Scheduling in mm-Wave IAB Networks

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Outline

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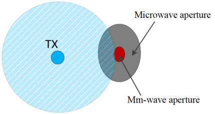
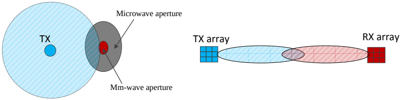
- Massive bandwidth available in mm-wave spectrum
- Friis equation: the free-space path loss is proportional to the square of radio frequency

$$P_r = \underbrace{\frac{P_t}{4\pi R^2}}_{\substack{\text{receive}\\ \text{spectral density}}} \times \underbrace{\frac{\lambda^2}{4\pi} G_r}_{\substack{\text{effective}\\ \text{receive aperture}}} \times \underbrace{G_t}_{\text{transmit gain}}$$

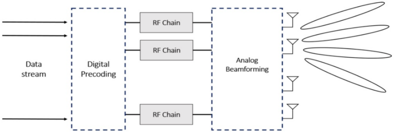


- Very small cells required
- How to get traffic into small-cell BSs?

- Beamforming needed!
- Massive MIMO: many antennas at BS, and at UE also

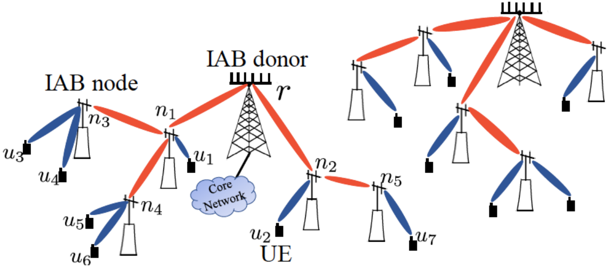


- Large number of antennas (phased array).
- Limited number of RF chains due to cost and power constraints.
- Small number of RF chains at BS, maybe 1 at a UE.
- One beam per RF chain.



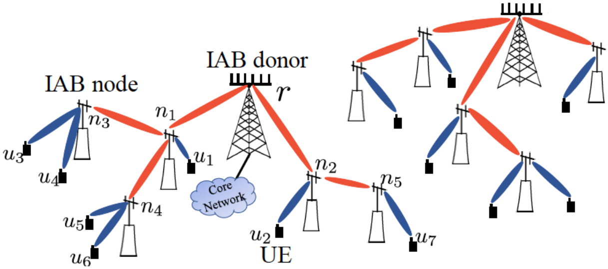
Hybrid Beamforming

mm-Wave IAB Networks



Red links are wireless backhaul, blue links are wireless access

- Dense networks required to overcome effects of blockage and pathloss.
- IAB: Integrated access and backhaul
- Multihop tree network for backhaul
- Backhaul links are LoS and more reliable than access links

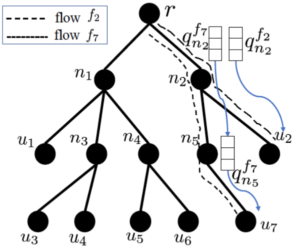


- How to prioritize backhaul links over UE links?
- How to prioritize UE links at different levels in the tree?
- How to prioritize UE links based on instantaneous channel rates?
- How to distribute the required information through the tree?

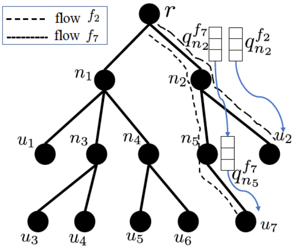
We take a network stability point of view

Flows and Flow Rates

- Each UE corresponds to a flow of packets
- Flow traffic arrives at the root node at a certain rate (different for each flow)



- First question is: are the flow rates achievable?
- Second, if achievable, find a scheduler that can keep the queues stable
- Existing methods include max-weight scheduling and back-pressure (both due to Tassiulas and Ephremides in 1990s)



- We address these questions in the paper below.
- This talk is about this paper but doesn't cover everything in it

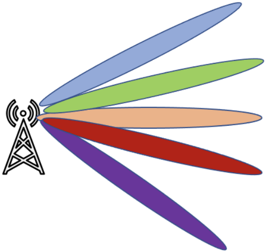
S. Gopalam, S.V. Hanly, P. Whiting, "Distributed and Local Scheduling Algorithms for mmWave Integrated Access and Backhaul" IEEE/ACM Transactions on Networking, Vol. 30, No. 4, pp. 1749-1764, Aug. 2022.

- In a single cell, channel state aware schedulers generally do not consider stability
  - Max rate Scheduler
  - Proportional Fair Scheduler
- Back-pressure scheduler achieves stability for general wireless networks
  - Invented by Tassiulas and Ephremides in early 1990s
  - Requires the solution of a combinatorial network-wide max-weight optimization at every scheduling instant
  - Generally requires network-wide information and is computationally hard to solve
  - Has not been applied to networks with hybrid beamforming

Outline

Hybrid Beamforming

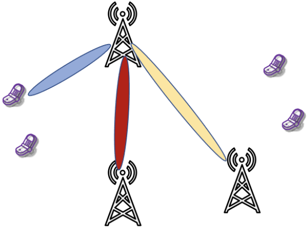
- Each Node has a limited number of RF Chains
- One beam per RF chain
- Point beam toward user or IAB node



5 RF chains, 5 beams

Scheduling Beams

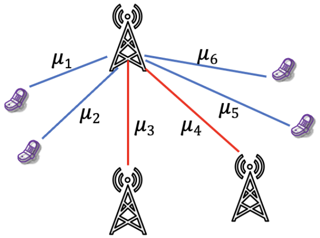
- Each timeslot, nodes need to choose links to schedule
- They choose between user links and backhaul links
- Node n has M_n beams



$M_n = 3$ Beams

Link Rates

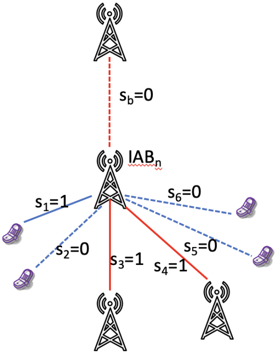
- μ_l = link rate in packets/slot
- For a backhaul link: $\mu_l \in \{0, \overline{\mu}\}$
- For a access link:
  - $\mu_l \in \{0, 1, 2, \ldots, \mu_{\max}\}$
  - fading determines link rate

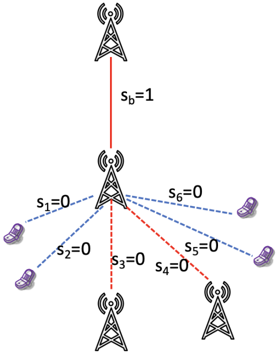


System Model

Scheduling Links

- One constraint is the RF chains constraint
- Another is the half duplex constraint





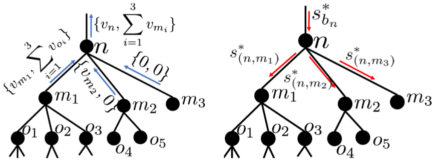
Either the parent backhaul link is active, or node n can schedule up to M_n downlink beams (*e.g.*$M_n = 3$ in network depicted).

Outline

Capacity and Backpressure:

- Characterize the capacity region for the IAB network
- Formulate back-pressure for the IAB network, show it achieves all rate vectors in capacity region
- Formulate a more general max-weight optimization problem for the IAB network
- Show max-weight optimization problem has almost linear complexity in size of network

- Using these results, we provide distributed forward-backward message passing implementation of backpressure



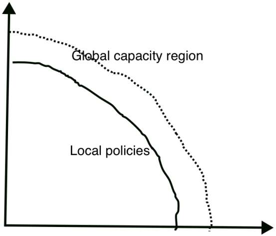
(a) Upstream message passing for weight computation

(b) Downstream message passing for schedule computation

Local Scheduling Algorithms:

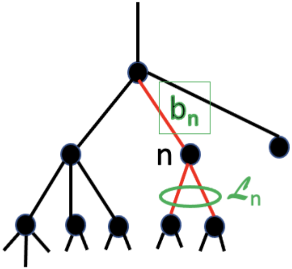
- What if each node has to make a decision based on the local link rate information?
- Single cell schedulers.
- Characterize stability region under local decisions (local stability region).

- The gap between the stability regions is proportional to σ_ℓ/μ_ℓ.
- There is no cost when link rates are deterministic (local region = global region).



We investigate the cost of local decisions

- Provide a local max-weight algorithm that achieves local stability region.
- If the link variation are small, local max-weight achieves most of the stability region.

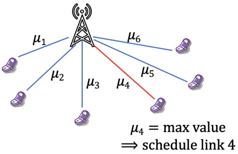


Node n makes a local scheduling decision

Compare global back-pressure, global max-weight, local max-weight, and local proportional-fair in mm-wave simulation (with random links)

Max sum-rate algorithm:

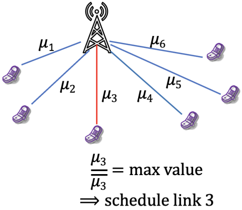
- Choose link with highest instantaneous rate
- Maximizes the long-term sum-rate



Max-rate Algorithm

Proportional-Fair algorithm:

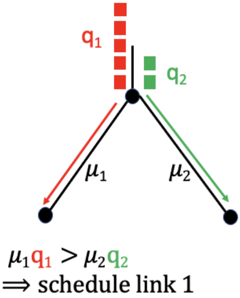
- Considers also the average rate of a link $\overline{\mu}$
- Choose link with highest rate relative to long-run rate
- Maximizes the Proportional-Fair objective function



Proportional Fair Algorithm

Max-weight algorithm:

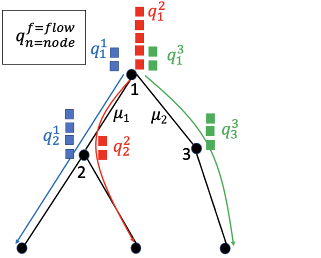
- Choose link with highest product $\mu \cdot q$ (the link weight)
- Algorithm actually chooses the *set* of feasible links with highest total weight
- Stabilizes a network with a single BS
- Doesn't stabilize a general network



Max-weight Algorithm

Back-pressure algorithm:

- Chooses flow f on link i with highest weight $\mu_i(q_n^f - q_{n+1}^f)$
- The weight is called the back-pressure across the link for this flow
- Algorithm actually chooses the *set* of feasible links with highest total backpressure
- Stabilizes a general network



$\mu_1(q_1^2\text{-}q_2^2) > \max\{\mu_1(q_1^1-q_2^1), \mu_2(q_1^3-q_3^3)\}$
$\Rightarrow$ schedule flow 2 on link 1

Back-pressure Algorithm

Outline

Find v_n, the maximum weight for the sub-tree with n at the top.

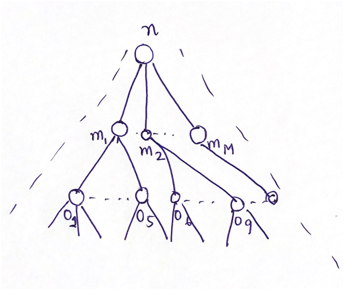
DP Maximum weight optimizaton:

$$v_n := \max_{S \subseteq C(n)} \sum_{m \in S} \left(w_{(n,m)} + \sum_{o \in C(m)} v_o \right) \dots$$

$$+ \sum_{m' \in C(n) - S} v_{m'} \qquad (1)$$

s.t.

$$|S| \leq M_n \qquad (2)$$



Sub-tree T_n with n as the top node

- A combinatorial optimization problem due to all the possible combinations of nodes for set S.
- We show there is a greedy solution to the optimization.

Received symbol can be obtained by sampling in the DD/Zak domain

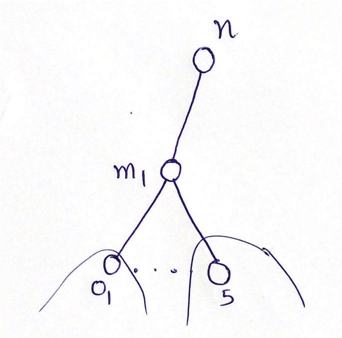
$$y[k,l] = \mathcal{Z}_y(l\frac{T}{M}, k\frac{\Delta f}{N}) \tag{3}$$

$$= \sqrt{T}\sum_{n=0}^{N} y(nT + \frac{lT}{M})e^{-j2\pi\frac{k}{N}} \tag{4}$$

since $y(t)$ is time-limited to $[0, NT)$, and by definition of Zak transform.
As can be seen DZT is equivalent to taking a DFT across the time-frame dimension n on the received signal samples.
Assuming integer channel and $k \geq k_p$ and $l \geq l_p$

$$y[k,l] = h_p' e^{j2\pi\frac{l\tau_p}{MN}} x[k-k_p, l-l_p] \tag{5}$$

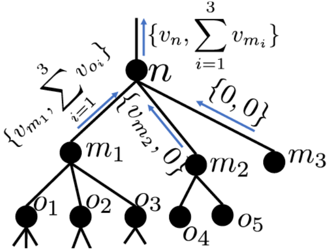
- If link (n, m_1) is not scheduled, then maximum weight for the graph in the figure is v_{m_1}.
- Suppose link (n, m_1) is scheduled, then maximum weight for graph in the figure is $w_{(n,m_1)} + \sum_{o \in C(m_1)} v_o$.
- Hence, scheduling (n, m_1) results in an increment in weight only if $w_{(n,m_1)} - v_{m_1} + \sum_{o \in C(m_1)} v_o$ is greater than 0.



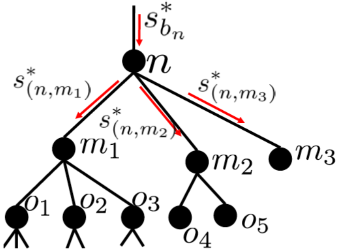
Situation with link (n, m_1)

The optimal solution for DP at n is to greedily pick M_n links with the highest positive increments.

Message passing algorithm to find maximum weighted schedule

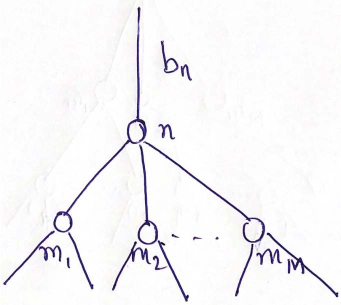


(a) Upstream message passing for weight computation



(b) Downstream message passing for schedule computation

- What if the network is too large and message passing incurs too much delay?
- If the backhaul link b_n is scheduled, no links can be scheduled at n due to the half-duplex constraint.
- Otherwise, a local scheduling algorithms picks links only according to the local information, i.e., link channel state, or queue sizes for links at n.

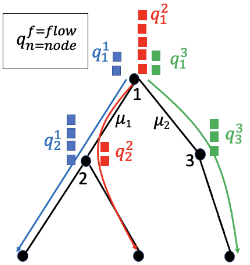


Situation with link (n, m_1)

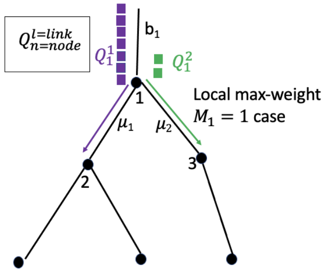
We will now present our Local Max-weight algorithm which is optimal among this class of policies.

Local Max-weight Algorithm

- Starts at the top (root), decisions propagate down (see figure on right below)
- Per link queueing (not per-flow)
- If backhaul link b_n is idle, node n can schedule up to M_n downlinks
- Use max-weight criterion $\max_{S \subset \mathcal{L}_n} \sum_{l \in S} Q_n^l \mu_l$ BUT need enough packets queued to fully utilize each chosen backhaul link

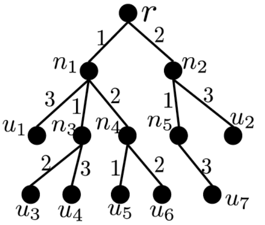


Back-pressure

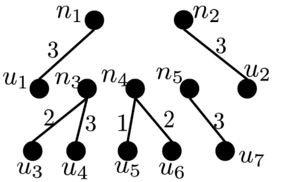


Schedule link 1 (of rate μ_1) provided:
b_1=0 and $\mu_1 Q_1^1 > \mu_2 Q_1^2$ and $Q_1^1 > \mu_1$

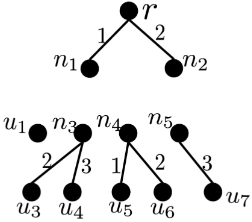
Local Max-weight Example



(a) Example network with weighted links



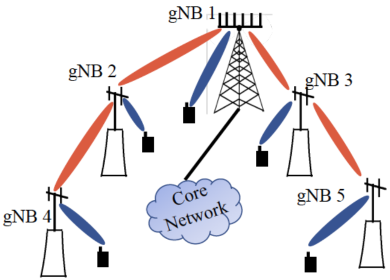
(b) Links scheduled under the traditional max-weight algorithm



(c) Links scheduled under the proposed local max-weight algorithm

mm-wave network simulation:

- gNBs 1-5 are IAB nodes
- gNB1 is root (donor) node
- Number of UEs is between 4 and 11, per IAB
- Backaul links between 330-440m
- UE links between 0-200m



Simulated Network

- UEs at gNBs 2 and 3 have a one-hop backhaul delay
- UEs at GNBs 4 and 5 have a two-hop backhaul delay

Simulation Parameters:

- Links go in and out of outage: Geometric distribution
- Backhaul links in outage with probability 0.01
- Access links in outage with probability 0.1

TABLE I
SIMULATION PARAMETERS

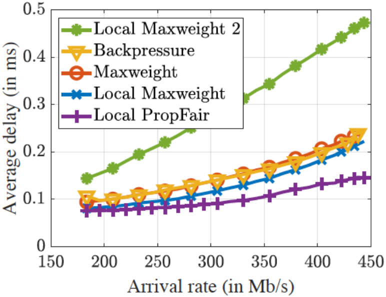
Paramter	Value
Carrier frequency	23 GHz
Bandwidth	1 GHz
Propagation model	3GPP Urban Micro
Slot duration	125 μs
Packet size	100 Kb
RF chains	4
Noise spectral density	-174 dBm/Hz
gNB transmit power	24 dBm per RF chain
Beamforming gain	30 dB (for access), 40 dB (for backhaul)
Noise figure	5 dB (for gNB), 7 dB (for UE)
Number of UEs at gNBs 1-5	10, 5, 9, 10, 8

- Fading on access links is Ricean: K=13dB (LoS), K=6dB (NLoS)
- Packets arrivals are *i.i.d.* Poisson, same mean for all UEs

- Local Maxweight 2
  - Like our proposed local algorithm, but without holding back on backhaul links
- Local Proportional Fair
  - Normal proportional fair, but only run if backhaul link is idle
- Back-pressure
  - Can be implemented with our forward-backward algorithm
- Maxweight
  - Not proven, but probably also stable for considered IAB network topology
- Local Maxweight - our proposed scheme
  - Like local maxweight 2, but backhaul links only scheduled when they are fully utilized

Average Delays for gNB 1 UEs

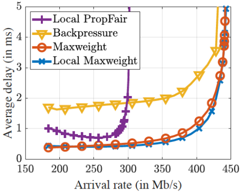
- Proportional-fair has lowest delays for UEs directly connected to root IAB node



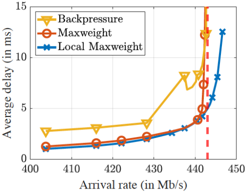
Average delays of UEs at the root gNB 1

Average Delays for gNB 2 or gNB 3 UES

- Local Maxweight 2 is unstable over rate range depicted so not depicted
- Local Proportional-fair is only stable up to 310 Mbps
- The red vertical line represents the capacity limit
- Local Maxweight can get more than this limit for users at this level



(a) Average end-to-end delay vs. arrival rate

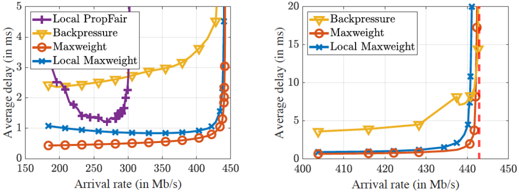


(b) Asymptotic behaviour at high arrival rates

Average end-to-end delays of users connected to gNBs 2 or 3

Average Delays for gNB 4 or gNB 5 UEs

- Local Maxweight has slightly less capacity than Backpressure (and Maxweight)

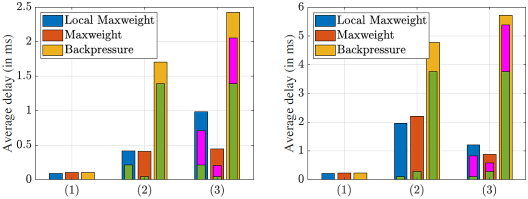


(a) Average end-to-end delay vs. arrival rate

(b) Asymptotic behaviour at high arrival rates

Average end-to-end delays of users connected to gNBs 4 or 5

- (1) are delays of UEs connected to root IAB node
- (2) are delays of UEs connected to gNBs 2 and 3
- (3) are delays of UEs connected to gNBs 4 and 5
- Green bar is delay of first hop
- Pink bar is delay of second hop



(a) For arrival rate of 214 Mb/s (b) For arrival rate of 428 Mb/s

- Reviewed some important results on scheduling in wireless networks
- Extended them to include constraints in mm-wave IAB networks
  - Showed backpressure has almost linear complexity
  - Forward-backward message passing implementation
  - Introduced a local max-weight algorithm
- Formulated notion of capacity for local algorithms: local capacity region
  - Showed local max-weight algorithm achieves local capacity region
  - Showed local capacity region = global capacity region for deterministic links
- Presented numerical results for mm-wave IAB network simulation
  - Backpressure not as good as max-weight for IAB networks
  - Local maxweight almost as good as global max-weight in terms of delays and achievable arrival rates

Future Wireless Communications Group

Future Wireless Communications Group
Macquarie University, Sydney, Australia

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Achievements

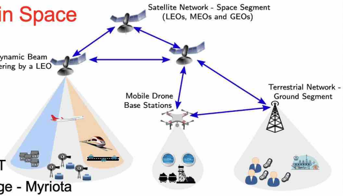
- 2 IEEE Fellows
- Top 100 in Telecommunications Engineering in the Shanghai Based Academic World Rankings 2018
- Best Paper Awards
- > $1M in currently funded projects

Research Areas

- Satellite Systems and Communications
- Remote sensing and IoT
- UAV Communications
- Next Gen Mobile Communications
- Mobile Network Performance
- Fog networks and edge computing
- Anomaly Detection
- Wireless Signals Analysis
- Position Location
- Distributed Cloud Services

Current Projects

HetNets in Space



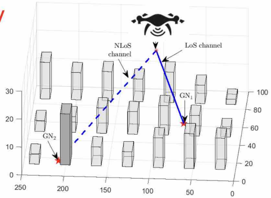
LEO network, SmartSat CRC

Remote IoT

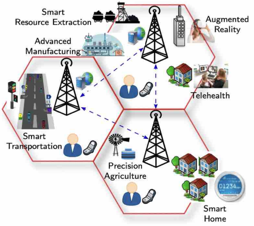
ARC Linkage - Myriota

Highways in the Sky

Airborne Base Station Communication Systems
- ARC Discovery Project

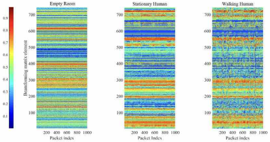


NextGen Mobile Networks



mm-wave wireless networks
- ARC Discovery Project

Machine Learning & Signal Processing



- Anomaly detection in Telstra's network

- Cybersecurity: human detection from WiFi signals -CSIRO/DSTG

PhD and Postdoc Opportunities

We have two research fellow positions available

Salary Package: Level A Step 6(PhD) from $97,621 to $104,622 (AUD) per annum, plus 17% employer's superannuation and annual leave loading.

Appointment Type: Full-time, fixed term for 2 years

Applications close: Thursday 13 April 2023

We also have PhD positions to be filled, please apply! Tuition scholarships plus stipends ($28,870 p/a AUD)

Contact: Stephen Hanly: stephen.hanly@mq.edu.au