Interference Mitigation via Power Control under the One-Power-Zone Constraint

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***Abstract*—Complexity and hardware constraints are two essential considerations in applying interference mitigation techniques to practical wireless systems. This paper considers a practical wireless backhaul network composed of several access nodes (AN), each serving several remote terminals (RT), and where the transmit frame structure at each AN is comprised of multiple zones, with different RTs scheduled on different zones. The objective of this paper is to design power control strategies to mitigation inter-AN interference in the downlink. Unlike prior studies, this paper adopts a practical constraint whereby every AN maintains the same power level across the different zones within one transmitted frame. The main advantage of imposing this new constraint, called the one-power-zone (OPZ) constraint in this paper, is that for a class of scheduling policies under which the number of zones assigned to each RT is fixed, the power optimization and the scheduling subproblems are decoupled under the OPZ constraint. This allows the design of efficient power control methods independent of scheduling. Further, it also simplifies the design of radio-frequency (RF) front-end. The main contribution of this paper is a set of efficient algorithms to solve this constrained power control problem based on an iterative function evaluation technique. The proposed algorithms have low computational complexity, and can be implemented in a distributed fashion. Some of these algorithms can be further implemented asynchronously at each AN.**

I. Introduction

Interference mitigation is a key challenge in improving the capacity of future wireless networks. In a densely deployed interference-limited network, an effective way to mitigate interference is via power control. The successful implementation of power control is, however, also dependent on its algorithmic complexity, the hardware limitations of the wireless front-end, and especially the ability to integrate power control with system-level operations such as scheduling. To address these implementation issues, this paper focuses on a specific class of design constraints, where the transmit power to different scheduled users within each frame is constrained to be at the same level, and proposes novel, simple, and practical methods for power control in wireless networks.

The power control problem considered in this paper is especially applicable to wireless backhaul networks, such as the one presented in our previous work [1], deployed as a means to increase the network throughput for areas with high data traffic demand. The wireless backhaul network under consideration here is composed of several access nodes (AN's), each serving several remote terminals (RT's). This paper assumes a downlink transmit framing structure at the AN in which the data intended for different RT's are scheduled into different zones in each frame. The optimization of the overall system performance therefore consists of a *joint* optimal selection of scheduled user in each zone and the optimal power level for each scheduled user.

The joint power control and scheduling problem is in general not easy to solve. Existing efforts in the literature often involve the exhaustive search (for small networks) or the iterative (local) optimization of scheduling and power control for which convergence and complexity may be issues for practical implementation [2], [3], [4], [5]. Further, scheduling may happen at a different time scale as power control, thus the iteration between the two is not necessarily practical.

This paper addresses this issue from a different perspective. Instead of directly tackling the joint scheduling and power control problem, we impose an extra constraint that the transmit signals for different RTs scheduled in different zones within each frame must have the same transmit power level. This new constraint is called the one-power-zone (OPZ) constraint in this paper. The main advantage of the OPZ constraint is the following. Under a class of scheduling policies for which the number of zones assigned to each RT is fixed, the OPZ constraint decouples the power optimization problem from scheduling, thus allowing the design of power control algorithm to be independent of the scheduling policy, thereby greatly facilitating practical implementation. Further, the OPZ constraint allows the allocation of power on a per-frame basis, rather than on a per-zone basis, which significantly reduces the implementation complexity of the radio-frequency (RF) transmitter front-end.

To solve the power control problem associated with the new OPZ constraint, this paper adopts an approach of iterative function evaluation. This approach, first proposed in our previous work [1], is based on the manipulation of the first-order condition of the optimization problem into an function iteration. The main contribution of this paper is to show that this approach leads to effective and low-complexity power control methods that can readily be applied to a wireless network with the OPZ constraint.

II. System Model and Problem Formulation

A. System Model

Consider a wireless backhaul network, composed by L ANs, each serving K RTs, such as the one in Fig. 1 in which a case

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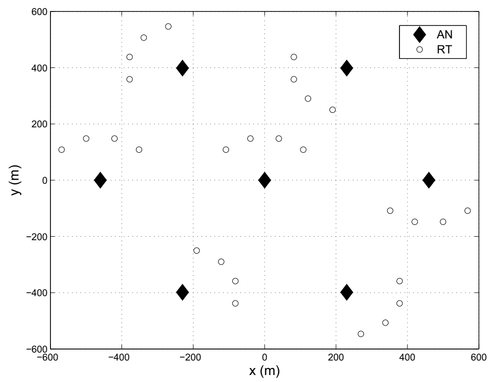

Fig. 1. A distributed antenna system with seven 7 ANs and 4 RTs per AN.

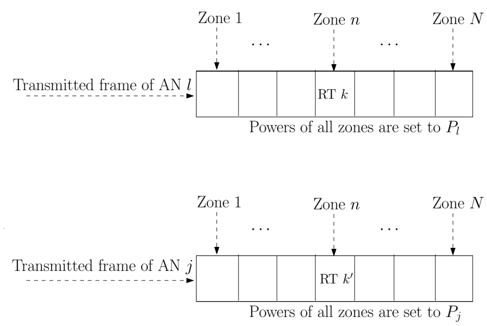

Fig. 2. One-power-zone allocation scheme.

of $L = 7$, $K = 4$ is illustrated. The transmitted frame of each AN is comprised of N zones (along the time dimension), each allocated to a different RT. Therefore, there is no interference among the RTs within the same AN, but there is inter-AN interference. Further, it is assumed that the transmission frames among the different ANs are aligned so that the signal on zone n at one particular AN interferes only with the same zone n in other ANs, and not other zones. Finally, it is assumed that the duration of entire frame is within the channel coherence time, so that the channel stays constant across the zones.

Let $k = f(l, n)$ and $k' = f(j, n)$ be the RTs assigned to zone n of the transmitted frames of the lth AN and the jth AN respectively. The signal received at the kth RT of the lth AN (which is in the nth zone of the received frame) is:

$$y_{lk} = h_{llk} x_{ln} + \sum_{j \neq l} h_{jlk} x_{jn} + z_{lk} \tag{1}$$

where $x_{ln} \in \mathbb{C}$ denotes the information signal transmitted on the nth zone of the lth AN, $h_{jlk} \in \mathbb{C}$ is the constant channel from the jth AN to the kth RT across all the zones, and z_{lk} is the additive white Gaussian noise with variance $\sigma^2/2$ on each of its real and imaginary components.

B. Problem Formulation

Let P_l^n be the power allocated to the lth AN at the nth zone. A classical weighted sum-rate maximization problem, extensively studied in the literature (see [1] and references therein), can be written as:

$$\begin{aligned} \max \quad & \sum_{l,n} \lambda_{lk} \log \left(1 + \frac{P_l^n |h_{llk}|^2}{\Gamma(\sigma^2 + \sum_{j \neq l} P_j^n |h_{jlk}|^2)} \right) \\ \text{s.t.} \quad & 0 \leq P_l^n \leq S^{max} \end{aligned} \tag{2}$$

where the summation is over the AN index l and over the zone index n. Note that a particular RT k is scheduled for each (l, n) pair. The weighted rate expression above therefore implicitly includes the scheduling function $k = f(l, n)$. In the above, λ_{lk} are the weights, Γ denotes the SNR gap, S^{max} is the maximum power constraint imposed on each AN in each zone. The maximization is over the set of powers P_l^n and the RT-to-zone scheduling function $k = f(l, n)$.

The above problem (2) is a joint scheduling and power allocation problem, so finding its optimal solution may require a combinatorial search. As mentioned earlier, existing approaches in the literature [3], [4], [5] typically involve iterative optimization between scheduling and power control, i.e., the the optimal schedule is determined assuming the powers are fixed, then the optimal power is found assuming that the schedules are fixed.

The existing iterative approach is unsatisfactory for two reasons. First, scheduling and power control typically need to be done on different time scales. Scheduling decisions are made with network considerations (e.g. the queue length of each user, the latency and delay requirements, etc), while power control needs to be done at the time scale of the channel variations. Second, the iterative approach may take many steps to converge; its complexity remains uncharacterized.

Further, the above formulation assumes that the radio-frequency (RF) transmit front-end is able to dynamically adjust transmit power *within* each frame. The RF front-end would be much simpler if the *same* power is used across the zones within each frame.

With these considerations in mind, this paper proposes an approach of maintaining the same power level across all zones, i.e., setting $P_l^n = P_l \ \forall n = 1, \cdots K$, within each frame. This is called the one-power-zone (OPZ) constraint in the paper. Fig. 2 illustrates such a power allocation scheme at two ANs. Note that different powers may still be used in different ANs or across different frames, adapting to the particular channel realizations.

The key observation here is that with the OPZ constraint, the instantaneous rate of the scheduled kth RT on the nth tone at the lth AN becomes

$$r_{lk} = \log \left(1 + \frac{P_l |h_{llk}|^2}{\Gamma(\sigma^2 + \sum_{j \neq l} P_j |h_{jlk}|^2)} \right) \tag{3}$$

and is now independent of n. Consequently, as long as the scheduling policy assigns a fixed number of zones to each RT, the objective function of (2) no longer depends on exactly which zones each user is being scheduled in.

The assumption that a fixed number of zones is assigned to each RT is easily satisfied with any round-robin scheduler.

Under this assumption, the OPZ constraint therefore decouples the power control and scheduling, and reduces the joint problem (2) into a power control problem alone. In addition, the OPZ assumption is particularly viable for RF platforms that are physically limited to having the same power level across the zones in any single frame.

By imposing the OPZ constraint, the OPZ power control problem now becomes:

$$\begin{aligned} \max \quad & \sum_{l,n} \lambda_{lk} \log \left(1 + \frac{P_l |h_{llk}|^2}{\Gamma(\sigma^2 + \sum_{j \neq l} P_j |h_{jlk}|^2)} \right) \\ \text{s.t.} \quad & 0 \leq P_l \leq S^{max} \end{aligned} \tag{4}$$

where the maximization is over the set of powers P_l. Note that this is essentially a set of parallel interference channels under a uniform power constraint. The focus of this paper is to find practical algorithms to solve the above OPZ problem.

III. OPZ Power Control Methods

The OPZ weighted sum-rate maximization problem (4) is a difficult nonconvex optimization problem for which only local optimality can be assured. The main contribution of this paper is a set of practical methods based on iterative function evaluation approach, first proposed in [1]. The derivation is based on specific manipulation of the first order condition of the optimization problem. The proposed algorithms have low computational complexity, and can be implemented in a distributed fashion across the network. Some of the proposed algorithms can be further implemented asynchronously at each AN, which make them a perfect fit for practical utilization.

A. OPZ Iterative Function Evaluation Method (OPZ-IFEM)

The objective function of problem (4) can be written as:

$$R(\{P_l\}_{l=1}^L) = \sum_{l,n} \lambda_{lk} \log \left(1 + \frac{P_l |h_{llk}|^2}{\Gamma(\sigma^2 + \sum_{j \neq l} P_j |h_{jlk}|^2)} \right) \tag{5}$$

The optimal solution of the the problem (4) must satisfy its first order optimality condition. We start by taking the gradient of R with respect to P_l:

$$\frac{\partial R}{\partial P_l} = \sum_n \lambda_{lk} \frac{\partial r_{lk}}{\partial P_l} + \sum_{j \neq l} \sum_n \lambda_{jk'} \frac{\partial r_{jk'}}{\partial P_l} \tag{6}$$

where $k' = f(j,n)$ is the scheduled RT in the nth zone of the jth AN transmitted frame. One can show that $\frac{\partial r_{lk}}{\partial P_l}$ and $\frac{\partial r_{jk'}}{\partial P_l}$ can be written as:

$$\frac{\partial r_{lk}}{\partial P_l} = \frac{1}{P_l} \left(\frac{\mathrm{SINR}_l^k}{1 + \mathrm{SINR}_l^k} \right) \tag{7}$$

$$\frac{\partial r_{jk'}}{\partial P_l} = - \frac{|h_{ljk'}|^2}{\sigma^2 + \sum_{i \neq j} P_i |h_{ijk'}|^2} \frac{\mathrm{SINR}_j^{k'}}{1 + \mathrm{SINR}_j^{k'}} \tag{8}$$

where SINR_l^k is the signal-to-interference-plus-noise-ratio:

$$\mathrm{SINR}_l^k = \frac{P_l |h_{llk}|^2}{\Gamma(\sigma^2 + \sum_{j \neq l} P_j |h_{jlk}|^2)} \tag{9}$$

The gradient expression (6) can therefore be written as:

$$\begin{aligned} \frac{\partial R}{\partial P_l} = & \sum_n \frac{\lambda_{lk}}{P_l} \left(\frac{\mathrm{SINR}_l^k}{1 + \mathrm{SINR}_l^k} \right) - \\ & \sum_{j \neq l} \sum_n \frac{\lambda_{jk'} |h_{ljk'}|^2}{\sigma^2 + \sum_{i \neq j} P_i |h_{ijk'}|^2} \frac{\mathrm{SINR}_j^{k'}}{1 + \mathrm{SINR}_j^{k'}} \end{aligned} \tag{10}$$

A local optimal solution of the problem (4) satisfies

$$\frac{\partial R}{\partial P_l} = 0, \quad \forall l = 1, \cdots, L \tag{11}$$

The key step here is that we can manipulate the above condition to derive the following power update equation:

$$P_l = \frac{\sum_n \lambda_{lk} \left(\frac{\mathrm{SINR}_l^k}{1 + \mathrm{SINR}_l^k} \right)}{\sum_{j \neq l} \sum_n \frac{\lambda_{jk'} |h_{ljk'}|^2}{\sigma^2 + \sum_{i \neq j} P_i |h_{ijk'}|^2} \frac{\mathrm{SINR}_j^{k'}}{1 + \mathrm{SINR}_j^{k'}}} \tag{12}$$

The equation (12) can be used to find the power allocation using an iterative function evaluation approach similar to [1], i.e. by computing all the terms on the right-hand-side of the equation using the current power allocation, and updating the new power allocation using equation (12). This method is called OPZ Iterative Function Evaluation Method (OPZ-IFEM).

To summarize, in OPZ-IFEM, the power level of every AN, P_l, is updated from step t to $t+1$ using the following update equation:

$$\begin{aligned} & P_l(t+1) = \\ & \left[\frac{\sum_n \lambda_{lk} \left(\frac{\mathrm{SINR}_l^k(t)}{1 + \mathrm{SINR}_l^k(t)} \right)}{\sum_{j \neq l} \sum_n \frac{\lambda_{jk'} |h_{ljk'}|^2}{\sigma^2 + \sum_{i \neq j} P_i(t) |h_{ijk'}|^2} \frac{\mathrm{SINR}_j^{k'}(t)}{1 + \mathrm{SINR}_j^{k'}(t)}} \right]_0^{S^{max}} \end{aligned} \tag{13}$$

where the maximum power constraint is also taken into account.

OPZ-IFEM update equation (13) has a particularly elegant interpretation. The denominator of the right hand side is a function of the interference price terms τ_{jl}, where

$$\tau_{jl} = \sum_n \frac{\lambda_{jk'} |h_{ljk'}|^2}{\sigma^2 + \sum_{i \neq j} P_i |h_{ijk'}|^2} \frac{\mathrm{SINR}_j^{k'}}{1 + \mathrm{SINR}_j^{k'}} \tag{14}$$

is directly related to the gain $|h_{ljk'}|^2$ and indicates the interference impact of lth AN on the RT's of the jth AN.

B. OPZ-HSIFEM

Simulations results of OPZ-IFEM show a fast convergence speed behavior. Furthermore, on the theoretical front, we can easily see that if OPZ-IFEM converges, it always converges to a local optimum solution of the original problem (4), as it satisfies the first order optimality condition (11). But the proof of convergence is hard to establish in full generality. However, using similar simplifications as in [1], we can derive new efficient algorithms whose convergence proofs can be established mathematically. For example, we can make a high-SINR approximation of the problem, the resulting update equation (13) becomes:

$$P_l(t+1) = \left[\frac{\sum_n \lambda_{lk}}{\sum_{j\neq l}\sum_n \frac{\lambda_{jk'}|h_{ljk'}|^2}{\sigma^2+\sum_{i\neq j}P_i(t)|h_{ijk'}|^2}}\right]_0^{S^{max}} \quad (15)$$

The resulting method is called OPZ-high-SINR-IFEM (OPZ-HSIFEM). OPZ-HSIFEM algorithm is guaranteed to converge to a unique fixed point as shown later in the paper.

C. OPZ-θ-IFEM

Despite its guaranteed convergence, OPZ-HSIFEM remains a suboptimal algorithm whose performance is quite sensitive to the level of SINR operation. To establish a method that guarantees a better performance than OPZ-HSIFEM, with a guaranteed convergence proof, we propose another efficient method similar to [1] that replaces the per-iteration SINR's in the update equation (13) with the values of SINR's calculated under the initial maximum power transmission strategy. This method, called OPZ-θ-IFEM, finds the power level P_l according to the following update equation:

$$P_l(t+1) = \left[\frac{\sum_n \lambda_{lk}\theta_l^k}{\sum_{j\neq l}\sum_n \frac{\lambda_{jk'}|h_{ljk'}|^2}{\sigma^2+\sum_{i\neq j}P_i(t)|h_{ijk'}|^2}\theta_j^{k'}}\right]_0^{S^{max}} \quad (16)$$

where

$$\theta_l^k = \frac{\widetilde{\mathrm{SINR}}_l^k}{1+\widetilde{\mathrm{SINR}}_l^k} \quad (17)$$

and where $\widetilde{\mathrm{SINR}}_l^k$ is the fixed SINR calculated from the maximum power transmission strategy, i.e.

$$\widetilde{\mathrm{SINR}}_l^k = \frac{S^{max}|h_{llk}|^2}{\Gamma(\sigma^2+\sum_{j\neq l}S^{max}|h_{jlk}|^2)} \quad (18)$$

D. Convergence Analysis

Both OPZ-HSIFEM and OPZ-θ-IFEM do possess convergence proofs as highlighted in the next proposition.

Proposition 1. *Starting from any initial $P_l(0)$, OPZ-HSIFEM and OPZ-θ-IFEM algorithms respectively converge to unique fixed points. Furthermore, the convergence is still guaranteed under a totally asynchronous model.*

Proof: Note first that OPZ-HSIFEM can be simply derived from OPZ-θ-IFEM by setting θ_l^k to 1 for all k and l. The focus here is on the convergence proof of OPZ-θ-IFEM. The proof hinges on the standard function properties, first introduced in [6].

Consider OPZ-θ-IFEM update equation (16). It can be rewritten as $P_l(t+1) = \left[g_l\big(\boldsymbol{\Psi}(t)\big)\right]_0^{S^{max}}$, where the variables $P_l, \forall \quad l = 1, \cdots, L$, are stacked into one vector $\boldsymbol{\Psi}$, and where the function $g_l(.)$ is defined as:

$$g_l\big(\boldsymbol{\Psi}\big) = \frac{\sum_n \lambda_{lk}\theta_l^k}{\sum_{j\neq l}\sum_n \frac{\lambda_{jk'}|h_{ljk'}|^2}{\sigma^2+\sum_{i\neq j}P_i(t)|h_{ijk'}|^2}\theta_j^{k'}} \quad (19)$$

We have:

1) If $P_l \geq 0 \;\forall l$, then $g_l\big(\boldsymbol{\Psi}\big) > 0$.
2) If $P_l \geq P'_l \;\forall l$, then

$$\frac{|h_{ljk'}|^2\theta_j^{k'}}{\sigma^2+\sum_{i\neq j}P_i|h_{ijk'}|^2} \leq \frac{|h_{ljk'}|^2\theta_j^{k'}}{\sigma^2+\sum_{i\neq j}P'_i|h_{ijk'}|^2}$$

Thus,

$$\frac{\sum_n \lambda_{lk}\theta_l^k}{\sum_{j\neq l}\sum_n \frac{\lambda_{jk'}|h_{ljk'}|^2}{\sigma^2+\sum_{i\neq j}P_i(t)|h_{ijk'}|^2}\theta_j^{k'}} \geq \frac{\sum_n \lambda_{lk}\theta_l^k}{\sum_{j\neq l}\sum_n \frac{\lambda_{jk'}|h_{ljk'}|^2}{\sigma^2+\sum_{i\neq j}P'_i(t)|h_{ijk'}|^2}\theta_j^{k'}}$$

Therefore, $g_l\big(\boldsymbol{\Psi}\big) \geq g_l\big(\boldsymbol{\Psi'}\big)$.

3) For $\rho > 1$, we have:

$$\begin{aligned}\rho g_l\big(\boldsymbol{\Psi}\big) &= \frac{\sum_n \lambda_{lk}\theta_l^k}{\sum_{j\neq l}\sum_n \frac{\lambda_{jk'}|h_{ljk'}|^2\theta_j^{k'}}{\rho\left(\sigma^2+\sum_{i\neq j}P_i(t)|h_{ijk'}|^2\right)}} \\ &> \frac{\sum_n \lambda_{lk}\theta_l^k}{\sum_{j\neq l}\sum_n \frac{\lambda_{jk'}|h_{ljk'}|^2\theta_j^{k'}}{\sigma^2+\sum_{i\neq j}\rho P_i(t)|h_{ijk'}|^2}} \\ &= g_l\big(\rho\boldsymbol{\Psi}\big)\end{aligned}$$

Thus, $g_l(.)$ satisfies the standard function properties, and so does the power constrained function $[g_l(.)]_0^{S^{max}}$; see Theorem 7 in [6]. Based on Corollary 1 in [6], starting from any initial $P_l(0)$, OPZ-θ-IFEM is guaranteed to converge to a unique fixed point.

Furthermore, OPZ-θ-IFEM can be implemented under the total asynchronous model using the following update equation:

$$P_l(t+1) = \left[\frac{\sum_n \lambda_{lk}\theta_l^k}{\sum_{j\neq l}\sum_n \frac{\lambda_{jk'}|h_{ljk'}|^2}{\sigma^2+\sum_{i\neq j}P_i(\varpi_i^j(t))|h_{ijk'}|^2}\theta_j^{k'}}\right]_0^{S^{max}} \quad (20)$$

where the index ϖ_i^j may point to possibly outdated information. Based on Theorem 4 of [6], the asynchronous update equation (20) is guaranteed to converge to the same unique fixed point of OPZ-θ-IFEM.

Similar results can be derived to OPZ-HSIFEM. ■

E. Distributed Implementation:

At each iteration $t+1$, updating the power level P_l of the lth AN, through either OPZ-IFEM, OPZ-HSIFEM, or OPZ-θ-IFEM, requires the knowledge of the interference price terms $\tau_{jl}(t)$, the power level $P_l(t)$, and the SINR terms $\mathrm{SINR}_l^k(t)$. The power level $P_l(t)$, and the SINR terms $\mathrm{SINR}_l^k(t)$ are typically locally known at each AN. In order to implement either method in a distributed manner, it suffices that ANs exchange the interference prices τ_{jl}, defined in (14), which makes distributed implementation feasible.

Cellular Layout	Hexagonal
Number of ANs	7
Frequency Reuse	1
Number of RTs per AN	4
Number of Zones per Frame	4
Scheduling	Round-robin
Weights λ_{lk}	1
AN-to-AN Distance	d_1
AN-to-RT Distance	d_2
Duplex	TDD
Channel Bandwidth	10 MHz
AN Max Tx Power per Subcarrier	-32.70 dBw
SINR Gap	12 dB
Total Noise Power Per Subcarrier	-158.61 dBw
Distance-dependent Path Loss	$128.1 + 37.6 \log_{10}(d)$
Sampling Frequency	11.2 MHz

TABLE I
SYSTEM MODEL PARAMETERS

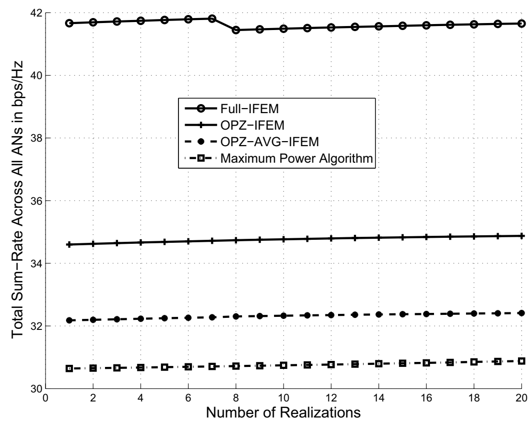

Fig. 3. Sum-rate in bps/Hz over 7 ANs, 4 RTs per AN. AN-to-AN distance is 0.5km. AN-to-RT distance is 333m.

Sum Rate (bps/Hz)	Small-cell ($d_1 = 0.5$km)	Large-cell ($d_1 = 1$km)
Full-IFEM	61.46	93.07
OPZ-IFEM	58.06	88.85
OPZ-AVG-IFEM	56.18	87.80
Max Power	53.0	86.30
OPZ-IFEM Gain	9.6%	3.0%
Full-IFEM Gain	16.0%	7.8%

TABLE II
7 ANs, 4 RTs PER AN. d_1 IS THE AN-TO-AN DISTANCE. AN-TO-RT DISTANCE d_2 IS 150M.

F. Comparison with Full-IFEM ([1])

The methods proposed in this paper are related to the methods proposed in [1]; however, the problem considered in [1] does not take the OPZ constraints into consideration. A direct application of the methods in [1] to the setup of this paper only gives a solution to formulation (2), rather than formulation (4). Nevertheless, one can use the solutions found in [1] to derive a suboptimal solution to the OPZ problem (4). First, relax the problem so as to allocate the power on a per-zone basis, i.e. find the power P_l^n at every zone n of the transmitted frame of the lth AN based on the full-IFEM method proposed in [1]:

$$P_l^n(t+1) = \left[\frac{\lambda_{lk} \frac{\mathrm{SINR}_l^k(t)}{1+\mathrm{SINR}_l^k(t)}}{\sum_{j \neq l} \lambda_{jk'} \frac{|h_{ljk'}|^2}{\sigma^2 + \sum_{i \neq j} P_i^n(t) |h_{ijk'}|^2} \frac{\mathrm{SINR}_j^{k'}(t)}{1+\mathrm{SINR}_j^{k'}(t)}} \right]_0^{S^{max}} \quad (21)$$

where $k = f(l, n)$ and $k' = f(j, n)$. To adapt it to the constrained problem (4), we then choose to set the common value of the power across each frame to the average value of the powers $\{P_l^n\}_{n=1}^N$; i.e. $P_l = \frac{\sum_{n=1}^N P_l^n}{N}$. We call this algorithm OPZ-AVG-IFEM. As expected, the performance of OPZ-AVG-IFEM is inferior to OPZ-IFEM; however, OPZ-AVG-IFEM always outperforms conventional systems with maximum power transmission, as the simulations suggest. Note that similar simplifications used in deriving OPZ-HSIFEM and OPZ-θ-IFEM in this paper are used in [1] to derive HSIFEM and θ-IFEM, respectively.

IV. Simulations

To evaluate the performance of the methods proposed in this paper, we simulate a wireless backhaul network formed by seven ANs, each serving four RTs, as shown in Fig. 1. The transmitted frame of each AN is composed of four zones, where only one RT is active in each zone. For illustration, RT-to-zone mapping is done using round-robin scheduling. For the sole goal of comparing the sum-rate between different methods, the weights λ_{lk} are set to 1 in the rest of the paper. Distance between adjacent ANs is set to d_1; distance between one AN and each of its RTs is set to d_2. Various simulations parameters are highlighted in Table I.

In Fig. 3, we plot the sum-rate across across all ANs for different realizations of the channel, so as to compare the performance of the proposed methods. Fig. 3 shows the performance improvement of the OPZ-IFEM as compared to maximum power transmission strategy for all channel realizations. The figure also shows the loss in the sum-rate due to imposing the OPZ constraints on the problem (2). We can see that full-IFEM which relaxes the OPZ constraints outperforms OPZ-IFEM which solves the constrained optimization problem (4). OPZ-IFEM, however, outperforms the suboptimal solution OPZ-AVG-IFEM, which in turn shows a better performance than maximum power transmission strategy.

To analyze the simulation results under different topologies, we vary the values of of d_1 and d_2 as shown in Tables II, III, and IV. Table II compares the methods performance between small and large cells. As expected, the proposed methods have a better performance gain in small cells, since interference mitigation technique is particularly effective in high interference regime. Likewise, the performance gain is higher for cell edge RTs, as shown in III and IV, where the interference is typically high. Tables II, III, and IV also show how full-IFEM performance gain is more pronounced than OPZ-IFEM gain. This is due to the fact that OPZ-IFEM solves

Sum Rate (bps/Hz)	Cell-edge ($d_2 = 333$m)	Cell-center ($d_2 = 125$m)
Full-IFEM	41.60	78.22
OPZ-IFEM	34.84	75.53
OPZ-AVG-IFEM	32.38	74.95
Max Power	30.82	71.85
OPZ-IFEM Gain	13.0%	5.1%
Full-IFEM Gain	35.0%	8.9%

TABLE III
7 ANs, 4 RTs PER AN. AN-TO-AN DISTANCE IS 0.5KM.

Sum Rate (bps/Hz)	Cell-edge ($d_2 = 667$m)	Cell-center ($d_2 = 250$m)
Full-IFEM	45.31	84.48
OPZ-IFEM	43.77	82.63
OPZ-AVG-IFEM	43.02	82.21
Max Power	41.45	80.24
OPZ-IFEM Gain	5.6%	3.0%
Full-IFEM Gain	9.3%	5.3%

TABLE IV
7 ANs, 4 RTs PER AN. AN-TO-AN DISTANCE IS $d_1 = 1$KM.

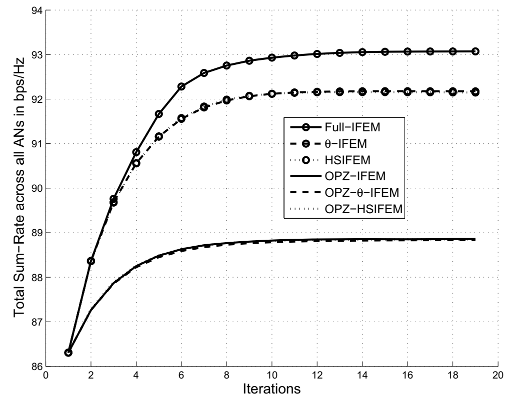

Fig. 4. Sum-rate in bps/Hz versus the number of iterations, over 7 ANs, 4 RTs per AN. AN-to-AN distance is 1km. AN-to-RT distance is 150m. It shows the convergence of the different methods at high SINR.

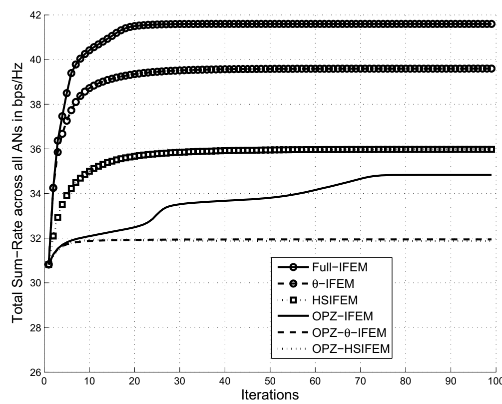

Fig. 5. Sum-rate in bps/Hz versus the number of iterations, over 7 ANs, 4 RTs per AN. AN-to-AN distance is 0.5km. AN-to-RT distance is 333m. It shows the convergence of the different methods at low SINR.

the constrained optimization problem (4), which places tighter bounds on the search space of the optimal values.

Finally, to compare the convergence behavior of the proposed methods, we plot the sum-rate across across all ANs versus the number of iterations as shown in Fig. 4 and 5. Fig. 4 considers a high SINR case where the performance of OPZ-θ-IFEM and OPZ-HSIFEM are similar to the performance of OPZ-IFEM. All three OPZ algorithms show fast convergence. However, in the low SINR case illustrated in Fig. 5, the simplifications used in deriving OPZ-θ-IFEM and OPZ-HSIFEM bring in a larger penalty. Interestingly, both OPZ-θ-IFEM and OPZ-HSIFEM show fast convergence behavior (although to a lower sum rate), while the convergence curve of OPZ-IFEM takes up a series of steps before landing in and converging to its local optimal solution, eventually outperforming both OPZ-θ-IFEM and OPZ-HSIFEM.

V. CONCLUSION

The performance improvement of futuristic wireless networks widely depends on the feasibility of the interference mitigation techniques, specifically developed to achieve higher data capacity and increase system reliability. This paper considers a practical power control problem for systems with one-power-zone constraints assumption. The assumption is attractive as it removes the coupling between the power control and the scheduling problems in the context of interference management, and permits to find efficient power control methods that are independent of the scheduling policy. The proposed algorithms have low computational complexity, can be implemented in a distributed fashion across all AN's; some of them can also be implemented asynchronously. Simulation results show that the proposed methods provide a significant performance improvement as compared to conventional systems with maximum power transmission.

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