'}^{sd}} b_{n'n}^{sd} s_{n'}^{sd}, \\ & + \sum_{k=1}^K \sqrt{F_k^{md} \Psi_n^{md}} \mathbf{b}_n^{md} \mathbf{d}_k^{md} s_k^{md} \\ & + \sum_{n'=1}^N \sqrt{F_{n'}^{bd} \Psi_n^{md}} \mathbf{b}_n^{md} \mathbf{d}_{n'}^{bd} s_{n'}^{bd} + n_n^{sd}. \end{aligned} \tag{8}$$

First term in (8) indicates the desired signal, second term denotes the intra-tier interference from SBSs, and third and fourth terms denote inter-tier interference from MBS.

Then, at the  $n$ th SBS' user, the received signal SINR is calculated as

$$\lambda_n^{sd} = \frac{F_n^{sd} \Psi_n^{sd} b_n^{sd 2}}{I_{\text{inter}} + \sum_{n'=1, \neq n}^N F_{n'}^{sd} \Psi_{n'}^{sd} b_{n'n}^{sd 2} + \sigma^2}, \tag{9}$$

where

$$I_{\text{inter}} = \sum_{k=1}^K F_k^{md} \Psi_n^{md} \|\mathbf{b}_n^{md} \mathbf{d}_k^{md}\|^2 + \sum_{n'=1}^N F_{n'}^{bd} \Psi_n^{md} \|\mathbf{b}_n^{md} \mathbf{d}_{n'}^{bd}\|^2. \tag{10}$$

### 2.1 Beamforming problem formulation

This topic describes about the algorithms which are used to solve the optimization problem. The constraints of QoS have complicated functions with the beam vectors. It creates a non-convex problem in the formulation of original vectors. It has a low convex structure and it is extracted through the semidefinite relaxation. This original approach is generalized into multiple low spatial transmission.

The matrix format is positive semidefinite, and it can be denoted as  $\mathbf{D}_n^{\text{sd}} = \mathbf{d}_n^{\text{sd}} (\mathbf{d}_n^{\text{sd}})^H \forall n$ . The rank of the matrix is  $(\mathbf{D}_n^{\text{sd}}) \leq \mathbf{1}$ . The rank of the matrix can

be zero, and it can be denoted as  $\mathbf{D}_n^{sd} = \mathbf{0}$ . In the above equation include the SBS and MBS. Hence, it can be written as,

$$\underset{\mathbf{d}_n^{sd} \geq \mathbf{0} \ \forall n}{\text{minimize}} \quad \sum_{k=1}^K \text{tr}(\mathbf{D}_n^{sd}) \tag{11}$$

$$\begin{aligned} \text{subject to} \quad & \text{rank}(\mathbf{D}_n^{sd}) \leq 1 \ \forall n, \\ & \sum_{n=1}^N (\mathbf{b}_n^{sd})^H \left( \left( 1 + \frac{1}{\tilde{\gamma}_k} \right) \mathbf{D}_n^{sd} - \sum_{k=1}^K \mathbf{D}_k^{md} \right) \mathbf{b}_n^{sd} \geq \sigma_k^2 \ \forall k, \end{aligned} \tag{12}$$

$$\sum_{k=1}^K \text{tr}(\mathbf{D}_n^{sd}) \leq q_n^{sd} \ \forall n, \tag{13}$$

where  $q_n^{sd}$  is per-antenna constraints of the transmitter and  $\sigma_k^2$  denotes variance.

Here the targets of QoS are changed into SINR targets such as  $\tilde{\gamma}_k = 2^{\gamma_k} - 1 \ \forall k$ . The above equation has the convex problem, and it is except for the constraints of ranks. Here it can be proved that it is possible to relax the constraints without the optimal loss.

The original problem is shown in [8] and the corresponding corollary [2], and it is solved by the convex optimization problem. It means the optimal solution has polynomial time, and it is guaranteed. It assigns only one transmitter for the user. The users who are close to the SBS can get exclusive service. But MBS is used to serve most of the users. The transition areas which are around the SBS has multiple flow transmission facility, and it is not fully supported by the QoS targets. This corollary gives a positive result [8]. Since it reduces the complexity of the transmission which is optimal. If the constraints of the power are removed, then the power transition areas will disappear.

### 2.1.1 Proposed beamforming algorithm

This algorithm describes about the coordination of the spatial soft cell. It has relatively modest complexity, and the algorithm is infeasible at the real time implementation with  $N$  and  $M$ . Here [8] is used to provide centralized algorithm, and it requires the knowledge about channel, and it is gathered in the MBS. The distributed algorithms are obtained by the decomposition of primary or dual techniques. But it also requires the iterative signal for the variables. It is also infeasible at the implementation time. In [8], multi flow-RZF beamforming is used for the demonstration of the usefulness with low complexity and non-iterative. Here the transmitter  $n = 1$  and it computes the following equation

$$\mathbf{u}_n^{sd} = \frac{\left( \sum_{n=1}^N \frac{1}{\sigma_i^2} \mathbf{b}_n^{sd} (\mathbf{b}_n^{sd})^H + \frac{N}{\tilde{\gamma}_k q_n} \mathbf{I} \right)^{-1} \mathbf{b}_n^{sd}}{\left\| \left( \sum_{n=1}^N \frac{1}{\sigma_i^2} \mathbf{b}_n^{sd} (\mathbf{b}_n^{sd})^H + \frac{N}{\tilde{\gamma}_k q_n} \mathbf{I} \right)^{-1} \mathbf{b}_n^{sd} \right\|} \ \forall k, \tag{14}$$



MBS is used to solve the convex optimization issue.

$$\underset{F_n^{sd} \geq 0 \forall k,n}{\text{minimize}} \quad \sum_{k=1}^K F_n^{sd} \tag{15}$$

$$\text{subject} \rightarrow \sum_{k=1}^K F_n^{sd} \leq q_n^{sd} \quad \forall n,$$

$$\sum_{n=1}^N F_n^{md} \left( 1 + \frac{1}{\tilde{\gamma}_k} \right) - \sum_{i=1}^K F_n^{sd} \geq \sigma_k^2 \quad \forall k \tag{16}$$

The power can be allocated as  $(F_n^{sd})^*$ . It solves the  $n$ th SBS, and the computation will become as follows:  $\mathbf{d}_n^{sd} = (\sqrt{F_n^{sd}})^* \mathbf{u}_n^{sd} \forall n$ .

This algorithm can be applied in the beamforming of heuristic RZF, and it can be transformed with the power allocation problem. It has low complexity, and it is irrespective of the count of antennas. It is a non-iterative algorithm, and the scalar parameters are changed in the SBS and MBS. It affects the SBS vicinity users. It handles only few parameters, and the other parameters are set as zero in default.

### 2.2 Power allocation problem formulation

The goal is to compute the required power to be transmitted by both MBS and SBS, i.e., finding the power allocated by the system in order to satisfy the peak power constraints considering overall power consumption. The level of interference at the SBS depends upon its transmission power. Thus, the optimal power allocation to meet the system requirement is desirable criteria to enhance the system performance.

The popular figure of merit for measuring the communication system performance is information rate which is given by Shannon theorem as  $\mathfrak{R} = \log\{1 + \text{SINR}/\omega\}$ . The solution for the optimization problem for power allocation can be solved by maximizing the sum rate of the users. The transmit power of both MBS and SBSs affects directly the user sum rate.

The information rate  $\mathfrak{R}$  from the total DL rate comprising MUs, SBSs and SUs defined by  $\mathfrak{R}_k^{md}$ ,  $\mathfrak{R}_n^{bd}$ , and  $\mathfrak{R}_n^{sd}$ , respectively, is expressed as [10]

$$\mathfrak{R}(\mathbf{F}) = \sum_{k=1}^K \mathfrak{R}_k^{md} + \sum_{n=1}^N \mathfrak{R}_n^{sd}, \tag{17}$$

where the power allocation plan of the MBS and SBSs is given by  $\mathbf{F} = [F_1^{md}, \dots, F_K^{md}, F_1^{bd}, \dots, F_N^{bd}, F_1^{sd}, \dots, F_N^{sd}]$ . Power allocation is an important issue in small-cell networks due to its ability in deciding the network interference level including inter- and intra-tier interference. More power is required in the MBS in order to support the backhaul access compared to conventional wired backhaul access schemes. In small-cell networks' self-backhaul employing FD scheme, power allocation plays a vital role because it decides the spectrum efficiency of SBSs.

The optimal power allocation policy of the MBS and SBSs denoted by  $\mathbf{F}$  is attained by solving

$$\begin{aligned} & \max_{\mathbf{F}} \mathfrak{R}(\mathbf{F}) \\ & \text{s. t.} \end{aligned} \tag{18}$$

- P1:  $\mathfrak{R}_n^{sd} \leq \mathfrak{R}_n^{bd}, \forall n$ , indicates to assure the quality of service (QoS) of SUs that the SBSs' backhaul DL rate must not be lesser than that of SBS' access DL rate,  
 P2:  $\sum_{l=1}^{K+N} F_l^{md} \leq F_{\max}^{md}$  denotes the MBS downlink transmission power constraint and  $F_{\max}^{md}$  indicates the MBS maximum transmission power,  
 P3:  $F_n^{sd} \leq F_{\max}^{sd}, \forall n$ , is the transmission power constraint of SBSs and  $F_{\max}^{sd}$  is the maximum transmission power of small-cell BSs  
 P4:  $\mathfrak{R}_k^{md} \geq \mathfrak{R}_{\min}, \forall k$ ,  
 P5:  $\mathfrak{R}_n^{sd} \geq \mathfrak{R}_{\min}, \forall n$

P4 and P5 specify the lowest QoS requirements of MUs and SUs, respectively.

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### Algorithm 1 Proposed power allocation algorithm

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1: **print** Power assignment  $F_k^{md} : F_1, \dots, F_K$ .  
**Require:** Number of user terminals(MUs):  $K$   
 2: Power increment:  $\Delta_f$   
 3: MBS maximum power:  $F_{\max}^{md}$   
 4: Backhaul maximum power:  $F_{\max}^{bd}$   
 5: Self-interference coefficient:  $\kappa$   
 6: Desirable channel gains:  $\chi_k^{md}$  and  $\chi_k^{bd}, k = 1, \dots, K$   
 7: Interfering channel gains:  $\phi_k, k = 1, \dots, K$   
 8: Variance:  $\sigma_k^{2md}$  and  $\sigma_k^{2bd}, k = 1, \dots, K$   
 9: Iteration counter:  $t = 1$   
 10: Rate difference:  $\Lambda = |\mathfrak{R}_k^{bd} - \mathfrak{R}_k^{md}|$   
 11: Backhaul power:  $F_k^{bd}$   
 12: Total power used by the MBS:  $F_k^{md}$   
 13: **while** stop == 0 **do**  
 14: Calculate  $F_k, k = 1, \dots, K$ , presuming the backhaul interference as noise ,  
 15: Calculate the effective access rate  $\mathfrak{R}_k^{md,t}$ ,  
 16: Calculate effective backhaul rate  $\mathfrak{R}_k^{bd,t}$ ,  
 17: Calculate the effective rate difference  $\Lambda = |\mathfrak{R}_k^{bd,t} - \mathfrak{R}_k^{md,t}|$   
 18: **if**  $\Lambda_{t-1} \leq \Lambda_t$  **then**  
 19: Halt iterative process: stop= 1.  
 20: **else if**  $\mathfrak{R}_k^{bd,t} > \mathfrak{R}_k^{md,t}$  **then**  
 21: Reduce backhaul power:  $F_k^{bd} = F_k^{bd} \Delta_f$ .  
 22:  $t = t + 1$ .  
 23: **else if**  $\mathfrak{R}_k^{md,t} > \mathfrak{R}_k^{bd,t}$  **then**  
 24: Reduce total access power:  $F_k^{md} = F_k^{md} \Delta_f$ .  
 25:  $t = t + 1$ .  
 26: **end if**  
 27: **end while**  
 28: **return** =0

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**Table 2** Simulation parameters

Parameter	Values
Cell radius	500 m
Number of MBS antenna	400
Number of SBS antenna	3
Minimal user distance from base station	0.04 km
Fading model	Small-scale Rayleigh fading
Penetration loss	20 dB
Carrier frequency	2 GHz
Number of channel realizations	10
Number of subcarriers in the LTE-like system	600
Total bandwidth	10 MHz
Subcarrier bandwidth in the LTE-like TDD system	30 kHz
Noise figure	5 dB
Number of users	10
QoS constraint	2 bits/s/Hz per user
SINR constraints per user	$(2^{\hat{QoS}} - 1) \times \text{ones}(\text{number of users}, 1)$

### 2.2.1 Proposed power allocation algorithm

Using decomposition method in (18) is solved by splitting the coupled problem into smaller subproblems. Here, both the access and backhaul sections will be solved iteratively by taking coupled interference as noise [15, 16]. The proposed algorithm allocates maximum amount of power in both the MBS and backhaul link to transmit maximum amount of information rate under the considered Gaussian noise channel. The algorithm further reduces the transmit power gradually in order to obtain a minimal value between  $\sum_{k=1}^K \mathfrak{N}_k^{md}$  and  $\sum_{k=1}^K \mathfrak{N}_k^{bd}$ . The power allocation is recapitulated in Algorithm 1. In this algorithm the backhaul power allocation is considered as fixed to solve the access network power allocation iteratively. The water filling algorithm is employed for power allocation to maximize the information rates in the access channel, and the backhaul interference is considered as noise.

$$F_k = \begin{cases} \frac{1}{\nu} - \Upsilon_k, & \text{if } \nu < \frac{1}{\Upsilon_k} \\ 0, & \text{otherwise,} \end{cases} \tag{19}$$

where  $\Upsilon_k = \frac{\sigma_k^2 + F_k^{bd} \varphi_k}{\chi_k}$  is  $k$ th MUs link condition,  $\nu$  indicates the water filling power allocation threshold. Desirable channel gains is indicated by  $\chi_k, k = 1, \dots, K$ , interfering channel gains denoted by  $\varphi_k, k = 1, \dots, K$  variance of the channel given by  $\sigma_k^2, k = 1, \dots, K$ .

The access channel rates and backhaul channel rates are attained when the access channel powers are computed. The unwanted power to the backhaul link  $F_k^{bd}$  is reduced when backhaul rate  $\mathfrak{N}_k^{bd}$  is comparatively higher than the access rate  $\mathfrak{N}_k^{md}$ . if  $\mathfrak{N}_k^{md}$

is higher than  $\mathfrak{R}_k^{bd}$  implies that the backhaul not able to sustain the sum of traffic produced by the MUs and, thus, MBS needs to reduce its transmit power  $F_k^{md}$ . Using the gradient descent methods [10, 12], the gradient power for backhaul link and access link is denoted by  $\Delta_f$ . To attain and accelerate convergence,  $\Delta_f$  should be small enough. The algorithm converges when the difference between  $\Lambda = |\mathfrak{R}_k^{bd} - \mathfrak{R}_k^{md}|$  decreases and reaches a optimum value.

### 3 Numerical evaluations

In this section, the analytic results of the proposed power allocation and beamforming algorithm are discussed with a circular macro-cell with small cells overlaid on it. The simulation parameters are shown in Table 2. To solve the convex optimization, algorithmic toolbox SeDuMi available in the modeling language CVX is used.

In Figs. 1 and 2, downlink and uplink sum rate with SNR=15 dB and SNR=5 dB is evaluated for half duplex mode, full duplex mode and full duplex with proposed power allocation and beamforming algorithm. Here, quasi-static fading channel is considered that means during the transmission channel matrices vary independently constantly over the transmission. The channel matrices have unit variance and zero-mean complex Gaussian random variables. The total system throughput achieved by the full duplex transmission mode with power allocation and beamforming is better compared with half duplex transmission mode under various  $\sigma^2$ .

The total sum rate of the system DL versus UL with power allocation and beamforming is shown in Fig. 3.

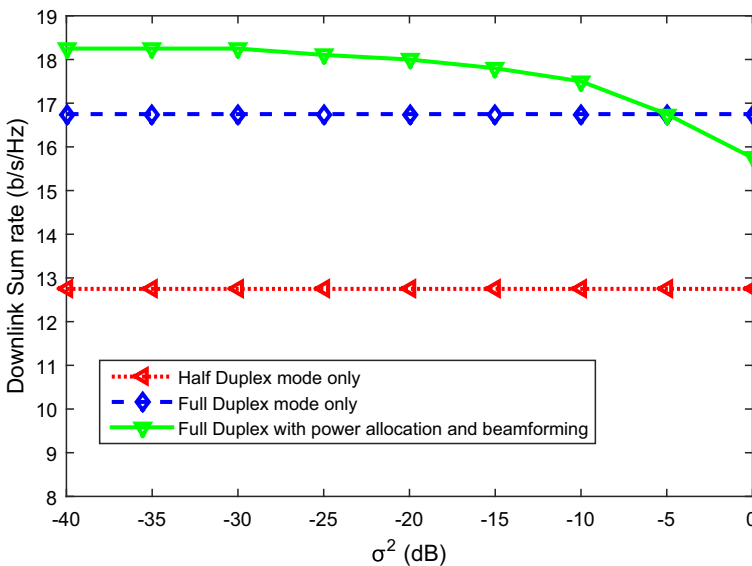


Fig. 1 Downlink sum rate with SNR = 15 dB

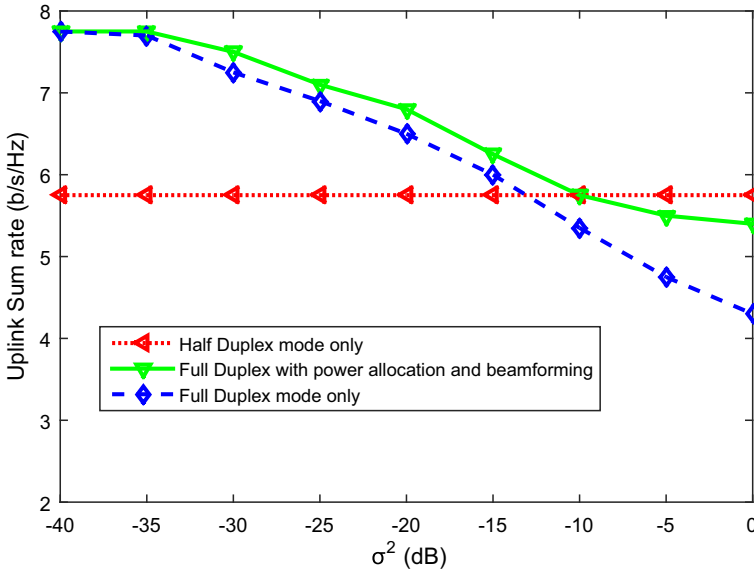


Fig. 2 Uplink sum rate with SNR = 5 dB

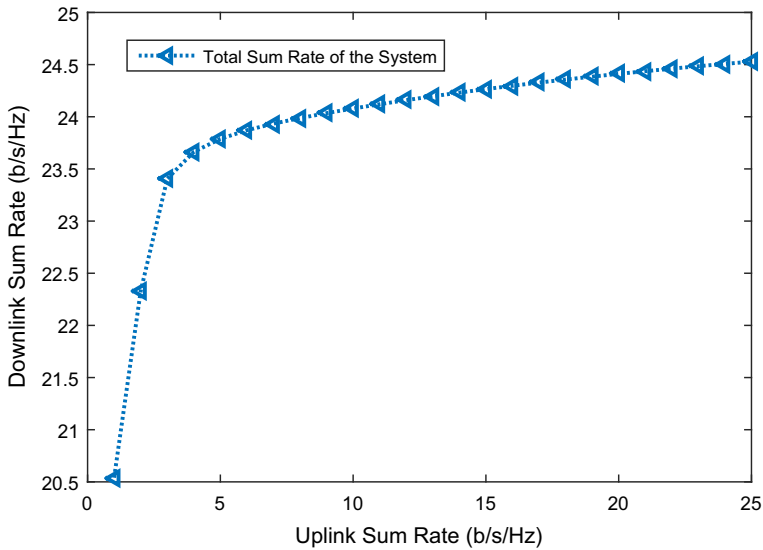
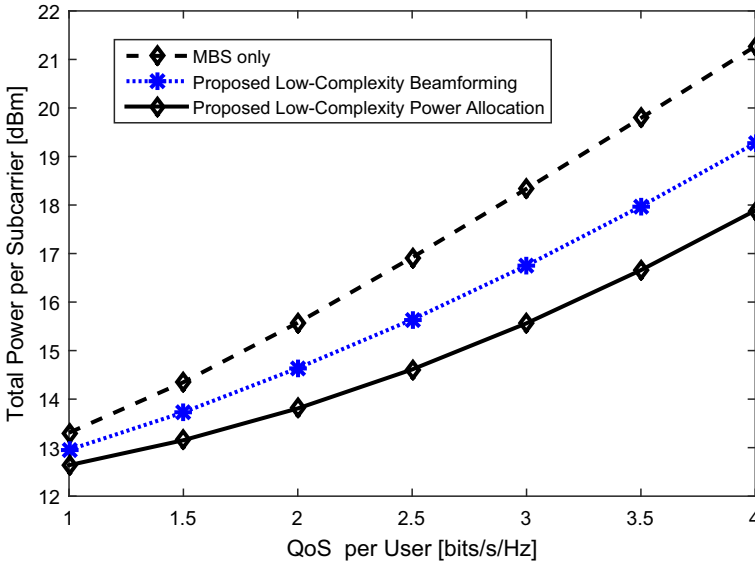


Fig. 3 Total sum rate of the system DL versus UL

The power consumption per subcarrier with QoS target of 2 bits/s/Hz per user is shown in Fig. 4 under proposed power allocation and beamforming algorithm. Employing Ma-MIMO and small cells brings higher energy efficiency by having half of the MBS antennas and few SBS antennas in the active user regions. To improve the energy efficiency in the system, multiantenna SBS is employed. In Fig. 4, three algorithms



**Fig. 4** Power consumption per subcarrier for different QoS constraints

are evaluated: (1) using MBS only; (2) proposed low-complexity beamforming; and (3) proposed low-complexity power allocation.

## 4 Conclusion

The application FD technique is employed to operate backhaul and access link in both uplink and downlink transmission concurrently in self-backhauled small-cell networks with Ma-MIMO. The system sum rate analysis is done to evaluate the performance of FD mode of transmission with beamforming and power allocation over HD mode of transmission. In this paper, we examined the power allocation and beamforming problem for the proposed FD Ma-MIMO with small-cell networks that enable the access and backhauling parallel in the same frequency band. The proposed iterative algorithm allocates the power to the users' to maximize the sum rate, and the proposed beamforming algorithm alleviates the interference problem. The simulation result shows that a Ma-MIMO and small cells employed full duplex with the proposed power allocation, and beamforming can improve the capacity compared to half duplex systems by nearly two times in both directions.

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