Scalable optimization of joint routing and resource allocation for mm wave backhaul mesh networks

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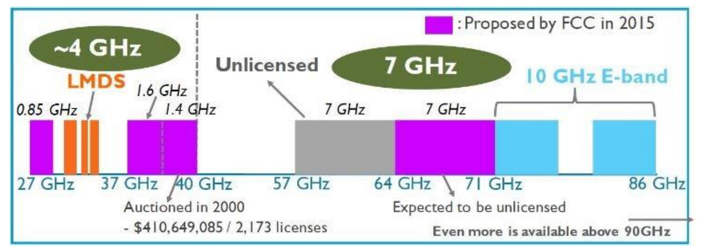
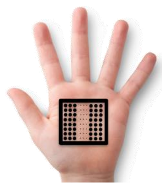
Scaling to picocells and the backhaul challenge

Push to increase mobile data rates by orders of magnitude (1000X)

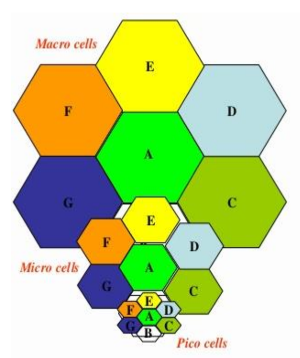
Can be achieved by **mm wave picocells**

- Bandwidth
- Frequency reuse (small cells)
- Spatial reuse (directional antennas)





Fiber (wired) backhaul is not scalable to the dense grid of picocell base stations



Mm wave wireless backhaul

High throughput

Small directional antennas that can be mounted anywhere => Low cost and robust deployment

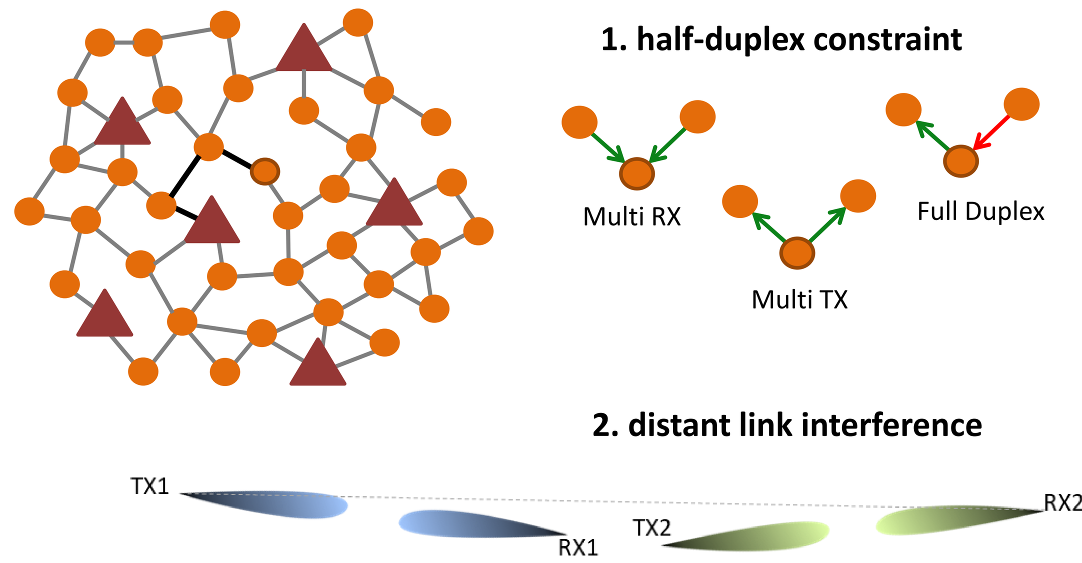
Limited disruption, low interference

The wireless backhaul structure

- Scaling to picocells is only possible with wireless backhaul
- Small subset of "gateway" nodes receive fiber (wired backhaul)
- Extended to all nodes through high-speed directional mm wave links

multihop structure requires

- routing and scheduling, with
- **interference** management



Resource allocation

Allocate resources to get maximum (downlink) throughput to nodes

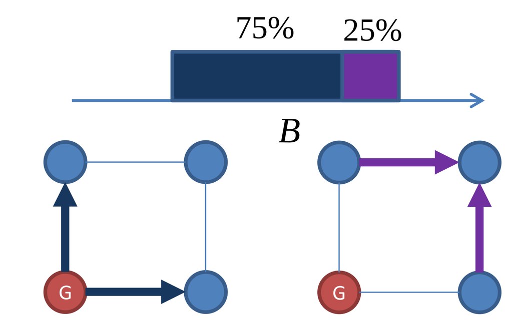
Blow up the problem:

overlapping portions allocated to **links**

→ disjoint portions allocated to **subsets of links** (patterns)

Good news: simple formulation

Bad news: exponential growth of problem size



Backhaul optimization: joint routing and scheduling

x_P ← Bandwidth allocated to pattern P

$\sum_{P\subset\{1,\ldots,L\}} x_P \le 1$ Resource constraint

Flow constraints: $\sum_{P\subset\{1,\ldots,L\}} x_P \sum_{j\in P} \gamma_{j,P} f_{j,i} \ge D$

(bandwidth allocated to pattern P; Direction/connectivity; spectral efficiency of link l when subset P is active; rate delivered to each node)

$$f_{j,i} = \begin{cases} 1 & j \text{ flows into } i \\ -1 & j \text{ flows out of } i \\ 0 & j \text{ unconnected to } i \end{cases} \qquad \gamma_{j,P} = \log_2\left(1 + \frac{S_j}{\sigma_n^2 + \sum_{k\in P} I_{k\to j}}\right)$$

$$\begin{aligned} &\underset{\{x_P, D\}}{\text{maximize}} \quad D \\ &\text{subject to} \\ &\sum_{P\subset\{1,\ldots,L\}} x_P \le 1 \\ &\sum_{P\subset\{1,\ldots,L\}} x_P \sum_{j\in P} \gamma_{j,P} f_{j,i} - D \ge 0 \quad \text{for all non-gateway nodes} \\ &x_P \ge 0 \end{aligned}$$

Simple linear programming problem!

... with $2^L - 1$ variables!!

Practicality: guarantees for sparsity of solution

Scheduling $2L - 1$ activation patterns is impossible!

however...

Caratheodory's theorem:

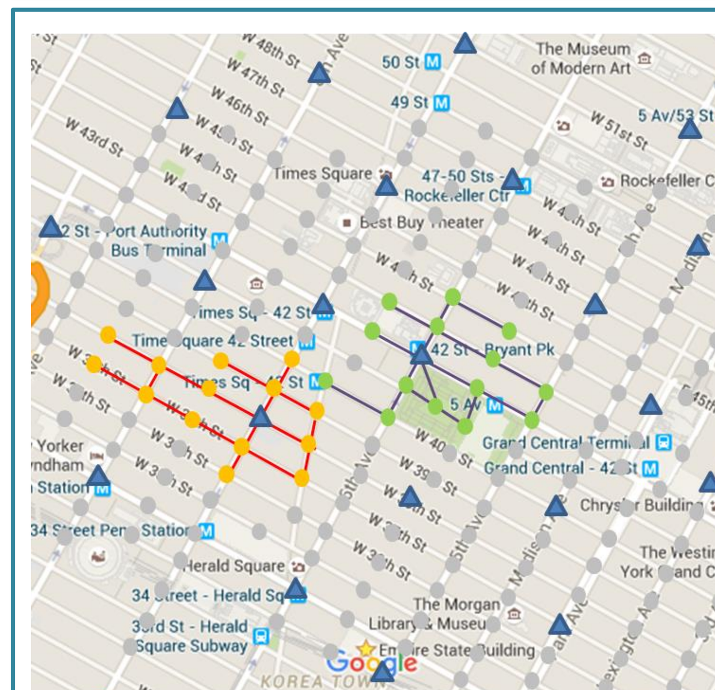
if a point x of $\mathbb{R}^d$ lies in the convex hull of a set P of points in $\mathbb{R}^d$, there is a subset P' of P consisting of $d+1$ or fewer points such that x lies in the convex hull of P'

$d_i = \sum_{P\subset\{1,\ldots,L\}} x_P \sum_{j\in P} \gamma_{j,P} f_{j,i}$ i: non-gateway node

$$\begin{bmatrix} d_1 \\ d_2 \\ \vdots \\ d_{N-N_g+1} \end{bmatrix} = \sum_{P\subset\{1,\ldots,L\}} x_P \begin{bmatrix} \sum_{j\in P} \gamma_{j,P} f_{j,1} \\ \sum_{j\in P} \gamma_{j,P} f_{j,2} \\ \vdots \\ \sum_{j\in P} \gamma_{j,P} f_{j,N-N_g+1} \end{bmatrix}$$

⇒ a solution **exists** with at most $N - N_G + 1$ active patterns

How do we connect Manhattan?



The combinatorial problem is too large to solve for the entire network → Quick fix: clustering

- assign nodes to nearest gateway,
- solve each gateway's cluster of nodes separately.

Yellow cluster: d/R = 17.16 %

Green cluster: d/R = 17.39 %

R = nominal link rate

Use the guarantee given by Caratheodory's theorem to build a **scalable formulation** with a smaller number of "local" patterns as variables.

Scalable formulation based on *local* patterns

Define N_{glob} **global** patterns, each the union of one or more **local** patterns

Resource constraint: $\sum_{l=1}^{N_{glob}} h_l \le 1$ (**Global** bandwidth allocation to pattern l)

Define: Neighborhood of link j: N_j

set of links with significant interference on link j

Local patterns: subsets of neighborhood $B \subset N_j$

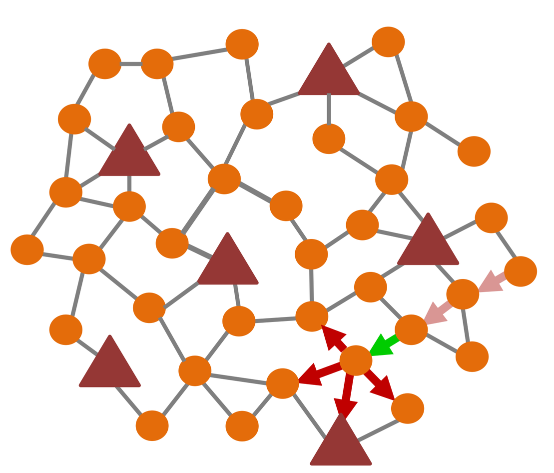
Local bandwidth allocations: $x_j^{B,l} \le h_l$

Link rate parameters: $r_j \le \sum_{B\subset N_j} \sum_{l=1}^{N_{glob}} \gamma_j^B x_j^{B,l}$

Flow constraints: $\sum_{j\in\Lambda} f_{ji} r_j \ge D$

Enforce **consistency** of local patterns with **binary** link activation parameters $q_j^{B,l}$

$$x_j^{B,l} \le q_j^{B,l} \qquad q_j^{B,l} + \sum_{\substack{A\subset N_k \\ B\cap N_k \ne A\cap N_j}} q_k^{A,l} \le 1$$

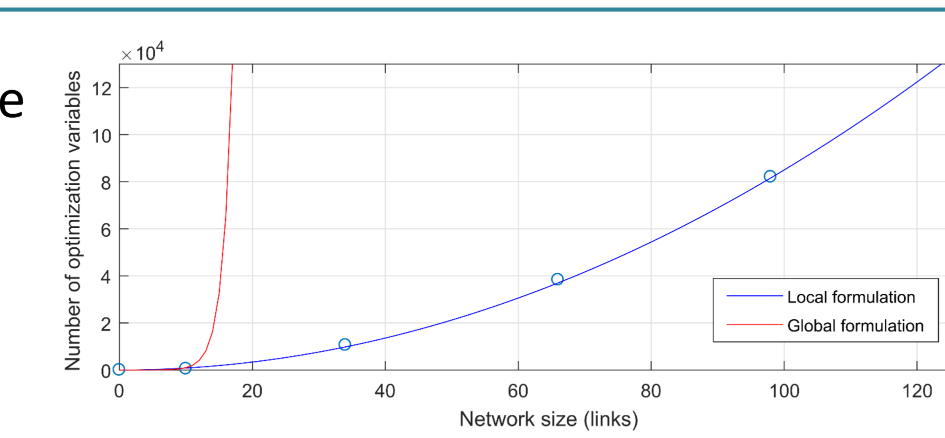


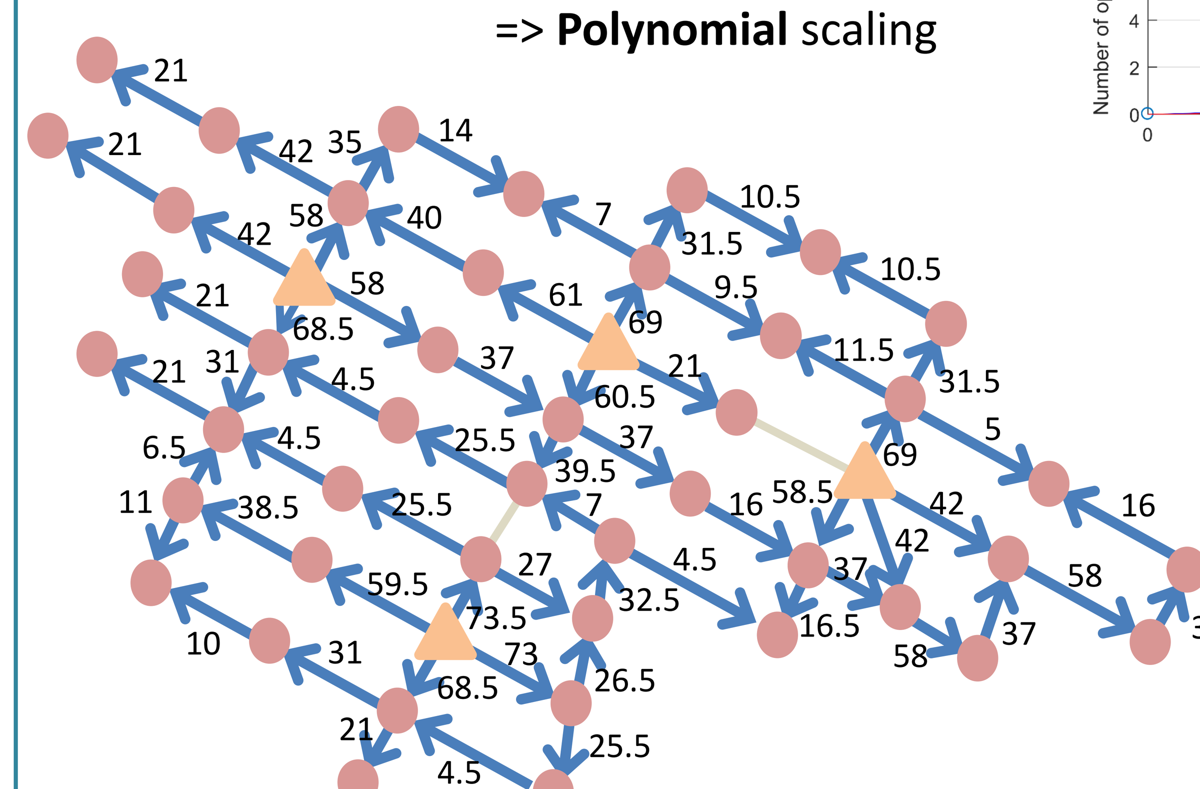
$$\begin{aligned} &\underset{\{r_j, x_j^{B,l}, q_j^{B,l}\}}{\text{maximize}} \quad D \\ &\text{subject to} \\ &\sum_{j\in\Lambda} f_{ji} r_j \ge D, && \leftarrow \text{flow constraints} \\ &0 \le r_j \le \sum_{B\subset N_j} \sum_{l=1}^{N_{glob}} \gamma_j^B x_j^{B,l}, && \leftarrow \text{link rate} \\ &0 \le x_j^{B,l} \le q_j^{B,l}, && \leftarrow \text{activation} \\ &q_j^{B,l} \in \{0,1\} \\ &q_j^{B,l} + \sum_{\substack{A\subset N_k \\ B\cap N_k \ne A\cap N_j}} q_k^{A,l} \le 1, && \leftarrow \text{consistency constraints} \\ &\sum_{B\subset N_j} x_j^{B,l} \le h_l, \\ &\sum_{l=1}^{N_{glob}} h_l \le 1 && \leftarrow \text{resource constraint} \end{aligned}$$

Binary linear programming problem of size

$$2N_{glob} L \overline{N_j} + L + 1$$

=> **Polynomial** scaling





Network of 48 nodes and 126 links solved in under **1 minute**

21% of nominal link rate delivered to all nodes

Acknowledgements

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