COORDINATED SCHEDULING FOR WIRELESS BACKHAUL NETWORKS WITH SOFT FREQUENCY REUSE

Hayssam Dahrouj[†], *Wei Yu*[†], *Taiwen Tang*[‡], *Jerry Chow*[‡], *and Radu Selea*[‡]

[†]Electrical and Computer Engineering Dept., University of Toronto, Canada
[‡]BlinQ Networks Inc., Kanata, Ontario, Canada
Emails: {hayssam,weiyu}@comm.utoronto.ca, {eric.tang,jerry.chow,radu.selea}@blinqnetworks.com

ABSTRACT

Coordinated resource allocation is a topic of significant interest for emerging wireless networks. This paper proposes and examines the benefits of coordinated scheduling in soft frequency reuse (SFR) based systems. Consider the downlink of a 3-sector-per-cell SFR-based wireless backhaul network consisting of N access nodes (ANs), each serving K remote terminals (RTs) multiplexed across the K time/frequency zones, with frequency reuse one between the sectors. Assuming a fixed transmit power, the paper considers the resource allocation problem of optimally scheduling each of the NK RTs to one of the NK power-zones, on a one-to-one basis, and in a coordinated manner, as opposed to conventional systems which schedule the RTs one at a time in an uncoordinated way. The paper solves the problem using the auction method, which offers a close-to-global-optimal solution. The paper further proposes heuristic methods with lower computational complexity. Simulation results show that coordinated scheduling offers significant performance improvement as compared to non-coordinated systems.

1. INTRODUCTION

Coordinated resource allocation is expected to play a major role in improving the performance of densely deployed interference-limited networks. This paper examines the idea of coordinated scheduling for wireless networks employing soft frequency reuse (SFR), an enhanced frequency-reuse technique proposed for LTE-based systems [1–3]. SFR provides both the flexibility of utilizing the available bandwidth, and the capability to reduce high inter-site interference levels associated with dense networks with aggressive frequency reuse. This paper focuses on one specific aspect of the design of SFR-based systems. It proposes practical schemes for coordinated scheduling in SFR systems, and examines its benefits when compared to conventional systems which incrementally schedule users one at a time in an uncoordinated manner.

The authors acknowledge Natural Science and Engineering Research Council (NSERC-CRD) and BLiNQ Networks Inc. for funding this work.

The model considered in this paper consists of the downlink of a 3-sector-per-cell wireless backhaul network with frequency reuse one between the sectors. The backhaul network, especially introduced to serve areas with dense data traffic, consists of N access nodes (ANs), each serving K remote terminals (RTs) multiplexed across the K time/frequency zones called power-zones. The paper assumes an equal number of RTs and power-zones, where each of the NK power-zones is utilized by one and only one RT. Under fixed power transmission, the problem of interest, known as power-zone-assignment, becomes that of optimally scheduling each of the NK RTs at one of the NK power-zones on a one-to-one basis. The paper considers this scheduling problem with an objective of maximizing a generic network-wide utility, thus the requirement that the ANs coordinate their respective scheduling decisions.

Scheduling is a well studied problem in the past literature on wireless systems. A classical solution to solve the problem is the proportional fairness scheduling [4, 5]. Such a solution, however, is based on a pre-assigned association of users to base-stations, and is performed on a per base-station (BS) basis with no inter-BS coordination. One contribution of the current paper is that it solves a joint scheduling and RT-to-AN-association problem on a network level. This contribution is further related to the base-station association problem studied in [6–8]. The aforementioned references, however, do not assume a priori model of power allocation, as SFR does. Further, unlike the classical cellular systems, the wireless backhaul network studied in this paper considers a relatively smaller number of RTs to be assigned to each AN, which allows the derivation of additional practical and feasible methods for optimization.

This paper considers the power-zone-assignment problem in the context of generic utility maximization, and proposes methods to assign each of the NK RTs to one of the NT power-zones in a coordinated manner. One of the proposed methods in this paper is based on the auction approach, a classical strategy first proposed in [9] to solve the one-to-one assignment problem. The auction method offers a close-to-global-optimal solution to the problem, and can be

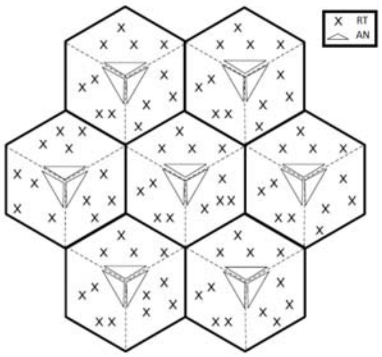

Fig. 1. Wireless backhaul network comprising 21 ANs, 1 AN per sector, and 84 RTs in total.

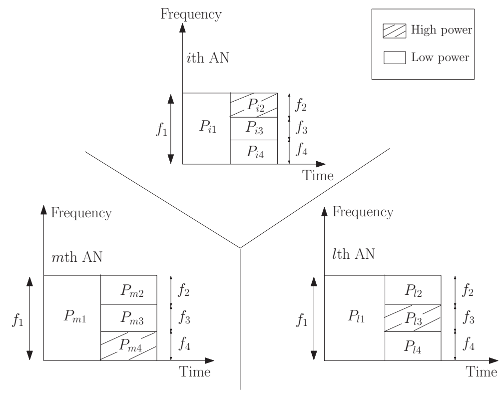

Fig. 2. Frame structure and power configuration of three ANs i, l, and m.

implemented in a distributed fashion across the backhaul network. The paper further proposes additional practical methods which first assign RTs to ANs heuristically based on signal-to-interference-plus-noise ratios (SINRs), then optimally assign RTs within each AN. These proposed methods are practically feasible for their low computational complexity, and are especially applicable to the downlink of the wireless backhaul system. Simulation results show that coordinated scheduling offers significant performance improvement as compared to non-coordinated systems.

2. SYSTEM MODEL AND PROBLEM FORMULATION

2.1. System Model

Consider the downlink of a 3-sector-per-cell SFR-based wireless backhaul network, with N access-nodes (ANs), serving KN remote terminals (RTs) in total, where K is the number of time/frequency resource blocks of each transmit frame. The jth resource block of the ith AN, called power-zone, is used by one RT only, and operates at a pre-assigned power P_{ij} using SFR-like strategy. The distinct KN RTs are separated from each other using different RT-to-power-zone scheduling on a network level. The transmission of the different frames are assumed to be perfectly synchronized across all ANs. Let $h_{ik}^{j} \in \mathbb{C}$ be the channel from the ith AN to the kth RT, where RT $k \in \{1, \cdots, NK\}$ is assigned to power-zone j of the ith AN transmit frame. The SINR of the kth RT assigned to power-zone j of the ith AN transit frame can be written as:

$$\mathrm{SINR}_{ik}^{j} = \frac{P_{ij}|h_{ik}^{j}|^2}{\Gamma(\sigma^2 + \sum_{l \neq i} P_{lj}|h_{lk}^{j}|^2)} \quad (1)$$

where σ^2 is the Gaussian noise variance, and Γ denotes the SINR gap.

2.2. Problem Formulation

This paper considers the power-zone-assignment problem, i.e., the determination of the optimal schedule $k = f(i,j) \in \{1, \cdots, NK\}$, where (i,j) represents the jth power-zone of the ith AN, $\forall i = 1, \cdots, N$ and $j = 1, \cdots, K$.

Let a_{ik}^{j} be the benefit of assigning RT k to power-zone (i,j). This paper considers the following network-wide optimization problem:

$$\max \quad \sum_{i,j} a_{ik}^{j} \quad (2)$$

where the optimization is over all mappings $k = f(i,j)$, based on a one-to-one assignment criterion across the whole network, thus the term coordinated scheduling.

One problem of interest in this paper is to maximize a total sum-rate across the network. In this case, $a_{ik}^{j} = W_{i,j}\log_2(1 + \mathrm{SINR}_{ik}^{j})$, where SINR_{ik}^{j} is defined in (1), and $W_{i,j}$ is the bandwidth allocation of power-zone (i,j).

2.3. Motivating SFR-Example

Consider the wireless backhaul network shown in Fig. 1. It consists of 84 RTs in total, and 21 ANs each covering one sector. The total system bandwidth of the system is f_1, divided into three orthogonal subbands f_2, f_3, and f_4. The transmit frame structure of every AN is formed by two time zones, and is capable of serving 4 distinct RTs, as shown in Fig. 2. The first time zone contains the data associated with one RT, and utilizes the entire bandwidth. The second time zone contains data for other three distinct RTs, which are separated from each other in frequency, using RT-to-power-zone scheduling. Such a structure, called Soft Fractional-Frequency-Reuse (SFFR) in [1, 3], adopts a non-uniform power profile among the different power-zones. It provides the flexibility in bandwidth and power utilization for different RTs, which helps improve the overall system throughput.

2.3.1. Power Configuration and SFR-Baseline

The power configuration considered in this paper follows an SFR-based structure similar to the one illustrated in [1–3]. For each sector $s \in \{1, 2, 3\}$ of cell $c \in \{1, \cdots, 7\}$, the AN (indexed as i in the rest of the paper) allocates a high power profile for one (and only one) of the power zones P_{i2}, P_{i3}, or P_{i4}. The other remaining power zones are set to a lower power level. For the other two ANs belonging to the same cell c, assign a high power profile to one of the power zones that has been assigned a low power profile in the other two ANs frames. For all ANs, P_{i1} is always set to a low power level. Typically, cell-edge RTs are assigned either the power zone with high power level or with full bandwidth, in order to increase their rates. This power configuration is illustrated in Fig. 2.

An SFR-baseline system first associates each RT with a specific AN, based on geographical location (i.e., use distance to assign 4 RTs per AN). Each AN i then maps its RTs to its power-zones using the available local channel information as follows (without using SINR values):

- First, sort the channel gains of the 4 RTs to their serving AN i in ascending order.
- The RT with the lowest gain is then assigned to the power-zone with the highest power.
- The RT with the second lowest gain is assigned to P_{i1}.
- The two remaining RTs are assigned to the two remaining power-zones arbitrarily.

While the above scheme is a simple strategy which is based on local channel information within each cluster, its solution does not account for the inter-AN interference, or the overall network utility. Consequently, its performance is not optimal, as the simulations show.

This paper considers a coordinated power-zone-assignment approach to solve (2), and compares it to the baseline uncoordinated approach. It shows that the performance of the SFR network can be significantly improved if joint assignment is enabled across the different ANs.

3. COORDINATED POWER-ZONE-ASSIGNMENT

The power-zone-assignment defined in (2) is a discrete optimization problem. A brute force approach to solve (2) would involve searching over all possible RT-to-power-zone assignments, i.e. $(NK)!$ permutations. Clearly, such an exhaustive search is infeasible for any reasonably sized network. This paper provides practical methods to solve this power-zone-assignment.

3.1. Auction-Based Power-Zone-Assignment (AB-PZA)

Let $\mathcal{A}$ be the set of ANs defined by $\mathcal{A} = \{1, \cdots, N\}$, and $\mathcal{P}$ be the set of power-zones of each AN defined by $\mathcal{P} = \{1, \cdots, K\}$. The one-to-one power-zone-assignment problem described in (2) can be rewritten as follows:

$$\begin{aligned} \max \quad & \sum_{i,j,k} a_{ik}^{j} x_{ik}^{j} \\ \text{s.t.} \quad & \sum_{k} x_{ik}^{j} = 1, \quad (i,j) \in \mathcal{A} \times \mathcal{P} \\ & \sum_{(i,j) \in \mathcal{A} \times \mathcal{P}} x_{ik}^{j} = 1, \quad x_{ik}^{j} \in \{0,1\} \end{aligned} \tag{3}$$

where the optimization is over the binary variable x_{ik}^{j}, and where x_{ik}^{j} is 1 if RT k is mapped to power-zone (i,j), and zero otherwise. The formulation (3) can be solved using the classical auction algorithm, first introduced in [9].

The auction algorithm is based on the optimal setting of the price, denoted by λ_i^j, that has to be paid for an RT to be assigned to the jth power-zone of the ith AN (denoted here as power-zone (i,j)). The net benefit from assigning RT k to power-zone (i,j) is $a_{ik}^{j} - \lambda_i^j$, and each RT i strives to be assigned to power-zone (i_k, j_k) that maximizes its own net benefit, i.e.: $\pi_k = a_{i_k k}^{j_k} - \lambda_{i_k}^{j_k} = \max_{(i,j)}\{a_{ik}^{j} - \lambda_i^j\}$, where π_k is defined as the profit margin for RT k. The auction process subsequently proceeds iteratively in power-zone-assignments (assignment phase) and price updates (bidding phase) across the network. This method, denoted as auction-based power-zone-assignment (AB-PZA) in this paper, can be summarized as follows:

- Initialize a positive scalar $\epsilon > 0$, introduced to guarantee the algorithm convergence.
- Start with an empty set of power-zone-assignment mappings, and a set of prices λ_i^j satisfying the following condition: $\max_{(l,m)}\{a_{lk}^{m} - \lambda_l^m\} - \epsilon \le a_{ik}^{j} - \lambda_i^j$, (also known as ϵ-complementary slackness; see [9] for more details).

1. Bidding phase:
   (a) For each unassigned RT k, find the power-zone (i_k, j_k) that maximizes the profit of RT k, i.e.: $(i_k, j_k) = \arg\max_{(i,j)}\{a_{ik}^{j} - \lambda_i^j\}$.
   (b) Compute b_k, defined as the best value offered by power-zones other than (i_k, j_k), i.e., $b_k = \max_{(i,j)\neq(i_k,j_k)}\{a_{ik}^{j} - \lambda_i^j\}$.
   (c) Compute $\beta_{i_k k}^{j_k}$, defined as the bid of RT k for power-zone (i_k, j_k): $\beta_{i_k k}^{j_k} = a_{i_k k}^{j_k} - b_k + \epsilon$.
   (d) Go to step 1(a); repeat for all unassigned RTs.
2. Assignment phase:

(a) For each power-zone (i, j), find the RT k_i^j that offers the highest bid to (i, j), as found in step 1 above, i.e. $k_i^j = \arg\max_k \beta_{ik}^j$.

(b) Assign power-zone (i, j) to RT k_i^j, and set (i, j)'s price to be the bid of its highest bidder, i.e., $\lambda_i^j = \beta_{ik_i^j}^j$.

(c) Go to step 2(a); and repeat for all (i, j).

3. Set $\epsilon = \alpha\epsilon$ for some $0 < \alpha < 1$; go to step 1(a); and stop when $\epsilon < \frac{1}{NK}$.

Note that AB-PZA can be seen as a joint AN-association and per-AN power-zone-assignment. It innately inherits the advantages of the classical auction method introduced in [9]. It can be implemented in a distributed fashion across all ANs and asynchronously at each AN, while offering an ϵ-optimum solution. Simulation results show that it offers significant performance improvement over non-coordinated systems.

3.2. Utility-Clustering PZA (UC-PZA)

As in ϵ-scaling methods (see [9] and the references therein), the complexity of AB-PZA is $O((NK)^3 \log(NKR))$, where $R = \max_{i,j,k} |a_{ik}^j|$. This section presents an alternative low complexity heuristic method, which shows good performance as the simulations suggest. The method, known as Utility-Clustering PZA (UC-PZA), assigns each of the RTs to one of the power-zones based on the individual utilities a_{ik}^j using the following strategy. Let A be the $NK \times NK$ matrix whose entries are the potential individual benefits, i.e., define the entries of the $NK \times NK$ matrix A as follows: $A_{k,(i-1)K+j} = a_{ik}^j$.

At each step, find the largest entry of the matrix A, call it $A_{k_x^{max},k_y^{max}}$. RT k_x^{max} then maps to power-zone $(i_{k_x^{max}}, j_{k_x^{max}})$, where:

$$\begin{aligned} i_{k_x^{max}} &= \left\lfloor \frac{k_y^{max} - 1}{K} \right\rfloor + 1, \\ j_{k_x^{max}} &= \left(\left(k_y^{max} - 1\right) \mod K \right) + 1, \end{aligned}$$

where $\lfloor . \rfloor$ and $\mod (.,.)$ represent the floor and modulo operators, respectively. Next, delete the $A_{k_x^{max}}$th row and the $A_{k_y^{max}}$th column of the matrix A, so that $A_{k_x^{max}}$ and power-zone $A_{k_y^{max}}$ are not involved in subsequent steps. Repeat this procedure until all the KN RTs are divided into disjoint clusters of equal cardinality K.

For example, if the problem of interest is to maximize the network throughput, i.e. choose $a_{ik}^j = R_{ik}^j = W_{i,j} \log_2(1 + \mathrm{SINR}_{ik}^j)$, the method above becomes a *rate-clustering* method. Such method offers a significant performance improvement over non-coordinated systems, even with no subsequent per-AN exhaustive search, as the simulations results in the next section show.

The heuristics above can be used with other clustering criteria, e.g. with geographical clustering to associate one RT k with the closest AN i. In this case, there can potentially be additional improvement by performing exhaustive search within each AN i to maximize $\sum_{jk} a_{ik}^j$. This additional per-AN exhaustive search is based on the observation that in the downlink, given pre-existing RT-to-AN association, the interference produced by AN l to the RT k served by AN i is independent of the power-zone-assignment strategy used by AN l. Thus, power-zone-assignment can be done independently on a per-AN basis without affecting the interference elsewhere in the network. Further, the number of RTs served by each AN in a wireless backhaul network is typically in the order of 4 to 6 RTs. This makes the per-AN exhaustive search over the $K!$ permutations practically feasible. The additional per-AN exhaustive search can bring in significant additional gain, if the clustering is not already based on the rate terms (i.e., rate-clustering).

3.3. Uncoordinated Power-Zone-Assignment

The method above requires a central processor which has access to all entries of the matrix A, and has the ability to assign RTs in a coordinated way. In conventional systems, however, networks are formed incrementally, i.e., one RT at a time. Whenever a RT k enters the network, it only has information about its own individual utilities $a_{ik}^j\ \forall i, j$. An uncoordinated strategy to assign RTs to power-zone can then be summarized as follows:

1. Whenever a RT k enters the network, consider row $A(k, :)$ solely, and choose the index k_y^{max} that corresponds to the maximum entry $A_{k,k_y^{max}}$.

2. Power-zone k_y^{max} is reserved to RT k and announced unavailable to all new comers (i.e., new RTs).

3. Repeat the process for all new comers k' ($k' \neq k$).

Because of the uncoordinated nature of the incremental deployment, the additional per-AN exhaustive search step here brings in significant additional gain.

4. SIMULATIONS

This section evaluates the performance of the proposed methods. It considers the 7-cell wireless backhaul network shown in Fig. 1, comprised of 21 ANs and 84 RTs, and 4 powers-zones per-AN frame as shown in Fig. 2. Cell-center-to-cell-center distance is set to 800 meters. Power allocation is fixed, and configured according to the SFR model described in Section 2. The simulations parameters are summarized in Table 1. To illustrate the performance of the proposed methods, this section considers the sum-rate maximization problem.

To show the gain of the coordinated scheduling methods proposed in this paper, Fig. 3 shows the percentage gain in

Cellular Layout	Hexagonal
Number of ANs	21
Number of RTs	84
Number of Zones per Frame	4
Cell-Center-to-Cell-Center Distance	800 meters
SINR Gap	12 dB
Path Loss Model	SUI-3 Terrain type B
AN Height	20 meters
RT Height	10 meters
Channel Estimation	Perfect
Power Configuration	SFR-Like
High Power	-42.60 dBm/Hz
Low Power	-44.15 dBm/Hz
Background Noise Power	-168.50 dBm/Hz
Bandwidth	10 MHz

Table 1. System model parameters

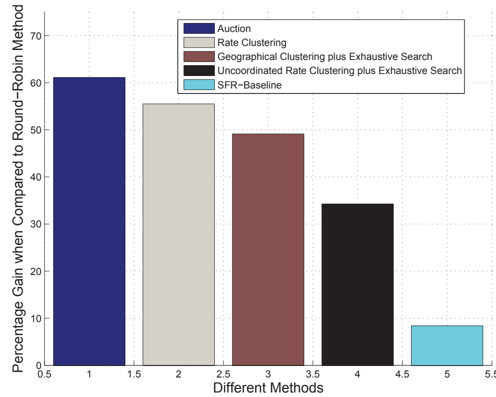

Fig. 3. It illustrates the significant gain in sum-rate of coordinated systems as compared to non-coordinated systems.

sum-rate for the proposed methods as compared to the simple round-robin assignment. As shown in the figure, auction algorithm which offers a close-to-global-optimal solution provides the best performance among the proposed methods. The other simple heuristic rate-clustering method already shows a performance gain of within 6% of auction method. Most importantly, Fig. 3 especially shows the significant performance gain that coordinated power-zone-assignment methods, i.e. auction, rate-clustering, and geographical-clustering-plus-exhaustive-search methods, offer when compared to the uncoordinated-rate-clustering-plus-exhaustive-search method. Auction method, in particular, offers up to 30% sum-rate improvement over uncoordinated systems.

Furthermore, Fig. 3 shows how all the proposed methods have a superior performance to the simple SFR-baseline method. Such method does not account for the possible SINR values of different assignments. Instead, it simply assigns RTs to power-zones based on local channel information.

5. CONCLUSIONS

Coordinated resource allocation is a topic of significant interest for emerging wireless networks. This paper considers and proposes methods to solve one type of coordinated scheduling problems, known as power-zone assignment. One of the proposed methods is based on the auction approach and offers a close-to-global-optimal solution. Other methods are based on low computational complexity heuristics. Simulations show that coordinated scheduling offers a significant performance improvement as compared to non-coordinated systems.

6. REFERENCES

[1] *4G++: Advanced Performance Boosting Techniques in 4th Generation Wireless Systems*, A National Telecommunication Regulatory Authority Funded Project, 2010.

[2] F. Khan, *LTE for 4G Mobile Broadband: Air Interface Technologies and Performance*, Cambridge University Press, 2009.

[3] IEEE 802.16 Broadband, *Fractional Frequency Reuse in Uplink*, LG Electronics, 2008.

[4] A. L. Stolyar and H. Viswanathan, "Self-organizing dynamic fractional frequency reuse for best-effort traffic through distributed inter-cell coordination," in *INFOCOM*, Apr. 2009.

[5] W. Yu, T. Kwon, and C. Shin, "Multicell coordination via joint scheduling, beamforming and power spectrum adaptation," *accepted in IEEE Trans. Wireless Commun.*, Apr. 2013.

[6] J. W. Lee, R. R. Mazumdar, and N. B. Shroff, "Joint resource allocation and base-station assignment for the downlink in CDMA networks," *IEEE/ACM Trans. Netw.*, vol. 14, no. 1, pp. 1–14, Jan. 2006.

[7] R. Sun, M. Hong, and Z. Q. Luo, "Optimal joint base station assignment and power allocation in a cellular network," in *IEEE Workshop on Signal Processing Advances in Wireless Communications (SPAWC)*, June 2012, pp. 234–238.

[8] L. Jiang, S. Parekh, and J. Walrand, "Base station association game in multi-cell wireless networks," in *IEEE Wireless Commun. Networking Conf. (WCNC)*, 2008, pp. 1616–1621.

[9] D. P. Bertsekas, "The auction algorithm: a distributed relaxation method for the assignment problem," *Annals of Operations Research*, vol. 14, pp. 105–123, 1988.