Joint Flow Control and Resource Allocation in mm-Wave IAB Networks

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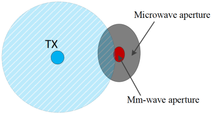
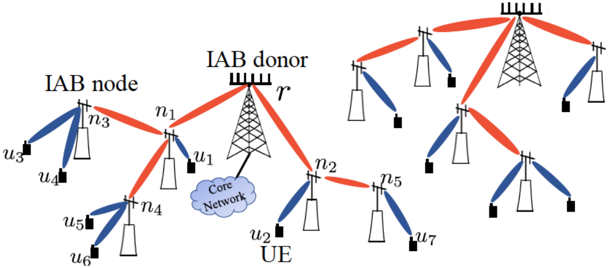
Outline

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

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

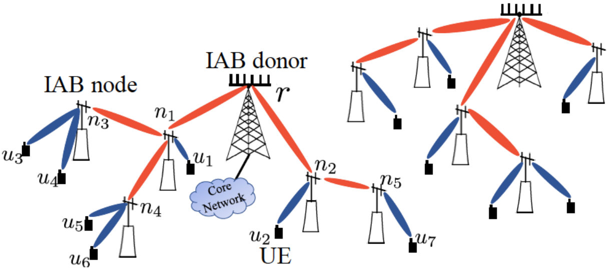


- Very small cells and beam-forming required.
- How to get traffic into small-cell BSs?



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

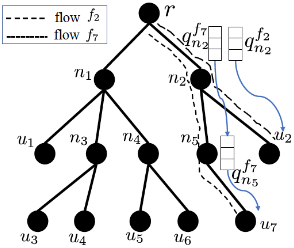


- How to prioritize backhaul links over UE links?
- How to control flow rates while scheduling links at different levels in the tree?
- How to distribute the required information through the tree?

Network Cross-layer Control: Jointly controlling flow rates and wireless link scheduling.

Flows and Flow Rates

- Each UE corresponds to a flow of packets
- Flow traffic rate at the root node is controlled by the network (could be different for each flow)



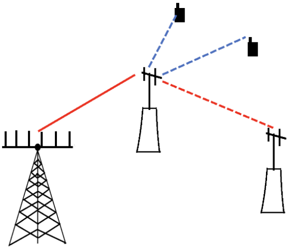
- Optimal Cross-layer Control : Network Utility Maximization subject to scheduling constraints.
  - Back-pressure algorithm for link scheduling.
  - Flow rate control using virtual queues.

- X. Lin and N. Shroff, “The impact of imperfect scheduling on cross- layer congestion control in wireless networks,” IEEE/ACM Transactions on Networking, vol. 14, no. 2, pp. 302–315, 2006.
- X. Lin, N. Shroff, and R. Srikant, “A tutorial on cross-layer optimization in wireless networks,” IEEE Journal on Selected Areas in Communica- tions, vol. 24, no. 8, pp. 1452–1463, 2006.
- A. Eryilmaz, A. Ozdaglar, D. Shah, and E. Modiano, “Distributed cross- layer algorithms for the optimal control of multihop wireless networks,” IEEE/ACM Transactions on Networking, vol. 18, no. 2, pp. 638–651, 2010.

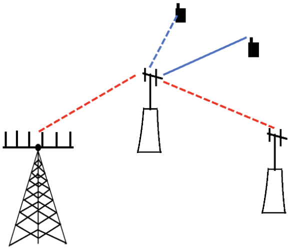
Outline

Link Scheduling Constraints

- One constraint is the half-duplex constraint
- Another is the single RF chain constraint



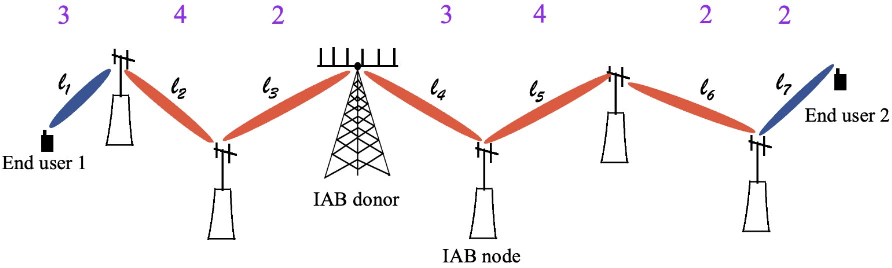
Half Duplex



Single RF chain

Either the parent backhaul link is active, or node n can schedule one downlink beam at a time, leading to *node-exclusive scheduling constraints*.

Link Scheduling Problem



Load τ_i = Bits over link/ Rate of link

Optimal Allocation

- An optimal allocation uses the minimum total slots to allocate all the links.

Optimal Allocation with 7 slots total

slot	1	2	3	4	5	6	7
ℓ_1	X	X	X				
ℓ_2				X	X	X	X
ℓ_3	X	X					
ℓ_4			X	X	X		
ℓ_5	X	X				X	X
ℓ_6			X	X			
ℓ_7	X	X					

A feasible allocation assigns slots to all the links without any conflicts.

Feasible Allocation.

slot	1	2	3	4	5	6	7	8	9
ℓ_1	X	X	X						
ℓ_2						X	X	X	X
ℓ_3				X	X				
ℓ_4	X	X	X						
ℓ_5					X	X	X	X	
ℓ_6			X	X					
ℓ_7	X	X							

The **Static Slot Reservation (SSR) algorithm** converges to an optimal allocation starting from an arbitrary feasible allocation.

Outline

- Initialization: Start with an arbitrary feasible allocation.

At time 1

slot	1	2	3	4	5	6	7	8	9
ℓ_1	X	X	X						
ℓ_2						X	X	X	X
ℓ_3				X	X				
ℓ_4	X	X	X						
ℓ_5					X	X	X	X	
ℓ_6			X	X					
ℓ_7	X	X							

- Slot booking/reservations of a link are updated in the last slot of the current block of booked slots, *e.g.* Booking of ℓ_7 will be updated now.

At time 2

slot	2	3	4	5	6	7	8	9	10
ℓ_1	X	X							
ℓ_2					X	X	X	X	
ℓ_3			X	X					
ℓ_4	X	X							
ℓ_5				X	X	X	X		
ℓ_6		X	X						
ℓ_7	X								

- Update Rule: At each update, each link books/reserves a new contiguous block of slots which do not overlap with its conflicting neighbors.

At time 3

slot	3	4	5	6	7	8	9	10	11
ℓ_1	X								
ℓ_2				X	X	X	X		
ℓ_3		X	X						
ℓ_4	X								
ℓ_5			X	X	X	X			
ℓ_6	X	X							
ℓ_7			X	X					

- This process is repeated.

At time 4

slot	4	5	6	7	8	9	10	11	12
ℓ_1							X	X	X
ℓ_2			X	X	X	X			
ℓ_3	X	X							
ℓ_4						X	X	X	
ℓ_5		X	X	X	X				
ℓ_6	X								
ℓ_7		X	X						

Initial Allocation.

slot	5	6	7	8	9	10	11	12	13
ℓ_1						X	X	X	
ℓ_2		X	X	X	X				
ℓ_3	X								
ℓ_4					X	X	X		
ℓ_5	X	X	X	X					
ℓ_6					X	X	X		
ℓ_7	X	X							

Initial Allocation.

slot	6	7	8	9	10	11	12	13	14
ℓ_1					X	X	X		
ℓ_2	X	X	X	X					
ℓ_3							X	X	
ℓ_4				X	X	X			
ℓ_5	X	X	X						
ℓ_6				X	X	X			
ℓ_7	X								

Allocation table showing all the allocated slots until $t = 15$.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	X	X	X							X	X	X			
2						X	X	X	X					X	X
3				X	X							X	X		
4	X	X	X						X	X	X				
5					X	X	X	X				X	X	X	X
6			X	X					X	X					
7	X	X			X	X	X	X			X	X	X	X	

Frame Title

Allocation table from $t = 4$ to $t = 17$.

	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1							X	X	X					
2			X	X	X	X					X	X	X	X
3	X	X							X	X				
4						X	X	X					X	X
5		X	X	X	X				X	X	X	X		
6	X					X	X						X	X
7		X	X	X	X			X	X	X	X			

Allocation table from $t = 4$ to $t = 17$.

	8	9	10	11	12	13	14	15	16	17	18	19	20
1			X	X	X						X	X	X
2	X	X					X	X	X	X			
3					X	X						X	X
4		X	X	X					X	X	X		
5	X				X	X	X	X				X	X
6		X	X						X	X			
7	X			X	X	X	X				X	X	X

Allocation table from $t = 4$ to $t = 17$.

	8	9	10	11	12	13	14	15	16	17	18	19	20
1			X	X	X						X	X	X
2	X	X					X	X	X	X			
3					X	X						X	X
4		X	X	X					X	X	X		
5	X				X	X	X	X				X	X
6		X	X						X	X			
7	X			X	X	X	X				X	X	X

Convergence of SSR algorithm

- The algorithm converges in linear time, at most $\sum_i \tau_i$ slots, to a steady state where allocations are optimal.

Allocation table from $t = 14$ to $t = 20$.

	13	14	15	16	17	18	19	20	21	22	23	24	τ_i
ℓ_1						X	X	X					3
ℓ_2		X	X	X	X				X	X	X	X	4
ℓ_3	X						X	X					2
ℓ_4				X	X	X					X	X	3
ℓ_5	X	X	X				X	X	X	X			4
ℓ_6				X	X						X	X	2
ℓ_7	X	X				X	X	X	X				2

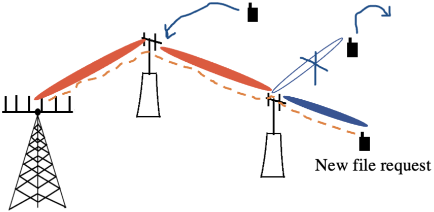
Optimal Allocation with 7 slots total

slot	1	2	3	4	5	6	7	$\rho_i = \tau_i/7$
ℓ_1	X	X	X					$3/7$
ℓ_2				X	X	X	X	$4/7$
ℓ_3	X	X						$2/7$
ℓ_4			X	X	X			$3/7$
ℓ_5	X	X				X	X	$4/7$
ℓ_6			X	X				$2/7$
ℓ_7	X	X						$2/7$

Flow rates under the SSR algorithm can be controlled by manipulating the loads τ_i's.

Outline

In a dynamic setup, there will be flow arrivals and departures. Hence, flow rate control is required.

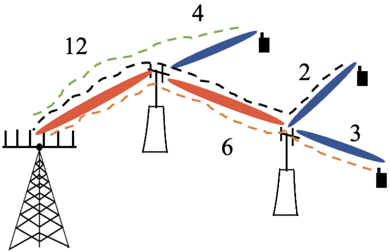


Dynamic Setup

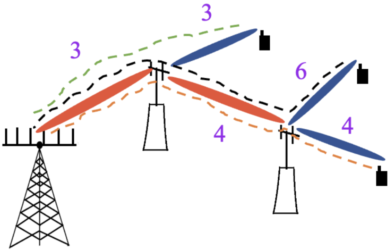
Dynamic Slot Reservation (DSR) Algorithm

- Scheduling: Use the slot reservation algorithm for scheduling links.
- Flow Control: Adapt the loads depending on the state of the network.

- In a given state, the load of a link is proportional to the number of flows over the link normalized w.r.t rate of the link.



Flows & Link Rates

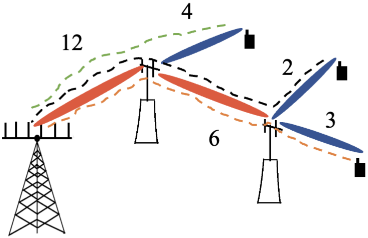


Load ∝ Flows over link / Rate of link

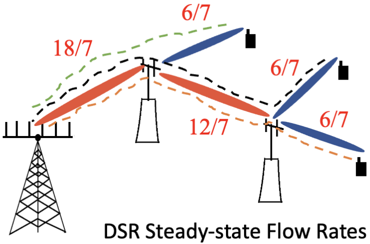
$$\tau_i = 12 \times \frac{\#\ flows}{rate}$$

DSR algorithm: Steady state flow rates

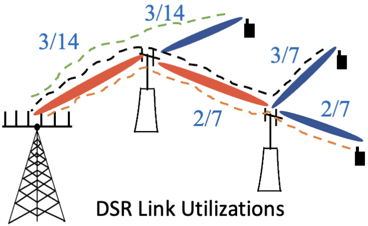
- A max-min steady state flow rate is guaranteed for each flow in the network, *e.g.* The flow rate $6/7$ is the max-min rate for this setup.



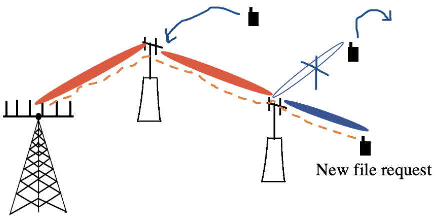
Flows & Link Rates



DSR Steady-state Flow Rates



DSR Link Utilizations



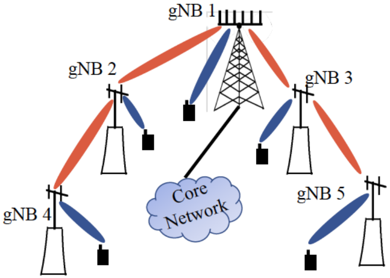
Dynamic Setup

- The stability region can be defined as set of the rate vector of flow arrivals that can be supported.
- The DSR algorithm achieves the stability region, same as the optimal cross-layer control algorithm using back-pressure algorithm.

Outline

mm-wave network simulation:

- gNBs 1-5 are IAB nodes
- gNB1 is root (donor) node
- Backaul link distances randomly chosen between 100-600m, have rates [13.2,8.9,11.8,12.6] Gbps.
- UE links between 0-300m



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:

- i.i.d Possion process of UE file requests (flows) with rate ν at each gNB.
- File sizes i.i.d exponential with mean 50 Mb.
- Access links in LoS state (K $=$ 13 dB) with probability 0.9, and NLoS state (K $=$ 6 dB) o.w.

TABLE I
SIMULATION PARAMETERS

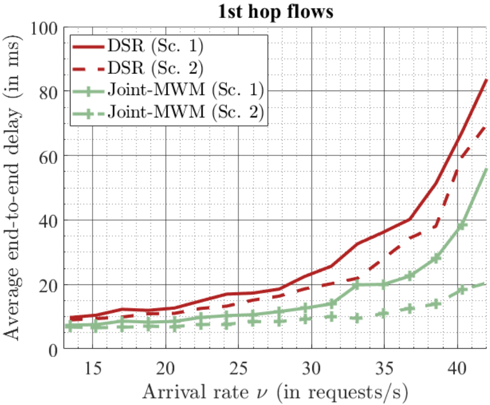
Parameter	Value
Carrier frequency	23 GHz
Bandwidth	1 GHz
Propagation model	3GPP Urban Micro
Slot duration	125 μs
Packet size	100 Kb
τ_s	200
Noise spectral density	-174 dBm/Hz
gNB transmit power	30 dBm
Beamforming gain	30 dB (for access), 40 dB (for backhaul)
Noise figure	5 dB (for gNB), 7 dB (for UE)

- In Scenario 1, the access link rates are fixed.
- In Scenario 2, the link access rates are modelled as a Gilbert-Elliot process between LoS and NLoS sates.

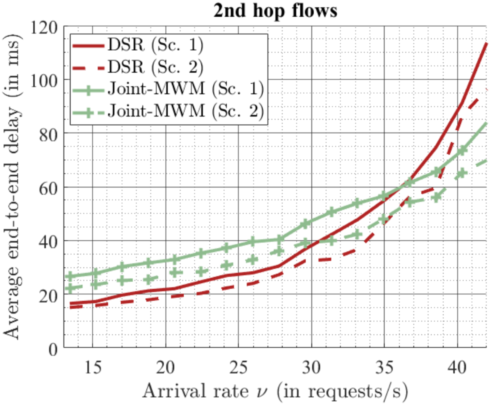
Considered Schemes

- Joint-MWM algorithm
  - Optimal Cross-layer control algorithm solves proportional fair utility maximization for flow rates and uses back-pressure scheduling algorithm in each slot.
- DSR algorithm
  - Our proposed slot reservation algorithm.

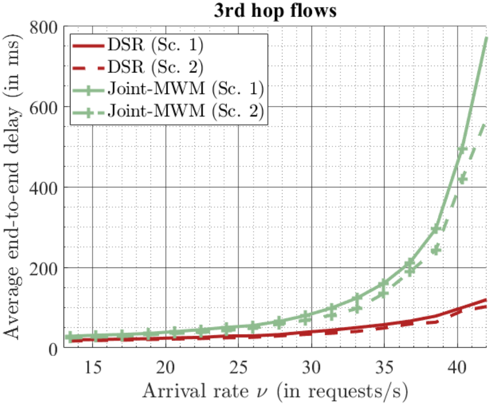
Average Delays for gNB 1 UEs

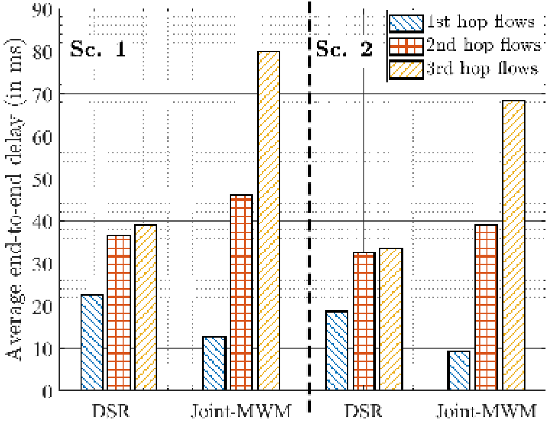


Average Delays for 2nd hop UEs



Average Delays for 3rd hop UEs




Average end-to-end delay (in ms)
0
10
20
30
40
50
60
70
80
90
Sc. 1
Sc. 2
1st hop flows
2nd hop flows
3rd hop flows
DSR
Joint-MWM
DSR
Joint-MWM

- This talk is about this paper but doesn't cover everything in it

S. Gopalam, S.V. Hanly, P. Whiting, "Distributed Resource Allocation and Flow Control Algorithms for mmWave IAB Networks" IEEE/ACM Transactions on Networking, 2023 (IEEE Early Access).