CONFIG SHEET

L = 1Mb

Delay v Pavg plot

30 GHz

$N_c = 4$ channels

1 req every minute

B = 10 MHz

$B_k = 2.5$ MHz, $\forall k \in \{1,2,3,4\}$

Pavg 1000W ⟶ 2000W

1200 | 1400 | 1600 | 1800

6 MAESTRO Runs:
- 1000
- 1200
- 1400
- 1600
- 1800
- 2000

~~30 GHz~~, 1Mb, 4 channels, 1 req / min, 2.5 MHz per channel

use MAESTRO policy and scale to 2, 3, 5 UAVs with piggybacking & freq reuse

L = 100 Mb

Delay v Pavg plot

30 GHz

$N_c = 4$ channels

1 req every 30 mins

B = 10 MHz

$B_k = 2.5$ MHz, $\forall k \in \{1,2,3,4\}$

Pavg 1000 W ⟶ 2000 W

1200 | 1400 | 1600 | 1800

6 MAESTRO runs:
- 1000
- 1200
- 1400
- 1600
- 1800
- 2000

30 GHz, 100Mb, 4 channels, 1 req every 30 mins, 2.5 MHz per channel

use MAESTRO policy and scale to 2, 3, 5, and 10 UAVs with piggybacking & freq reuse

SGA
- SCA 1,2,3
- DDQN-PER 1,2,3
- ~~BS only~~
- ~~static~~ CUAV 1,2,3,5,10
- CSCA-DDMM 1,2,3
- CIRCLE 1,2,3
- DDPG 1,2,3

Spectral efficiency = what avg percentage of the 10MHz spectrum is being used throughout a simulation for 3 UAVs, 1BS with ~~PB~~ FR

30 GHz, 10,000 requests

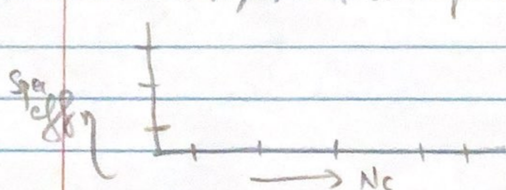
for each policy for NC ⟵ 5 MAESTRO runs:
- $N_c = 1$
- $N_c = 2$
- $N_c = 4$
- $N_c = 8$
- $N_c = 10$

L = 10 Mb

1 req every 5 mins

30 GHz, 1BS, 1UAV

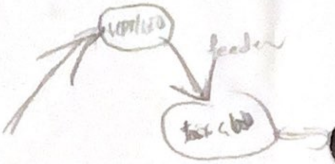
Pavg = 1.2 kW



Use VI V values of $N_c=2$ to train $N_c = 4$, $N_c = 8$, $N_c = 10$

what time boost?

tgpt v distance
- HAP (with feeder)
- LEO (with feeder)
- BS-only
- decode (static UAV)
- forward (static UAV)
- decode + forward (static UAV)



$L = 10\,Mb$
$B_k = 2.5\,MHz$

delay v distance
- BS-only
- decode (static UAV)
- forward (static UAV)
- decode + forward (static UAV)
- LEO (with feeder)
- HAP (with feeder)

waiting policy visualization
$L = 100\,Mb$
1 req per 30 mins
$BW = 10\,MHz$
$N_c = 4$ channels
$P_{avg} = 1.2\,kW$
$B_k = 2.5\,MHz$
1 UAV
1 BS
30 GNs

traj visualization
$L = 100\,Mb$
1 req every 30 mins
$BW = 10\,MHz$
$N_c = 4$ chanel
$B_k = 2.5\,MHz$
$P_{avg} = 1.2\,kW$
1 UAV
1 BS
30 GNs

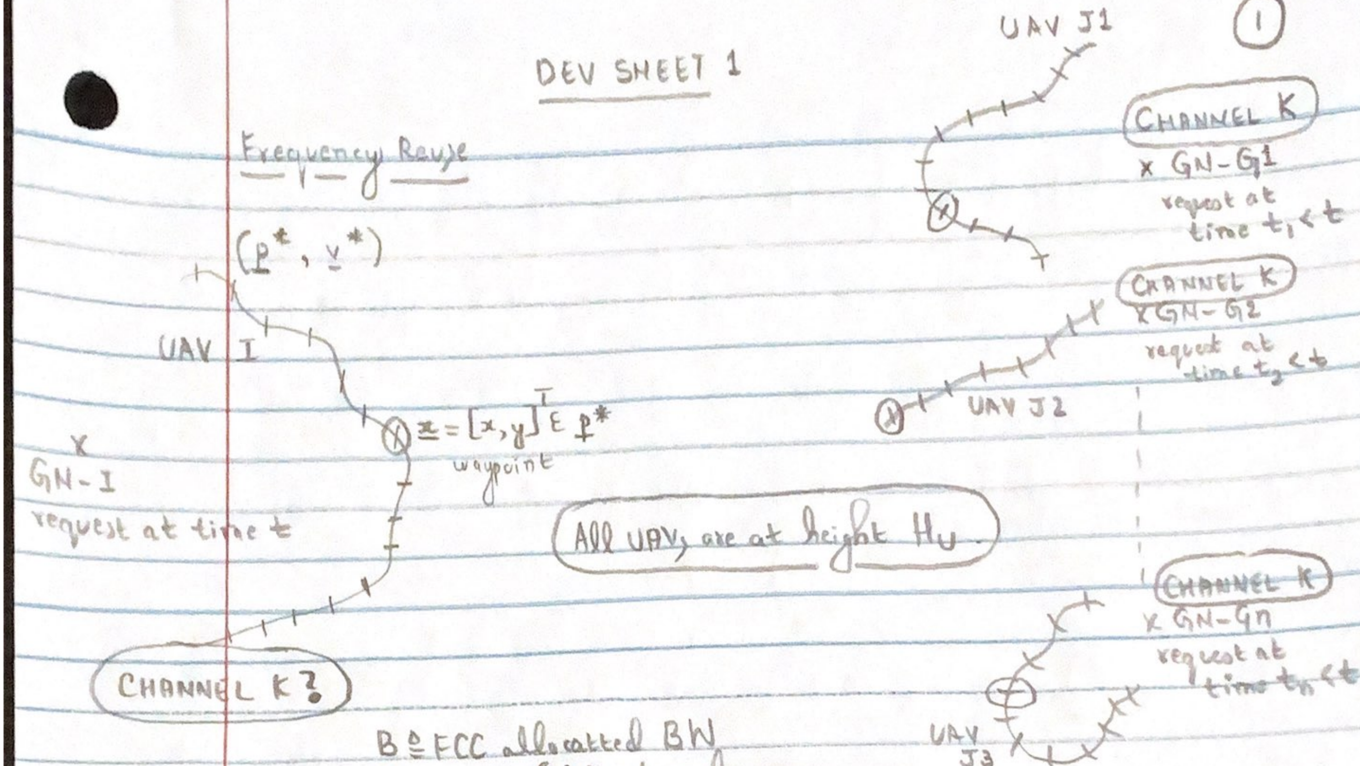
Convergence v Time
- CSO
- HCSO
- SCA
- LCSO ? (maybe)
- PSO

sanitize AERPAW simulations

policy convergence v N_U
- SCA
- CSCA-ADMM
- MAES TAO-X
- DDPG
- PDQN-PER

DEV SHEET 1

Frequency Reuse



$B \triangleq$ FCC allocated BW

$N_c \triangleq$ number of data channels

$$\underset{\text{set of data channels}}{\mathcal{K}} \triangleq \left\{ k \in \{1, 2, \ldots, N_c\} \mid N_c \in \mathbb{Z}, \; B_k \triangleq \text{BW of channel } k = \frac{B}{N_c} \right\}.$$

DECODE ONLY

$$\underset{\substack{\text{potential non-orthogonal}\\ \text{data channel choices for}\\ \text{UAV } i}}{\mathcal{K}'} \triangleq \left\{ k \in \mathcal{K} \mid \text{SINR}_{\min|i,k} > \underbrace{\text{SINR}_{th}}_{\text{preset SINR tolerance threshold}} \right\},$$

FORWARD always uses orthogonal channels

$\mathcal{U}_k$

set of UAVs using the potential non-orthogonal data channel $k \in \mathcal{K}$.

$$\mathcal{U}_k \triangleq \left\{ U_i \mid i \in \{1, 2, \ldots, N_U\}, \underbrace{DCh(U_i)}_{\substack{\text{function that maps UAV index } i\\ \text{to the data channel being}\\ \text{used by } U_i \text{ for DECODE}}} = k \right\}$$

(1) At point $\underline{x} = [x, y]^T \in p^*$ in UAV U_i's trajectory to serve GN-I, let $d_{GU|i}$ be the distance to the GN-I, let $\phi_{GU|i}$ be the elevation angle between the UAV and GN-I, and let $d_{min|ij_n,k}$ be the distance between UAV U_i and the closest point in UAV U_{j_n}'s remaining service trajectory.

(2) The interference analysis on data channel k assumes purely LoS links between UAV U_i and UAV $U_{j_n} \in \mathcal{U}_k$.

WORST-CASE Expected SINR at $\underline{x}$ for UAV U_i on channel k

$$\triangleq \mathrm{SINR}^{\underline{x}}_{min|i,k} = \mathbb{E}\left[\frac{|h_{GU|i,k}|^2 P_{Tx}}{N_0 B_k \Gamma + \sum_{j \in \mathcal{U}_k} |h_{ij,k}|^2 P_{Tx}}\right]$$

$$= \mathbb{E}\left[\frac{\left(\beta_0 d_{GU|i}^{-\alpha} P_{LoS} + \kappa \beta_0 d_{GU|i}^{-\tilde{\alpha}} P_{NLoS}\right) |g_{GU|i,k}|^2 P_{Tx}}{N_0 B_k \Gamma + P_{Tx} \beta_0 \sum_{j \in \mathcal{U}_k} d_{min|ij}^{-\alpha} |g_{ij,k}|^2}\right],$$

where $P_{LoS} \triangleq \dfrac{1}{1 + z_1 \exp\left(-z_2\left[\phi_{GU|i} - z_1\right]\right)}$ and $P_{NLoS} \triangleq 1 - P_{LoS}$,

with $\mathbb{E}\left[|g_{GU|i,k}|^2\right] = 1$ and $2(K+1)|g|^2 \sim \chi^2_{\underset{\text{degrees of freedom}}{2}}\left(\underbrace{2K}_{\text{non-centrality parameter}}\right)$.

$$\mathrm{SINR}^{\underline{x}}_{min|i,k} = P_{Tx}\left(\beta_0 d_{GU|i}^{-\alpha} P_{LoS} + \kappa \beta_0 d_{GU|i}^{-\tilde{\alpha}} P_{NLoS}\right) \cdot \mathbb{E}\left[Z\right],$$

where $Z \triangleq \dfrac{1}{N_0 B_k \Gamma + P_{Tx} \beta_0 \underbrace{\sum_{j \in \mathcal{U}_k} Y_j}_{Y}} = \dfrac{1}{N_0 B_k \Gamma + P_{Tx} \beta_0 Y}.$

$$Y_j \triangleq d_{min|ij,k}^{-\alpha} |g_{ij,k}|^2 .$$

$$F_{Y_j}(y_j) = \mathbb{P}\left(Y_j \leq y_j \right) = \mathbb{P}\left(d_{min|ij}^{-\alpha} |g_{ij,k}|^2 \leq y_j \right)$$

$$= \mathbb{P}\left(2(K_{ij}+1)|g_{ij,k}|^2 \leq \frac{2(K_{ij}+1)y_j}{d_{min|ij}^{-\alpha}} \right)$$

$$= 1 - Q_1\left(\sqrt{2K_{ij}} , \sqrt{\frac{2(K_{ij}+1)y_j}{d_{min|ij}^{-\alpha}}} \right),$$

where $K_{ij} = k_1 \exp\left(k_2 \underbrace{\phi_{ij}}_{=0} \right) = k_1$.

$$\therefore \boxed{F_{Y_j}(y_j) = 1 - Q_1\left(\sqrt{2k_1} , \sqrt{2(k_1+1) d_{min|ij}^{+\alpha} y_j} \right)}.$$

$$Y \triangleq \sum_{j \in \mathcal{U}_k} Y_j .$$

$$F_Y(y) = \mathbb{P}\left(Y \leq y \right) = \mathbb{P}\left(\sum_{j \in \mathcal{U}_k} Y_j \leq y \right)$$

recursion in python

$$= \Big(\underbrace{F_{Y_{j_1}}}_{1-Q_1\left(\sqrt{2k_1},\, \sqrt{2(k_1+1)d_{min|ij_1}^{+\alpha}}\right)} \underbrace{* f_{Y_{j_2}} * f_{Y_{j_3}} * \cdots}_{(j-1) \text{ times}} \Big)(y)$$

$$F_Z(z) = \mathbb{P}(Z \leq z)$$

$$= \mathbb{P}\left(\frac{1}{N_0 B_k \Gamma + P_{Tx}\beta_0 Y} \leq z\right)$$

$$= \mathbb{P}\left(N_0 B_k \Gamma + P_{Tx}\beta_0 Y \geq \frac{1}{z}\right)$$

$$= \mathbb{P}\left(Y \geq \frac{1}{\beta_0 P_{Tx} z} - \frac{N_0 B_k \Gamma}{\beta_0 P_{Tx}}\right)$$

$$= 1 - F_Y\left(\frac{1}{\beta_0 P_{Tx} z} - \frac{N_0 B_k \Gamma}{\beta_0 P_{Tx}}\right)$$

$$\therefore \mathbb{E}[Z] = \int_0^\infty \left(1 - F_Z(z)\right) dz$$

$$= \int_0^\infty F_Y \underbrace{\left(\frac{1}{\beta_0 P_{Tx} z} - \frac{N_0 B_k \Gamma}{\beta_0 P_{Tx}}\right)}_{fn(z)} dz$$

found numerically in python

$$\therefore \mathrm{SINR}^{\underline{x}}_{min|i,k} = P_{Tx}\left(\beta_0 d_{GU|i}^{-\alpha} P_{LoS} + x\beta_0 d_{GU|i}^{-\tilde{\alpha}} P_{NLoS}\right) \cdot \int_0^\infty F_Y\left(fn(z)\right) dz,$$

with $fn(z) \triangleq \dfrac{1}{\beta_0 P_{Tx} z} - \dfrac{N_0 B_k \Gamma}{\beta_0 P_{Tx}}$ and

found recursively in python

$$F_Y\left(fn(z)\right) = \left(F_{Y_{j1}} * f_{Y_{j2}} * f_{Y_{j3}} * \dots * f_{Y_{j|u_k|}}\right)\left(fn(z)\right),$$

where $F_{Y_{j1}}(y_{j1}) = 1 - Q_1\left(\sqrt{2k_1}, \sqrt{2(k_1+1) d^{+\alpha}_{min|i,j1} y_{j1}}\right)$.

$\mathrm{SINR}_{min|i,k} \triangleq \min\left\{\mathrm{SINR}^{\underline{x}}_{min|i,k}, \forall \underline{x} \in \underline{p}^*\right\}$ and $k_{u_i} \triangleq \operatorname{argmax}\left\{\mathrm{SINR}_{min|i,k} : k \in \mathcal{X}'\right\}$.

$L = 1\,Mb, 100\,Mb$
$N_c = 1, 2, 4, 8, 10$

DEV SHEET 2

1 UAV $P_{avg} = P\,W$ $N_c = Y$ channels
$L = X\,Mb$ MAESTRO $B_k = Z\,Hz$
30 GNs
parameterize L, N_c, B_k, P_{avg}
(X, Y, Z, P)

1

Control Frame Design & Broadcast

CONTROL FRAME

number of UAV (excluding BS) = 2

- seq_num
- src_node_id (BS = 0 ; $UAV_i = 1, 2, \ldots, N_U$)
- timestamp (NTP synchronized)
- state flag (wait (0), comm (1), soft-fault (-1))
  - for BS: no new seq (0), new seq (-1), soft-fault (-1)
- curr pos GPSEvent (lat (y), long (x), alt (h_U), speed) — current position & speed
- remaining traj [GPSEvent ( ) for (p, v) in $\underline{p}^*, \underline{v}^*$]
- channel used decode ($k_1 \in \mathcal{K}$)
- channel used forward ($k_2 \in \mathcal{K}$)
- GN position GPSEvent (lat (y), lon (x), alt (0))
- cost of service (Lagrangian = ; decode-wait = ; forward-wait = ; total =)
- GNs being served ( )
- piggyback : (ControlFrame ( ) for any GN piggybacked)

piggybacking multiple? after timing primary)

move the piggybacker FIFO to primary!

BS — number of BS tx/rx channels = 10 — SINGLETON

P_{avg}, N_c, Λ

policy lookup table $\{ \underline{s} : (a, \text{Lagrangian}) \}$ comm states

control_frame_parser ( ) → swarm + env state

control_frame_constructor ( ) ← my state

BS current operational state

perf_metrics_logger ( )

for every GN served: time_start, time_end, serv time, wait time, [id : Lag for all], [id : dec for all], [id : fwd wait for all]

UAV U_i — N_U instances

policy lookup table $\{ \underline{s} : a \}$ wait states

policy lookup table $\{ \underline{s} : (a, \text{Lagrangian}) \}$ comm states

P_{avg} N_c Λ

control_frame_parser ( ) → swarm + BS + env states

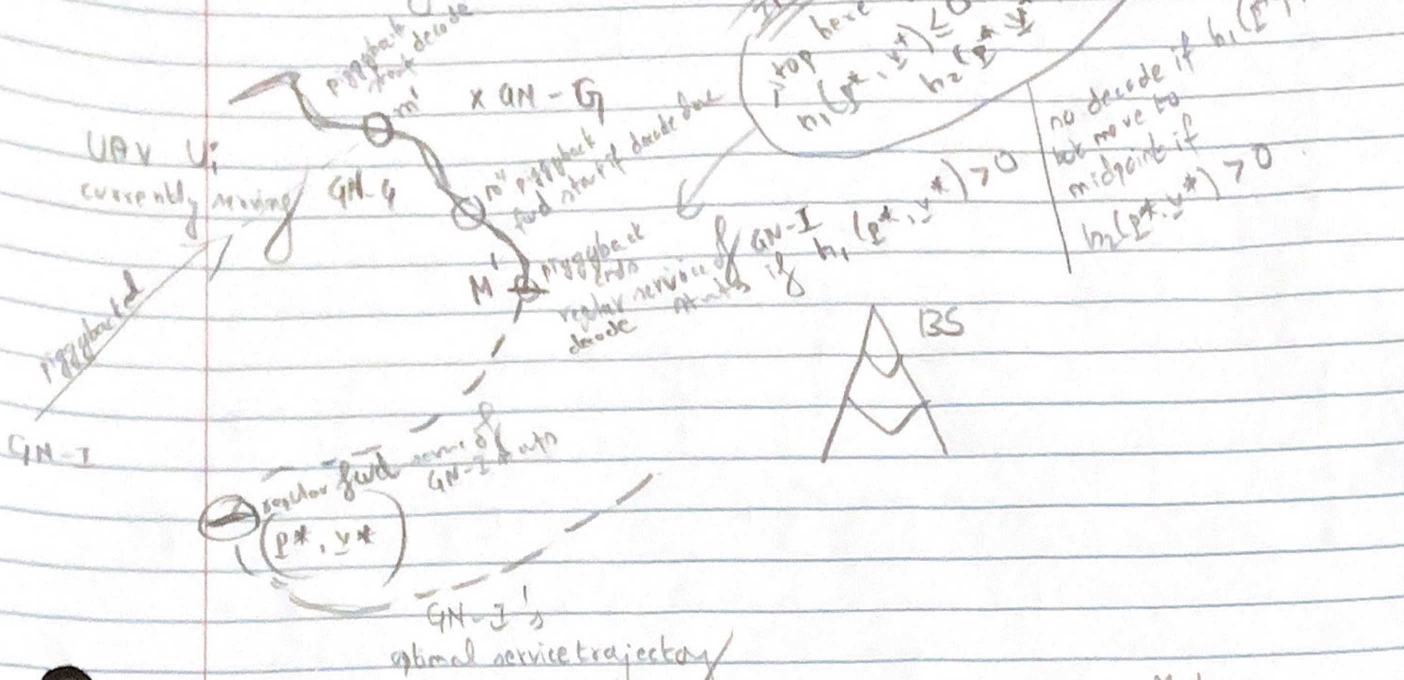
control_frame_constructor ( ) ← my state — UAV U_i current op states

perf_metrics_logger ( )

for every GN served: time_start, time_end, serv time, [id : Lag for all GS] [id : decode wait for all], fwd wait

DEV SHEET 3

Piggybacking



cost shared

$$\text{Lagrangian} \triangleq \hat{f}(p^*, \underline{v}^*) = (1-\partial P_{avg}) \sum_{m=0}^{M-1} \frac{\|v_m\|_2}{V_m} + \partial \sum_{m=0} \frac{\|v_m\|_2 P_{mob}(V_m)}{V_m}$$

$$+ \; (1-\partial P_{avg})\left(\hat{t}_{p,1} + \hat{t}_{p,2}\right) + \partial\left(\hat{E}_{p,1} + \hat{E}_{p,2}\right),$$

where

$$t_{p,1} \triangleq \frac{h_1(p^*, \underline{v}^*)\, \mathcal{I}\left(h_1(p^*, \underline{v}^*) > 0\right)}{\bar{R}_{GU}\left(\|\underline{x}_{\frac{M}{2}} - \underline{x}_G\|_2\right)};$$

$$\hat{t}_{p,2} \triangleq \frac{h_2(p^*, \underline{v}^*)\, \mathcal{I}\left(h_2(p^*, \underline{v}^*) > 0\right)}{\bar{R}_{UB}\left(\|\underline{x}_M\|_2\right)};$$

if decode complete $\rightarrow$ $L'' \triangleq \sum_{m=m''}^{M} F_m$

$$L' \triangleq \underbrace{\sum_{m=m'}^{M} F_m}_{\sum_{k=0}^{m'-1} t_k R_{GN_I U_i, k}}$$

$$\hat{E}_{p,1} \triangleq P_{mob}(v_{p_{min}})\, \hat{t}_{p,1}; \quad \hat{E}_{p,2} \triangleq P_{mob}(v_{p_{min}})\, \hat{t}_{p,2}, \text{ where}$$

$$h_1(p^*, \underline{v}^*) \triangleq L - \underbrace{L'}_{\text{expected decode payload while serving GN-G}} - \sum_{m=0}^{\frac{M}{2}-1} F_m; \quad h_2(p^*, \underline{v}^*) \triangleq L - \underbrace{L''}_{\text{expected fwd payload while serving GN-G}} - \sum_{m=\frac{M}{2}}^{M} F_m$$

IFQ

N_c queue

freq sense block

new GM request from GM-I

UAV U_i already serving GM-G on channel k (currently at $\underline{x}_M$)

What is UAV U_i's lagrangian to serve GM-I with piggybacking?

$\hat{f}(p^*, \underline{v}^*)$

If decode channel available → Assuming U_i starts piggyback decode at $\underline{x}_{M+1}$,

find L'. If $L' > L$, find $\underline{x}_{M'}$ where L is decoded fully.

If forward channel available → Then, find L'', 0 if $L' \leq L$

If $L' > L$ and $L'' > L$, excellent!

If decode channel available after t',

find L' assuming where U_i is going to be after t'

If $L' > L$, If forward channel avail. after t'',

find L'' using where U_i is going to be after t''.

share $\hat{f}(p^*, \underline{v}^*) + t' + t''$.

DEV SHEET 4

Conflict Resolution

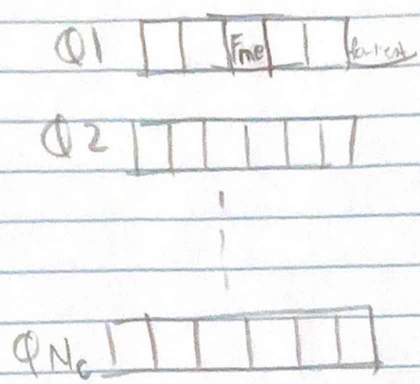
When a request arises in the cell from GN I at (r, θ):

At the BS: $\dfrac{L}{\bar{R}_{GB}(r)} + \underbrace{t_{Q}|_{BS}}$

time wait to get a channel assigned

M|G|N_c modeling

No REUSE ALLOWED



Join-Fastest-Queue

JFQ heuristic

which queue is the fastest? give me that wait time.

At an available UAV: without piggybacking

$$\hat{f}(p^*, v_i^*) + \underbrace{t'_{Q}|_{U_i}} + \underbrace{t''_{Q}|_{U_i}}$$

time to get a channel assigned for decode

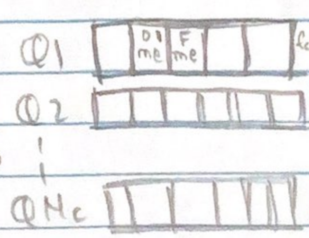
time to get a channel assigned for forward

Decode Freq reuse available?

YES? $t'_{Q}|_{U_i}$

No?

$t''_{Q}|_{U_i} = 0$



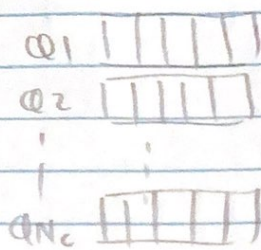
JFQ

current queue states

add my Fme to the fastest queue

once a F_{me} req is being served by a queue, it's not used for freq reuse

No FREQ REUSE ALLOWED FOR FORWARD



$t''_{Q}|_{U_i}$ is how much time do I have to wait for the queue in which Fme is to become FULLY available?

D_{U2}

D_{U1}

1

x

Freq reune
consider the req in front of me

U1 & U2 considered (?)

D_{BS}

Q1 | D^0_{U1} | D^0_{U2} | D^1_{U3} | | |

U2 & U3 can be considered together

Q2 | | | | | |

QN | | | | | |

D^0_{U1} (D^1_{U2} D^1_{U3})

D_{U1} ← (1) D_{U2}

If the guy in front of me has a 0, then consider only him!

If the guy in front of me has a 1, then consider every one ahead of me containing 1,

considered

$\boxed{D^0_{U1}}$ $D^?_{U3}$

considered

D^0_{U1} D^1_{U2} $\boxed{D^0_{U4}}$ $D^?_{U3}$

$\boxed{D^0_{U0}\ \ D^1_{U1}\ \ D^1_{U2}}$ $D^?_{U3}$

0 .. 1 1 1 1 1 1

1 $\boxed{0\,1\,1}$

For every channel, find $t^1_Q|_{Ui,k}$ pick the smallest

forward = 0

Q1 | D^0_{BS} | D^1_{U1} | D^1_{U2} | D^0_{U3} | F^0_{U3} |

x + max (of these three) time = ?

arg min

once chosen, flush!

Q2 | D^0_{BS} | D^1_{U1} | D^1_{U2} | D^1_{U3} | F^0_{U3} |

x

= $\cancel{x}$ time = ?

take a copy of state

analyze

then apply to global

Q3 | D^0_{BS} | D^0_{U1} | D^1_{U2} | D^1_{U3} | F^0_{U3} |

x

x + D_{BS}

time = ?

0 1 1 1

find_time(queue) : 0, 1, 1, 1, $\boxed{0}$

x + max

x 0, 1, 1, 1, $\boxed{1}$ $\cancel{x}$

x 1, 1, 1, $\boxed{1}$ = 0

x 0, 0, 1, 1 = x + D_{BS}