Joint Routing and Power Allocation for IDMA Applied in Multi-Hop Wireless Networks

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Motivation

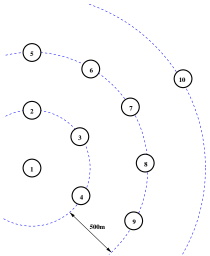
- Mesh networks gain increasing interest with a multitude of possible applications like
  - wireless meshed "backhaul" networks
  - machine to machine communication (M2M)
- Interleave-Division Multiple Access (IDMA)
  - can be seen as a new interpretation of the core idea of CDMA
  - is capacity-achieving
  - has the potential to increase physical layer efficiency in practical systems

New aspects

- Application of IDMA in mesh networks
- First time the IDMA concept is explicitly considered in a joint routing and power allocation problem

Problem Definition

- Goal: Efficiently find a solution to
  - transmit data from source nodes to receiver nodes (multiple unicast sessions)
  - minimize overall power while meeting QoS constraints
  - guarantee a maximum delay
- Subquestions
  - How to distribute data across edges at nodes?
  - Which transmission paths to take?
  - When to transmit which data with what power at which node? And how?



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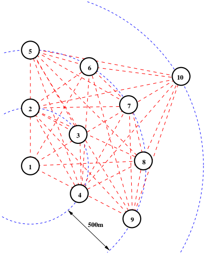
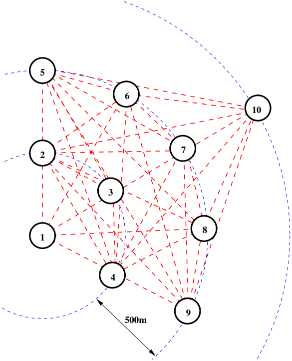


Wireless Mesh Networks

- Link capacities are not fixed and are influenced by resources of interfering links
- Adjustment of capacities by resource allocation such as scheduling and power allocation
- Need for integrated routing, scheduling, and power control strategy



Edge Capacity

Signal-to-interference-plus-noise ratio (SINR)

$$\mathrm{SINR}_{e,t} = \frac{G_t\left(T\left(e\right), R\left(e\right)\right) \cdot p_{e,t}}{\sum_{\substack{l \in E_{e,t} \\ l \neq e}} G_t\left(T\left(l\right), R\left(e\right)\right) \cdot p_{l,t} + \sigma_e^2} \qquad (1)$$

- Maximum mutual information that can on average be transmitted within time duration τ over a bandwidth B is given by the capacity $C_G(\mathbf{p}) = B\,\tau\,\log_2\left(1 + \mathrm{SINR}_{e,t}\right)$

Problem Breakdown

Integrated Routing, Scheduling & Power Allocation Problem
with
IDMA Transmission on each Edge

↓

Simultaneous Routing & Power Allocation Problem
with
Solution p,b,c

↓

Power Allocation Breakdown on Link Level
with
IDMA

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②

SRPC problem

$$\begin{aligned} \text{minimize} \quad & f(\mathbf{p}, \mathbf{b}, \mathbf{c}) \\ \text{subject to} \quad & (\mathbf{b}, \mathbf{c}) \in C_c, \\ & \mathbf{p} \in C_p, \\ & \sum_{m \in M} c_{e,m,t} \leq R_{e,t}(\mathbf{p}) \leq C_G(\mathbf{p}) \\ & (e \in E^+(v), \; t \in T). \end{aligned} \tag{2}$$

- C_p and C_c contain communication and flow constraints
- At any time $t \in T$ each node $v \in V$ can map all part of messages $m \in M$ onto a single link $e \in E$ for transmission
- Coupling constraints are the only coupling between network flow variables $(\mathbf{b}, \mathbf{c})$ and communication variables $\mathbf{p}$

Routing and Power Control Decomposition

- If f is strictly monotone in $\mathbf{p}$ then all coupling constraints are active at each optimum solution of the SRPC problem (2) in $\mathbf{p}$, i.e., $\sum_{m \in M} c_{e,m,t} = R_{e,t}(\mathbf{p}^*)$
- As shown later, with IDMA we obtain the important property that

$$\sum_{m \in M} c_{e,m,t} = R_{e,t}(\mathbf{p}^*) = C_G(\mathbf{p}^*), \qquad (3)$$

i.e., the coupling constraints in the SRPC problem (2) are fulfilled with equality for IDMA

Motivation for RPCD

Use these both properties to find a problem equivalent to the SRPC problem, which can be solved by an algorithm with very low computational complexity

RPCD Algorithm

Equivalent SRPC Problem

$$\begin{aligned} \text{minimize} \quad & f\left(\mathbf{J}\left(\mathbf{p},\mathbf{c}\right),\mathbf{c},\mathbf{b}\right) \\ \text{subject to} \quad & \mathbf{p} \in C_p, \\ & (\mathbf{b},\mathbf{c}) \in C_c, \\ & \mathbf{p} \succeq \mathbf{J}\left(\mathbf{p},\mathbf{c}\right). \end{aligned} \tag{4}$$

with standard interference function

$$\begin{aligned} J_{e,t}\left(\mathbf{p},\mathbf{c}\right) \quad := \quad & \frac{2^{\left(\frac{\sum_{m\in M} c_{e,m,t}}{B\,\tau}\right)} - 1}{G_t\left(T\left(e\right),R\left(e\right)\right)} \cdot \\ & \cdot \left(\sum_{\substack{l\in E_{e,t} \\ l\neq e}} G_t\left(T\left(l\right),R\left(e\right)\right) \cdot p_{l,t} + \sigma_e^2\right) \end{aligned} \tag{5}$$

RPCD Algorithm

- Combinatorial structure of equivalent SRPC problem allows for formulation as two sub-problems:
  1. Fix power variables (link capacities) and formulate a flow problem with primal flow variables
  2. Fix flow variables and formulate a power control problem with primal power variables

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Fixed power variables

$$\begin{aligned} \text{minimize} \quad & f\left(\mathbf{J}\left(\hat{\mathbf{p}},\mathbf{c}\right),\mathbf{c},\mathbf{b}\right) \\ \text{subject to} \quad & (\mathbf{b},\mathbf{c}) \in C_c, \\ & \hat{\mathbf{p}} \succeq \mathbf{J}\left(\hat{\mathbf{p}},\mathbf{c}\right). \end{aligned} \tag{6}$$

- Objective of this problem strictly convex in $\mathbf{c}$
- Solution unique and depends continuously on $\hat{\mathbf{p}}$

RPCD Algorithm

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Fixed flow variables

$$\begin{aligned} \text{minimize} \quad & f\left(\mathbf{p}, \hat{\mathbf{c}}, \hat{\mathbf{b}}\right) && (7) \\ \text{subject to} \quad & \mathbf{p} \in C_p, && (8) \\ & \mathbf{p} \succeq \mathbf{J}\left(\mathbf{p}, \hat{\mathbf{c}}\right). \end{aligned}$$

- Solution unique and depends continously on $\left(\hat{\mathbf{b}}, \hat{\mathbf{c}}\right)$

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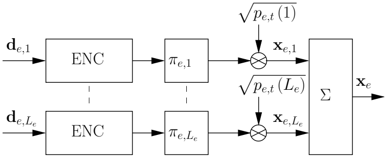
Interleave-Division Multiple Access (IDMA)

- Data transmission over edge e and time slot t
- Split amount of data $\sum_m c_{e,m,t}$ into L_e data sequences $\mathbf{d}_{e,1} \ldots \mathbf{d}_{e,L_e}$ of equal length
- Transmit data sequences simultaneously with different interleavers and powers
- Channel encoder may be the same for all data sequences



- Transmit signal $\mathbf{x}_e$ with sum power $p_{e,t} = \sum_{l=1}^{L_e} p_{e,t}(l)$

Multiple access with L_e virtual users ("layers")

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- IDMA is capacity-achieving solely by properly allocating the power values $p_{e,t}(l)$, $l = 1 \ldots L_e$

Optimum power allocation

Assuming stripping decoding, each power value $p_{e,t}(l)$, $l = 1 \ldots L_e$ has to follow a distribution given by

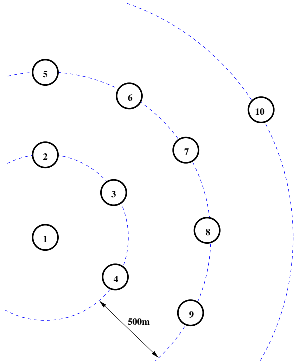
$$p_{e,t}(l) = (1+\chi)^{L_e - l} \cdot \chi \cdot \frac{p_{e,t}}{\mathrm{SINR}_{e,t}} \qquad (9)$$

with constant

$$\chi = \sqrt[L_e]{\mathrm{SINR}_{e,t} + 1} - 1. \qquad (10)$$

Numerical Example

- Cellular wireless mesh backhaul network



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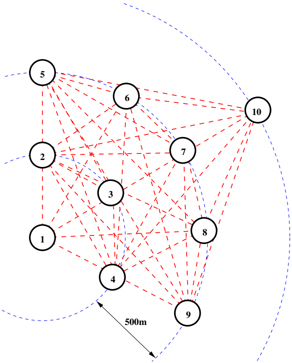

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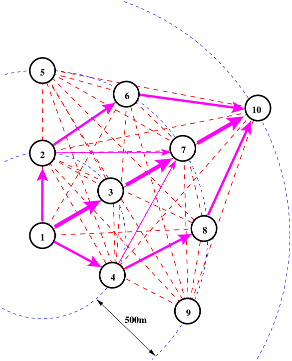

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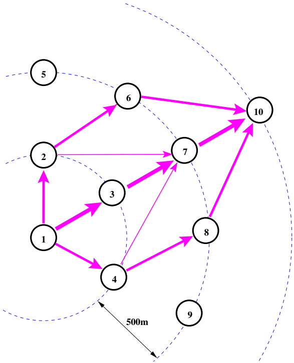

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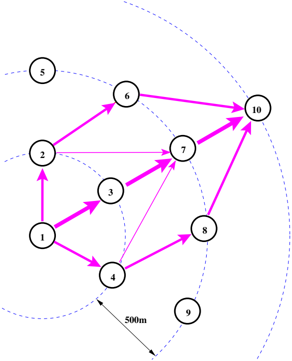

- Power allocations along [1,2,6,10] path

$\sum_m c_{e,m,t}$	$p_{e,t}$	L_e	$p_{e,t}(1)$	$p_{e,t}(L_e)$
1.4 Mbit	0.03 W	14	3.2348 mW	1.3137 mW
1.1 Mbit	0.02 W	11	2.5106 mW	1.2553 mW
1.1 Mbit	0.1 W	11	12.5528 mW	6.2764 mW

Summary

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- Algorithmic solution taking explicitely into account
  - information-theoretical properties of the underlying IDMA scheme of virtual users
  - the resulting combinatorial structure of the overall problem
- Solution offers
  - fast convergence to an optimum solution
  - robust capacity-achieving transmission in each link of a given network

Assumptions

- Multiple messages/multiple sources: Each source can transmit multiple messages to different destinations
- Multiple path routing: Each node can send different data to many nodes and receive data from many resources - no multicast, no broadcast
- Single frequency network
- Transmission organized in equal size time slots (scheduling)
- Point-to-point transmission: No relaying, but decoding & forwarding at intermediate nodes
- Channel state information at transmitting nodes (enables resource/power allocation)

Optimization Problem (more detailed)

- Objective to minimize a convex cost function $f(\mathbf{p},\mathbf{c},\mathbf{b})$ (or to maximize a concave utility function)
- Design variables $\mathbf{b}$, $\mathbf{c}$ and $\mathbf{p}$ are subject to constraints
- Polyhedral sets defined by communication and flow constraints

Polyhedral set C_p fulfills communication constraints

$$0 \leq p_{e,t} \leq P_e^{\max} \tag{11}$$

$$\sum_{e \in E^+(v)} p_{e,t} \leq P_v^{\max} \tag{12}$$

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Polyhedral set C_c fulfills flow constraints

$$c_{e,m,t} \geq 0 \quad (13)$$

$$0 \leq b_{v,m,t} \leq B_{v,m} \quad (14)$$

$$b_{s_m,m,1} = S_m \quad , \quad b_{v,m,1} = 0 \qquad (v \in V \setminus \{s_m\}) \quad (15)$$

$$b_{d_m,m,t^{\max}} = S_m \qquad (m \in M \setminus M_V) \quad (16)$$

$$c_{e,m,t} = 0 \qquad (\mathrm{co}_E(e) \neq \mathrm{co}_T(t)) \quad (17)$$

$$b_{v,m,t+1} - b_{v,m,t} = \sum_{e \in E^-(v)} c_{e,m,t} - \sum_{e \in E^+(v)} c_{e,m,t} \quad (18)$$

$$(v \in V \setminus \{d_m\}, t \in T \setminus \{t^{\max}\},$$

$$m \in M, e \in E, v \in V, t \in T)$$