Joint User Association and Resource Allocation in Small Cells with Backhaul Constraints

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Mobile Data Crunch:

- Explosive growth in mobile data demand by rapid development and adoption of rich multimedia applications

Heterogeneous Networks (HetNets):

- Overlay traditional large cells with dense deployment of small cells (SCs)
- Increased frequency reuse

Small Cells

Increase system capacity:

- Low transmit power increases spatial reuse
- Densely deployed to offload traffic from macrocells

Backhaul is a major challenge:

- Impractical and expensive to have "macro" quality links to core network
- Backhaul capacity is limited

How do we efficiently utilize backhaul to maximize data rates of users?

User Association:

- Which APs serve which users?

Spectrum Allocation:

- Who gets subchannel?
- How often can we reuse spectrum?

Interference Management:

- How much power to transmit per subchannel?

Limited Backhaul Capacity:

- How much of an AP's backhaul capacity should be allocated to an user?

Coordinated Multipoint (CoMP)

- APs cooperate to improve throughput via managing interference and resource allocation
- **Joint scheduling and beamforming**: user data at serving AP
- **Joint transmission/processing**: user data at available at every AP
- Backhaul constraints studied mainly in terms of reducing overhead costs (Huang et al., 2013; Tolli et al., 2009)

Resource Allocation with Backhaul Constraints

Recent works account for backhaul capacity:

- (Chowdhery et al., 2011): effective heuristic algorithm accounts for backhaul with overhead
- (Marić et al., 2011): wireless backhaul for Picocells with backhaul scheduling and power control
- (Agustin et al., 2011): decentralized algorithm for power and backhaul constrained AP

Upper bounds:

- (Kim et al., 2013): upper bounds for system utility in backhaul constrained APs

Resource allocation for backhaul capacity constrained:

- Extend results of Multiuser Waterfillling with Crosstalk (Yu, 2007)
- Maximizing Weighted Sum Rate (WSR) Objective
- User association, spectrum allocation and power control done jointly
- Convergence to locally optimal solutions
- Computationally efficient iterative waterfilling solution

System

- Single tier small cell network in downlink OFDMA transmission
- M access points (APs), K users, N orthogonal subchannels

Objective

Weighted Sum Rate:

$$\sum_{k=1}^{K} \alpha_k R_k \tag{1}$$

Notation

mkn denotes the link from AP m to user k over subchannel n.

- Achieved transmission rate on link *mkn*:

$$R_{mkn} = \log_2 \left(1 + \frac{P_{mkn} G_{mkn}}{I_{mkn} + \sigma^2} \right), \tag{2}$$

where P_{mkn}, G_{mkn} and I_{mkn} are allocated power, channel gain and interference respectively

- User k can be served by multiple APs on different subchannels, the total rate for user k is:

$$R_k = \sum_{m,n} R_{mkn} \tag{3}$$

Interference Model

Interference I_{mkn} is function of all other transmissions on subchannel n:

$$I_{mkn} = \sum_{\substack{k'=1, \\ k' \neq k}}^{K} P_{mk'n} G_{mkn} + \sum_{\substack{m'=0, \\ m' \neq m}}^{M} \sum_{k''=0}^{K} P_{m'k''n} G_{m'kn}. \quad (4)$$

Interfering transmissions from own AP and other APs are accounted for.

Access Point Constraints

AP m is subject to a sum-power and backhaul constraint:

$$P_{total,m} = \sum_{k,n} P_{mkn} \leq P_{max,m}, \forall\ m, \tag{5}$$

$$R_{total,m} = \sum_{k,n} R_{mkn} \leq B_{max,m}, \forall\ m, \tag{6}$$

$$P_{mkn} \geq 0, \forall m, k, n. \tag{7}$$

Signaling overhead is ignored in backhaul capacity computation.

- User k is scheduled by AP m on subchannel n if $P_{mkn} > 0$
- **User Scheduling Property**: only one user may be scheduled per subchannel by an AP

$$\prod_{k=1}^{K} P_{mkn} = 0, \ \forall m, n, \quad (8)$$

this constraint is not enforced explicitly but a valid solution must have this property.

- Our inteference model allows us to solve scheduling problem efficiently without using Integer Programming.

$$
\begin{aligned}
\text{maximize} \quad & \sum_{k=1}^{K} \alpha_k R_k && (9) \\
\text{subject to} \quad & P_{total,m} = \sum_{k,n} P_{mkn} \leq P_{max,m}, \forall\ m, \\
& R_{total,m} = \sum_{k,n} R_{mkn} \leq B_{max,m}, \forall\ m, \\
& P_{mkn} \geq 0, \forall m, k, n.
\end{aligned}
$$

Rearrange to have explicit equation for power:

$$P_{mkn} = \left(\frac{\alpha_k - \nu_m}{t_{mkn} - \lambda_m} - \frac{I_{mkn} + \sigma^2}{G_{mkn}} \right)^+, \qquad (10)$$

where:

- α_k is the priority weight of user k
- λ_m is the power dual variable for AP m
- ν_m is the backhaul dual variable for AP m
- t_{mkn} is the price associated with using link mkn
- $(x)^+$ denotes $\max(x, 0)$.

Encapusulate incentive to use a particular link *mkn*:

$$t_{mkn} = \sum_{k' \neq k} \frac{(\alpha_{k'} - \nu_m)\, G_{mk'n}}{I_{mk'n} + \sigma^2} \cdot \frac{P_{mk'n} G_{mk'n}}{P_{mk'n} G_{mk'n} + I_{mk'n} + \sigma^2} \qquad (11)$$

$$+ \sum_{m' \neq m} \sum_{k'} \frac{(\alpha_{k'} + \nu_{m'})\, G_{mk'n}}{I_{m'k'n} + \sigma^2} \cdot \frac{P_{m'k'n} G_{m'k'n}}{P_{m'k'n} G_{m'k'n} + I_{m'k'n} + \sigma^2},$$

when $\boldsymbol{t}'s$ converge, the KKT system is solved.

Coupled Constraints and Complementary Slackness

- For fixed t_{mkn} and I_{mkn}:

$$P_{mkn} = f\left(\lambda_m, \nu_m\right) \quad (12)$$

$$R_{mkn} = g\left(P_{mkn}\right) = g\left(f\left(\lambda_m, \nu_m\right)\right), \quad (13)$$

  P_{mkn} and R_{mkn} are strictly monotonic functions of λ_m and ν_m!

- **Complementary Slackness**: only the active constraints have non-zero dual variable

Single Bisection: Two Constraints

- **Both** constraints can be satisfied by using bisection on **either** dual variable
- Set $\nu_m = 0$ and use bisection search on λ_m to waterfill on the active constraint
- Find λ_m that satisfies any of the following:
  1. $P_{max,m} - P_{total,m} \leq \epsilon$
  2. $B_{max,m} - R_{total,m} \leq \epsilon$
  3. $\lambda_m \leq \epsilon$ (AP m is unconstrained)
- When both constraints are tight, the waterlevel is the same.

Improved Iterative Waterfilling with Backhaul (IIWFB)

- Outer Loop: Update t_{mkn}
- Inner Loop: Each infeasible AP
  - Measure I_{mkn}
  - Compute λ_m, update $\boldsymbol{P}$
- Terminate when t_{mkn} & WSR converge and KKT conditions are satisfied

- Difficult to prove in general for iterative waterfilling algorithms

- Can be forced by slowing down update of t_{mkn}

$$t_{mkn}^{new} = \beta t_{mkn}^{old} + (1 - \beta)\hat{t}_{mkn} \tag{14}$$

  for some $0 < \beta < 1$ and $\hat{t}_{mkn}$ is computed from current $\boldsymbol{P}$

- Converges quickly in simulations even with larger problem sizes (e.g $M = 20$, $K = 30$, $N = 25$) which are difficult to solve by subgradient method

Scheduling Property

- Occasional convergence to $\boldsymbol{P}$ and $\boldsymbol{t}$ that don't satisfy this property due to numerical issues

- When at converged t_{mkn}, if the property is not satisfied:

  1. Fix scheduled users k as

$$P_{\mathbf{m_0},k,\mathbf{n_0}} = \begin{cases} P_{\mathbf{m_0},\mathbf{n_0}}^{max}, & \text{if } k = k_0. \\ 0, & \text{otherwise.} \end{cases} \tag{15}$$

  2. Repeat algorithm until convergence

  3. Simulations show the achieved objective is at least as good as the before

Complexity and Performance

- Efficient inner loop bisection on single dual variable can satisfy both constraints

- Prices $\boldsymbol{t}$ and interference model allows fast computation of user schedules, spectrum allocations and power control

- Intermediate steps guarantee power feasibility, backhaul feasibility guaranteed when interference terms converges

- Solves KKT system directly: locally optimal solutions for non-convex problem

Setup

- APs and users distributed randomly in d_{area}^2 square area
- All users have same priority $\alpha_k = 1, \ \forall k$
- Fix $P_{max,m} = 24 \ dBm$ and vary $B_{max,m}$
- Fading and noise model described in paper

Simulation

Benchmark against Greedy scheme:

- Assign subchannel n to AP-user pair with best channel
- Each AP computes λ_m and $\boldsymbol{P}$

Two scenarios considered:

- Standard deployment: $M = 3, K = 10, N = 16, d_{area} = 500 \ m$
- Dense deployment: $M = 20, K = 30, N = 25, d_{area} = 100 \ m$

Weighted Sum Rate (Standard)

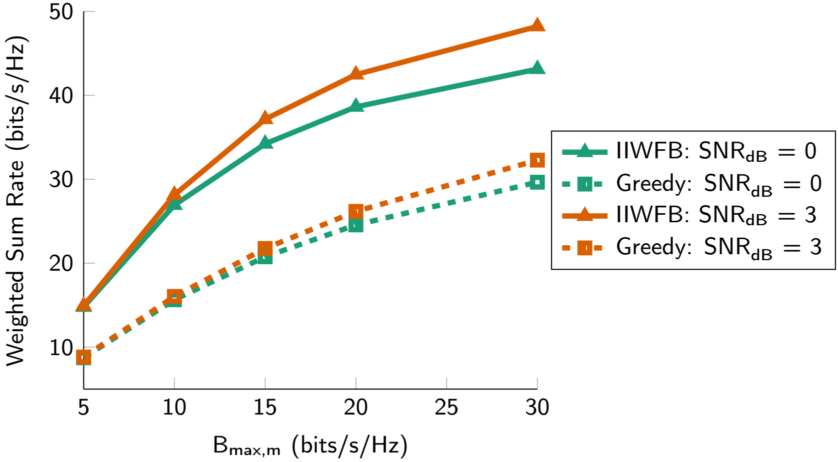

Figure 1: Plot of Weighted Sum Rate versus $B_{max,m}$.

Backhaul Utilization (Standard)

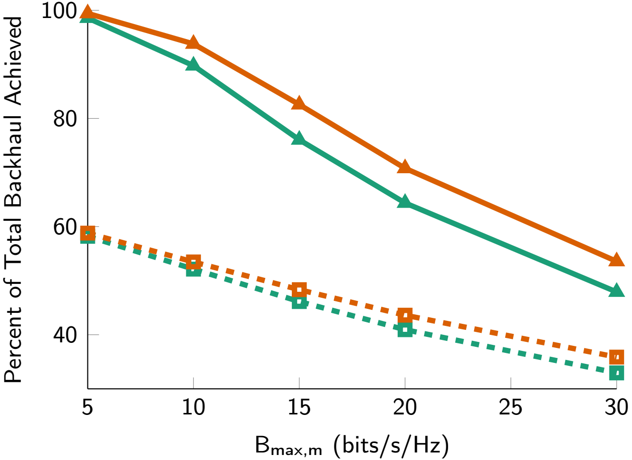

Figure 2: Plot of Percent Backhaul Used versus $B_{max,m}$.

Frequency Reuse Factor (Standard)

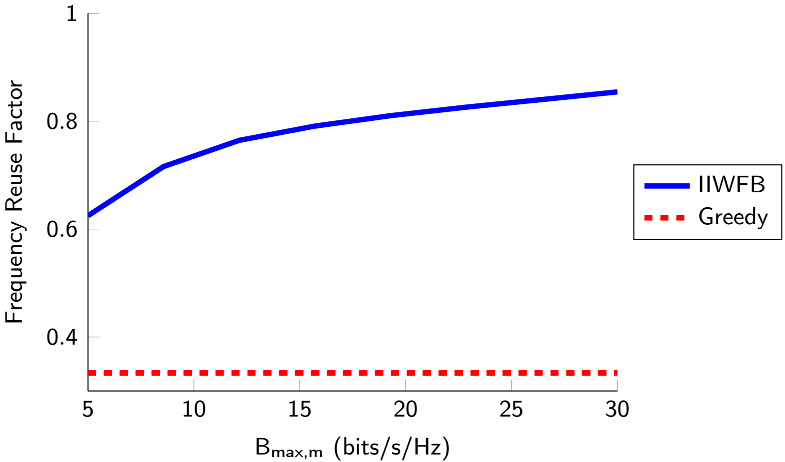

Figure 3: Plot of Frequency Reuse Factor versus $B_{max,m}$ for $SNR_{dB} = 10$.

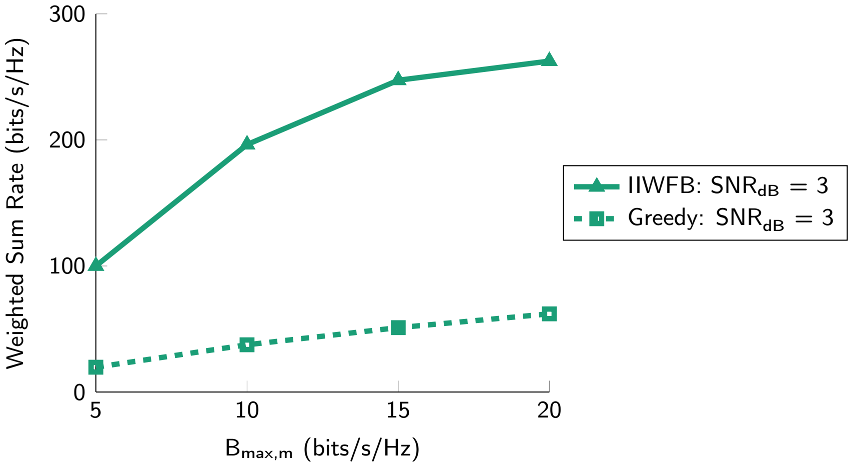

Figure 4: Plot of Weighted Sum Rate versus $B_{max,m}$ for $SNR_{dB} = 3$.

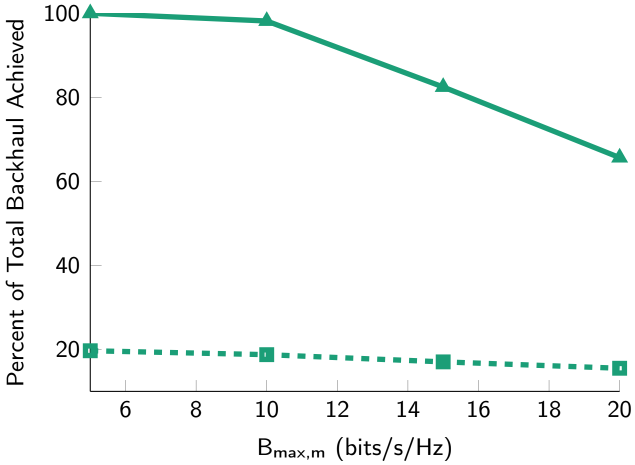

Figure 5: Plot of Percent Backhaul Used versus $B_{max,m}$ for $SNR_{dB} = 3$.

Remarks and Future Work

Remarks:

- Under severely limited backhaul capacity can achieve globally optimum objective (full backhaul utilization)
- Each AP can perform inner loop asynchronously
- Updating prices t_{mkn} requires all CSI and power allocations known at a central node

Next Steps:

- Investigate distributed schemes to reduce overhead needed and allow for decentralized implementations

Thank You!

Y. Huang, C. W. Tan, and B. D. Rao, "Joint beamforming and power control in coordinated multicell: Max-min duality, effective network and large system transition," *arXiv:1303.2774*, Mar. 2013.

A. Tolli, H. Pennanen, and P. Komulainen, "Distributed coordinated multi-cell transmission based on dual decomposition," in *IEEE Global Telecommunications Conference, 2009. GLOBECOM 2009*, 2009, pp. 1–6.

A. Chowdhery, W. Yu, and J. M. Cioffi, "Cooperative wireless multicell OFDMA network with backhaul capacity constraints," in *Communications (ICC), 2011 IEEE International Conference on*, 2011, p. 1–6.

I. Marić, B. Boštjančič, and A. Goldsmith, "Resource allocation for constrained backhaul in picocell networks," in *Information Theory and Applications Workshop (ITA), 2011*, 2011, pp. 1–6.

A. Agustin, J. Vidal, O. Muñoz-Medina, and J. R. Fonollosa, "Decentralized weighted sum rate maximization in MIMO-OFDMA femtocell networks," in *GLOBECOM Workshops (GC Wkshps), 2011 IEEE*, 2011, p. 270–274.

C. Kim, R. Ford, Y. Qi, and S. Rangan, "Joint interference and user association optimization in cellular wireless networks," *arXiv preprint arXiv:1304.3977*, 2013.

W. Yu, "Multiuser water-filling in the presence of crosstalk," in *Information Theory and Applications Workshop, 2007*, 2007, p. 414–420.

S. Mehryar, A. Chowdhery, and W. Yu, "Dynamic cooperation link selection for network MIMO systems with limited backhaul capacity," in *Communications (ICC), 2012 IEEE International Conference on*, 2012, p. 4410–4415.

F. Pantisano, M. Bennis, W. Saad, M. Debbah, and M. Latva-aho, "On the impact of heterogeneous backhauls on coordinated multipoint transmission in femtocell networks," in *2012 IEEE International Conference on Communications (ICC)*, 2012, pp. 5064–5069.

Y. Cui, V. K. N. Lau, and H. Huang, "Dynamic partial cooperative MIMO system for delay-sensitive applications with limited backhaul capacity," arXiv e-print 1307.2320, Jul. 2013.

Extra Slides

Waterfilling Equations

$$P_{mkn} = \left(\frac{\alpha_k - \nu_m}{t_{mkn} - \lambda_m} - \frac{I_{mkn} + \sigma^2}{G_{mkn}} \right)^+, \tag{16}$$

$$P_{max,m} \geq \sum_{n,k} \left(\frac{\alpha_k - \nu_m}{t_{mkn} - \lambda_m} - \frac{I_{mkn} + \sigma^2}{G_{mkn}} \right)^+, \tag{17}$$

$$B_{max,m} \geq \sum_{n,k} \log \left(1 + \frac{P_{mkn} G_{mkn}}{I_{mkn} + \sigma^2} \right). \tag{18}$$

We form the Lagrangian and set the derivative to 0:

$$\mathcal{L}\left(\boldsymbol{P},\boldsymbol{\nu},\boldsymbol{\lambda}\right)=\sum_{k=1}^{K}\alpha_k\sum_{\forall m,n}\log\left(1+\frac{P_{mkn}G_{mkn}}{I_{mkn}+\sigma^2}\right)$$
$$+\sum_{m=1}^{M}\nu_m\left(B_{max,m}-\sum_{\forall k,n}R_{mkn}\right)$$
$$+\sum_{m=1}^{M}\lambda_m\left(P_{max,m}-\sum_{\forall k,n}P_{mkn}\right) \qquad (19)$$

$$\frac{\partial\mathcal{L}\left(\boldsymbol{P},\boldsymbol{\nu},\boldsymbol{\lambda}\right)}{\partial P_{mkn}}=0 \qquad (20)$$

where λ_m and ν_m correspond to AP m's dual variables for power and backhaul constraints.

Initialize $\boldsymbol{P}$, t_{mkn}
loop until t_{mkn} converges
    loop until $\boldsymbol{P}$ converges
        for AP $m = 1 \cdots M$ **do**
            Calculate I_{mkn} according to (4).
            Obtain λ_m via bisection search in Algorithm 2.
            Calculate $\boldsymbol{P}$ using (10).
        end for
    end loop
    Update t_{mkn} according to (12).
end loop

Algorithm: Bisection Search

Fix t_{mkn} and I_{mkn}.
Initialize $\lambda_{m,min}$, $\lambda_{m,max}$, λ_m.
loop until $B_{max,m} - R_{total,m} \leq \epsilon$ or $P_{max,m} - P_{total,m} \leq \epsilon$
    Calculate P_{mkn} from (10) and update $P_{total,m}$.
    Calculate R_{mkn} from (2) and update $R_{total,m}$.
    if $P_{total,m} > P_{max,m}$ or $R_{total,m} > B_{max,m}$ **then**
        $\lambda_{m,min} = \lambda_m$.
        $\lambda_m = (\lambda_{m,min} + \lambda_{m,max})/2$.
    else
        $\lambda_{m,max} = \lambda_m$.
        $\lambda_m = (\lambda_{m,min} + \lambda_{m,max})/2$.
    end if
end loop

(Chowdhery et al., 2011)

- Effective heuristic algorithm for dynamic link selection which accounts for backhaul capacity and overhead costs.
- Performs user scheduling, spectrum allocation, power control and backhaul feasibility steps separately
- (Mehryar et al., 2012) extends this to multiple antennae

(Marić et al., 2011)

- Studied novel architecture wireless backhaul nodes for picocell
- Backhaul scheduling and power control steps are done separately

(Agustin et al., 2011)

- Proposed decentralized algorithm for power and backhaul capacity constrained BS
- Uses two dimensional search to obtain dual parameters for power and backhaul feasibility

(Kim et al., 2013)

- Proposed framework for deriving upper bounds on utility for backhaul constrained networks
- Augmented Lagrangian based algorithm for near optimal performance

Backhaul Delay

- Not considered in this work, studied in such as (Pantisano et al., 2012; Cui et al., 2013).