A Cross-Layer Design for Generic Interference-Limited Multicarrier Networks

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Introduction

Future wireless communication systems:

- Support large number of users,
- Provide High data rates,
- Offer flexibility in QoS.

To meet these prospective demands, scarce resources including time, frequency and power must judiciously exploited.

Challenges

- Separate design of the network functionalities degrades the performance.
- Using a subcarrier exclusively by one node (i.e., without reuse) or throughout the signalling interval (i.e., without time-sharing) is relatively easy to implement but deprives the network from achieving potential higher rates.

Approach

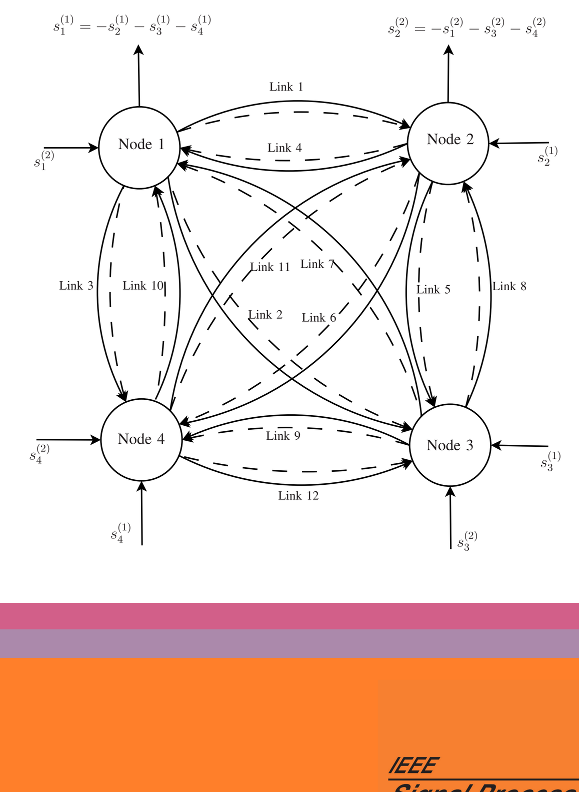
- A cross-layer design that incorporates joint routing, scheduling and power allocation (JRSPA).
- Subcarriers are allowed to be reused and time-shared jointly by multiple links.
- This design generalizes currently existing designs.

Previous Work

- JRSPA (w/o TS, w/o FR): is NP-hard. Efficient algorithms were proposed.
- JRSPA (w. TS, w/o FR): is convex. Efficiently solved.
- JRSPA (w/o TS, w. FR): is NP-hard. A Suboptimal algorithm was proposed.
- JRSPA (w. TS, w. FR): is the main focus of this work.

System Model

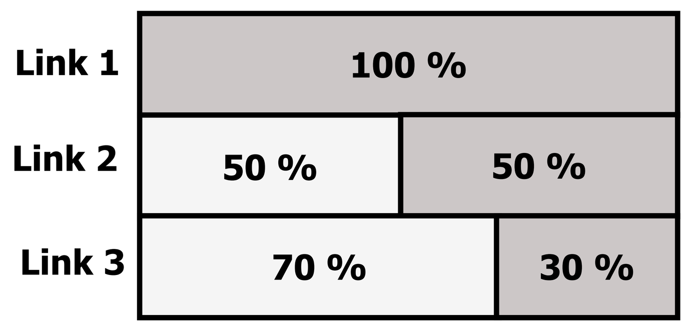
- An OFDMA network with N nodes and $L = N(N-1)$ links is considered.
- Each link has K subcarriers.
- There are D receivers across the network, $D \leq N$.
- Channels are time-invariant during each signalling interval.
- Nodes are able to send, receive and/or relay data.
- Half duplex operation mode, infinite backlog at source nodes and multihop routing are assumed.
- Spectral efficiency is $\log_2(1 + SINR)$.
- This network is represented by a complete weighted directed graph.



Design Variables

- **Data Routes:** $x_{\ell k}^{(d)}$ is the rate of the data intended for destination d on subcarrier k of link ℓ and $s_n^{(d)}$ is the rate of data injected into the network at node n and intended for destination d.
- **Power Allocations:** $p_{\ell k}$ is the power allocated for transmission on subcarrier k of link ℓ.
- **Subcarrier Schedules:** $\gamma_{\ell_1 \ell_2 \ldots \ell_m}^{(k)}$ is the variable that determines the fraction of the signalling interval during which links $\ell_1, \ell_2, \ldots, \ell_m \in \mathcal{L}$ are simultaneously 'active' on subcarrier $k \in \mathcal{K}$ and the $L - m$ remaining links in $\mathcal{L}$ are 'silent'.
  - For example, a network with $L = 3$ links and $K = 1$ subcarrier: $\gamma_1^{(1)} = 0.5$, $\gamma_{1,2}^{(1)} = 0.2$, $\gamma_{1,2,3}^{(1)} = 0.3$ and $\gamma_2^{(1)}, \gamma_3^{(1)}, \gamma_{1,3}^{(1)}, \gamma_{2,3}^{(1)} = 0$.

Signalling interval for k=1



Design Problem

$$\max_{\{s_n^{(d)}\},\{x_{\ell k}^{(d)}\},\{p_{\ell k}\},\{\gamma_{\ell_1 \ell_2 \ldots \ell_m}\}} \sum_{d \in \mathcal{D}} \sum_{n \in \mathcal{N} \setminus \{d\}} w_n^{(d)} s_n^{(d)},$$

subject to

$$\sum_{\ell \in \mathcal{L}} \sum_{k \in \mathcal{K}} a_{n\ell} x_{\ell k}^{(d)} = s_n^{(d)}, \quad \text{(Flow conservation law)}$$

$$\sum_{k \in \mathcal{K}} \sum_{\ell_1 \in \mathcal{O}(n)} \sum_{m=1}^{L} \sum_{\ell_2 \in \mathcal{L}} \cdots \sum_{\ell_m \in \mathcal{L}} \gamma_{\ell_1 \ldots \ell_m}^{(k)} p_{\ell_1 k} \leq P_n, \quad \text{(Power Budget)}$$

$$\sum_{m=1}^{L} \sum_{\ell_1 \in \mathcal{L}} \cdots \sum_{\ell_m \in \mathcal{L}} \gamma_{\ell_1 \ldots \ell_m}^{(k)} \leq 1, \quad \text{(Non-overlapping schedules)}$$

$$a_{n\ell_1}^{+} a_{n\ell_2}^{+} \sum_{m=2}^{L} \sum_{\ell_3 \in \mathcal{L}} \cdots \sum_{\ell_m \in \mathcal{L}} \gamma_{\ell_1 \ldots \ell_m}^{(k)} = 0, \quad \text{(Broadcasting)}$$

$$a_{n\ell_1}^{+} a_{n\ell_2}^{-} \sum_{m=2}^{L} \sum_{\ell_3 \in \mathcal{L}} \cdots \sum_{\ell_m \in \mathcal{L}} \gamma_{\ell_1 \ldots \ell_m}^{(k)} = 0, \quad \text{(Half-duplex)}$$

$$\sum_{d} x_{\ell k}^{(d)} \leq \gamma_{\ell}^{(k)} \log(1 + p_{\ell k} g_{\ell k}) + \sum_{m=1}^{L} \gamma_{\ell, \ell_1 \ldots \ell_m}^{(k)} \log\left(1 + \frac{p_{\ell k} g_{\ell k}}{1 + \sum_{m=1}^{L} p_{\ell_m k} g'_{\ell_m k}}\right), \quad \text{(Link capacity)}$$

$$x_{\ell k}^{(d)}, s_n^{(d)}, \gamma_{\ell_1 \ell_2 \ldots \ell_m}, p_{\ell k} \geq 0, \quad \text{(Non-negativity)}$$

Design Problem Overview

This problem is nonconvex, but shares some common features with the GP framework. To take the advantage of this framework, we define $s_n^{(d)} = \log_2 t_n^{(d)}$, $x_{\ell k}^{(d)} = W \log_2 r_{\ell k}^{(d)}$.

Geometric Programming

Let $z \in \mathbb{R}_{+}^{n}$. A standard GP is

$$\begin{aligned} \min_{z} \quad & f_0(z), \\ \text{st.} \quad & f_i(z) \leq 1, \quad i = 1, \ldots, m, \\ & g_i(z) = 1, \quad i = 1, \ldots, p, \end{aligned}$$

$g_i = c_0 \prod_i z_i^{\alpha_i}$ are monomials, and $f_i = \sum_k c_k \prod_i z_i^{\alpha_{ik}}$ are posynomials.

- A GP can be easily converted to a convex problem.

Monomial Approximation

A monomial approximation of a differentiable function $h(z) \geq 0$ near $z^{(0)}$ is

$$h(z) \approx h(z^{(0)}) \prod_{i=1}^{n} \left(\frac{z_i}{z_i^{(0)}}\right)^{\beta_i}.$$

where $\beta_i = \frac{z_i^{(0)}}{h(z^{(0)})} \frac{\partial h}{\partial z_i}\Big|_{z=z^{(0)}}$.

- The product of monomials is a monomial.

GP-Approximated Design Problem

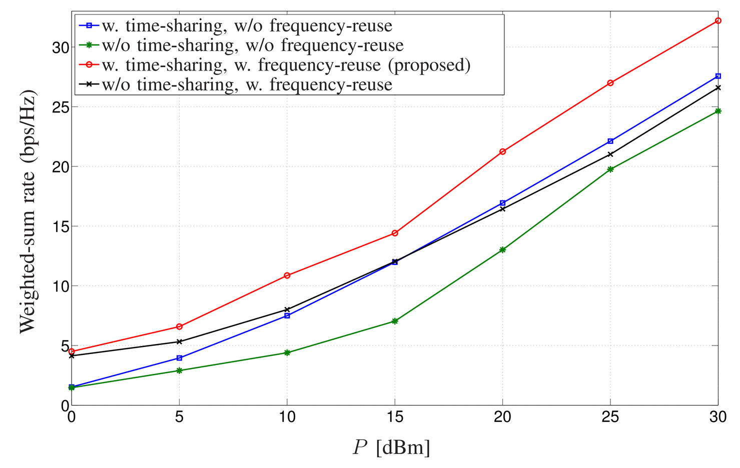
- Using the new variables, the objective and flow constraints are GP-compatible.
- The power budget and non-overlapping constraints are GP-compatible.
- In broadcasting and half-duplex constraints "$= 0$" is replaced with "$\leq \epsilon$" to make it GP-compatible.
- The RHS of capacity constraint is approximated with a product of monomial approximations of each term.
- The non-negativity constraints are GP-compatible.

Starting from a feasible power allocation and iterating on this GP is guaranteed to converge to a locally optimal solution, satisfying the KKT conditions.

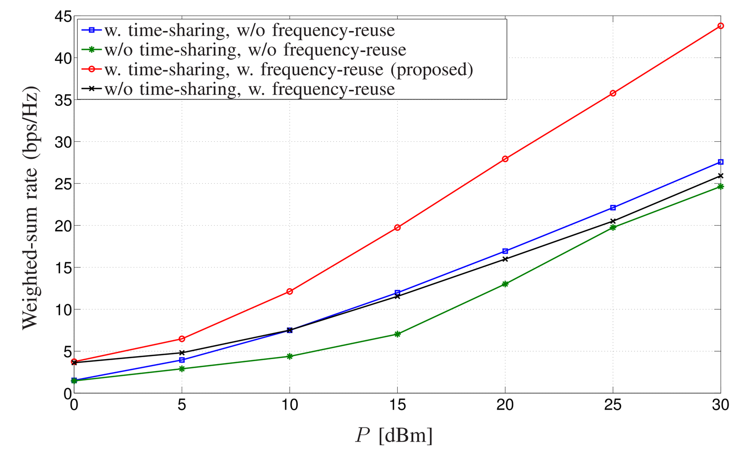
Numerical Example

- An exemplary network of $N = 4$ nodes and $K = 4$ subcarriers.
- The channels are quasi-static frequency flat Rayleigh fading with log-normal shadowing and pathloss components.
- Monte carlo simulation over 10 independent drops.
- 16380 time-share variables, 98 flow variables and 48 power variables.

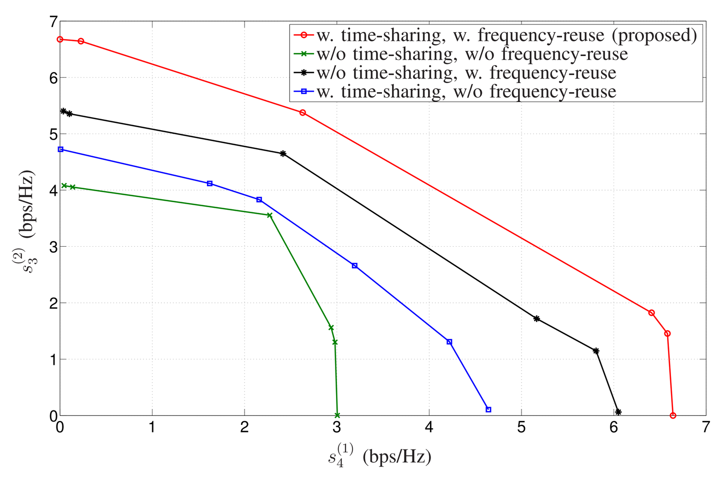
Sum-Rate (equal weights)



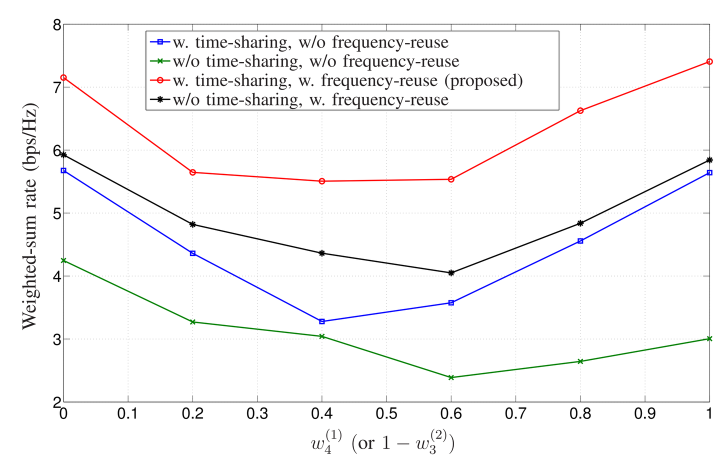
Sum-Rate (unequal weights)



Rate Region



Weighted Sum-Rate



Conclusion

- We considered a cross-layer design that incorporates joint routing, scheduling and power allocation with both FR and TS.
- We developed an efficient iterative algorithm that its convergence to a locally optimum is guaranteed.
- This design generalizes the existing designs in which only one of these aspects are considered and offers significant gains over them.

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