GLOBAL

$N_c \triangleq$ number of channels
$B_k \triangleq$ BW of channel $k = \frac{B}{N_c}$; $B \triangleq$ total FCC-allocated BW

BS $N_{X|BS} \triangleq$ number of transceivers available at the BS
$\triangleq$ number of GNs that can be simultaneously served by the BS

A request arises from GN G_j at (r, θ):

1. When a transceiver is available:

(a) SERVICE_TIME = LAGRANGIAN $= \frac{L}{\bar{R}_{GB}(r)}$.

↓

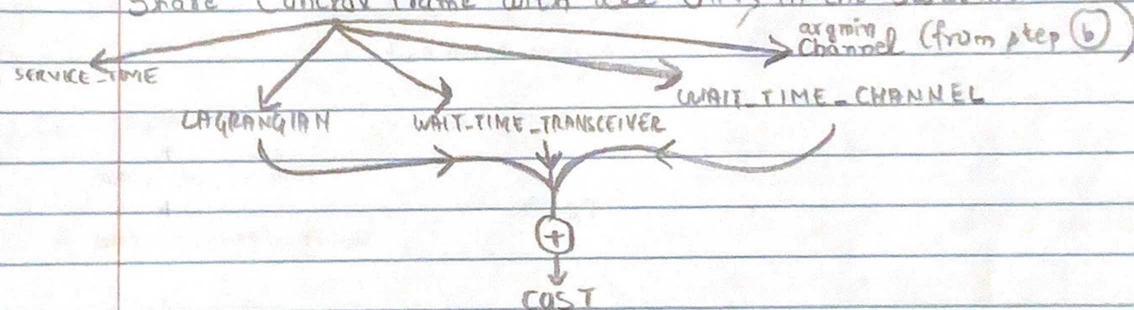
(b) WAIT_TIME_CHANNEL $= \min_{k \in \{1,2,\ldots,N_c\}}$ find_wait_time_channel (current queue state of channel k).

↓

(c) WAIT_TIME_TRANSCEIVER = 0.

↓

Share Control Frame with all UAVs in the swarm.



2. When a transceiver is not available:

(a) SERVICE_TIME = LAGRANGIAN $= \frac{L}{\bar{R}_{GB}(r)}$.

↓

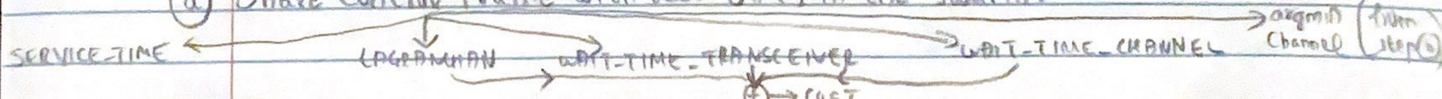
(b) WAIT_TIME_CHANNEL $= \min_{k \in \{1,2,\ldots,N_c\}}$ find_wait_time_channel (current queue state of channel k).

↓

(c) WAIT_TIME_TRANSCEIVER $= \min_{x \in \{1,2,\ldots,N_{X|BS}\}}$ find_wait_time_transceiver (estimated queue state of Transceiver x after WAIT_TIME_CHANNEL)

↓

(d) Share Control Frame with all UAVs in the swarm.



$N_c \triangleq$ number of channels

$B_k \triangleq$ BW of channel $k = \frac{B}{N_c}$; $B \triangleq$ total FCC-allocated BW GLOBAL

UAV $N_{x|UAV} \triangleq$ number of transceivers available at the UAV

$\triangleq$ number of GNs that can be served simultaneously by this UAV

A request arises from GN G at (r, θ):

1) UAV is 'available' (not serving any other GN) and obviously 'capable' (Transceiver available)

Optimal trajectory $= (\underline{p}^*, \underline{v}^*)$, where $\underline{p}^* = \{\underline{x}_m\}_{m=0}^{M} = \{(x_m, y_m)\}_{m=0}^{M}$,

and $\underline{v}^* = \{v_m\}_{m=0}^{M}$.

obtained from single-agent MAESTRO policy

a) $$\text{SERVICE\_TIME} = \sum_{m=0}^{M-1} \frac{\|\Psi_m\|_2}{v_m} + \hat{t}_{p,1} + \hat{t}_{p,2},$$

where $\Psi_m \triangleq \underline{x}_{m+1} - \underline{x}_m$;

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

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

$$h_1(\underline{p}^*, \underline{v}^*) \triangleq L - \sum_{m=0}^{\frac{M}{2}-1} F_m;$$ and

number of bits communicated for the m^{th}-segment

$$h_2(\underline{p}^*, \underline{v}^*) \triangleq L - \sum_{m=\frac{M}{2}}^{M-1} F_m.$$

number of bits communicated for the m^{th}-segment

(b) LAGRANGIAN $= \hat{f}(\underline{p}^*, \underline{v}^*) \triangleq (1-\vartheta)P_{avg} \sum_{m=0}^{M-1} \frac{\|\psi_m\|_2}{v_m}$

$$+ \vartheta \sum_{m=0}^{M-1} \frac{\|\psi_m\|_2 \, P_{mob}(v_m)}{v_m}$$

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

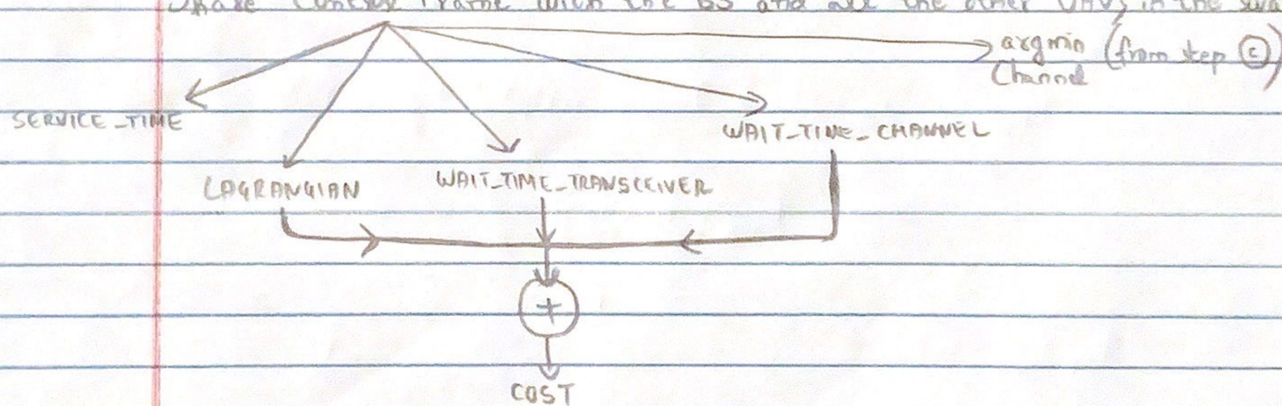
$$+ \vartheta\left(\hat{E}_{p,1} + \hat{E}_{p,2}\right),$$ where

$\hat{E}_{p,1} \triangleq P_{mob}(v_{p_{min}})\hat{t}_{p,1}$ and $\hat{E}_{p,2} \triangleq P_{mob}(v_{p_{min}})\hat{t}_{p,2}$.

(c) WAIT_TIME_CHANNEL $= \min_{k \in \{1,2,\ldots,N_c\}}$ find-wait-time-channel (current queue state of channel k).

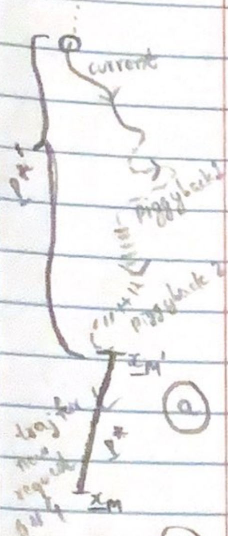
(d) WAIT_TIME_TRANSCEIVER = 0.

Share Control Frame with the BS and all the other UAVs in the swarm.



(2) UAV is 'not available' (currently serving other GNs) and 'capable' (Transceiver available)

number of GNs being served by this UAV $< N_x|_{UAV}$



Current trajectory $= \underbrace{(\underline{p}^{*'}, \underline{v}^{*'})}$, End position $= \underline{x}_{M'}$.

concatenation of the remaining primary trajectory and the optimal trajectories of previously piggybacked requests (if any)

(a) WAIT_TIME_CHANNEL $= \min_{k \in \{1,2,\ldots,N_c\}}$ find_wait_time_channel (current queue state of channel k).

(b) WAIT_TIME_TRANSCEIVER $= 0$

(c) Estimated position (may or may not be along current trajectory) after WAIT_TIME_CHANNEL is $\underline{x}_{m'}$ ($\in \underline{p}^{*'}$ or $\notin \underline{p}^{*'}$).

If $\underline{x}_{m'} \notin \underline{p}^{*'}$: $L' = 0$, $L'' = 0$, SERVICE_TIME $= \sum_{m=M'}^{M-1} \frac{\|\psi_m\|_2}{v_m} + \hat{t}_{p,1} + \hat{t}_{p,2}$,

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

- $(\underline{p}^*, \underline{v}^*)$ is the optimal trajectory action for the new GN request G from (r,θ).
  $\{x_m\}_{m=M'}^{M-1}$
- $\underline{x}_M$ is the end position for GN G service.

Else :

$L' = \sum_{m=m'}^{M'-1} F_m$

If $L' < L$: $L'' = 0$,

SERVICE_TIME $= \sum_{m=M'}^{M-1} \frac{\|\psi_m\|_2}{v_m} + \hat{t}_{p,1} + \hat{t}_{p,2}$,

where $\hat{t}_{p,1}$ considers $h_1(\underline{p}^*, \underline{v}^*) = L - L' - \sum_{m=M'}^{M-1} F_m$;

LAGRANGIAN $= \hat{f}(p^*, v^*)$ with $\hat{t}_{p,1}$ considering $h_1(p^*, \underline{v}^*) = L - L' - \sum_{m=M'}^{M-1} F_m$.

If $L' > L$: let m'' be the position along the current trajectory where decode for GN G completes.

$L'' = \sum_{m=m''}^{M'-1} F_m$

If $L'' < L$:

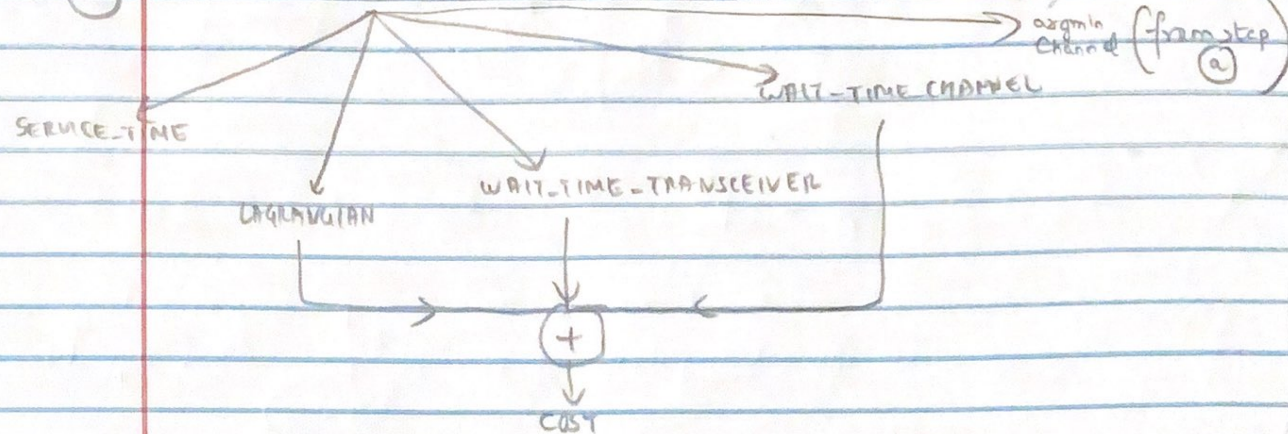
SERVICE_TIME $= \sum_{m=M'}^{M-1} \frac{\|\psi_m\|_2}{v_m} + \hat{t}_{p,1} + \hat{t}_{p,2}$,

where $\hat{t}_{p,1} = 0$ and $\hat{t}_{p,2}$ considers $h_2(\underline{p}^*, \underline{v}^*) = L - L'' - \sum_{m=M'}^{M-1} F_m$.

LAGRANGIAN $= \hat{f}(p^*, v^*)$ with $\hat{t}_{p,1} = 0$ and $\hat{t}_{p,2}$ considering $h_2(\underline{p}^*, \underline{v}^*) = L - L'' - \sum_{m=M'}^{M-1} F_m$

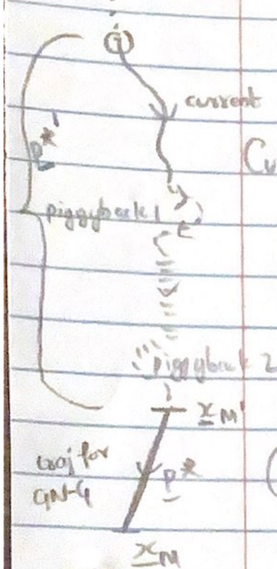
If $L'' \geq L$; SERVICE_TIME $= 0$; LAGRANGIAN $= 0$

d Share Control Frame with the BS and all the other UAVs in the swarm.



③ UAV is 'not available' (currently serving other GNs) and 'not capable' (transceiver not available)

$$\text{number of GNs being served by this UAV} = N_{x|UAV}$$



Current trajectory = $\underbrace{(\underline{p}^{*'}, \underline{v}^{*'})}$; End position = $\underline{x}_{M'}$.

concatenation of the remaining primary trajectory and the optimal trajectories of the previously piggybacked requests (if any)

ⓐ $\text{WAIT\_TIME\_CHANNEL} = \min_{k \in \{1,2,\dots,N_C\}}$ find_wait_time_channel (current queue state of channel k).

↓

ⓑ $\text{WAIT\_TIME\_TRANSCEIVER} = \min_{x \in \{1,2,\dots,N_{x|UAV}\}}$ find_wait_time_transceiver (estimated queue state of Transceiver x after WAIT_TIME_CHANNEL)

↓

ⓒ Estimated position (may or may not be along current trajectory) after WAIT_TIME_CHANNEL + WAIT_TIME_TRANSCEIVER

is $\underline{x}_{m'}$ ($\in \underline{p}^{*'}$ or $\notin \underline{p}^{*'}$).

Using the same logical flow as in step ⓒ of case ③ :
find SERVICE_TIME and LAGRANGIAN.

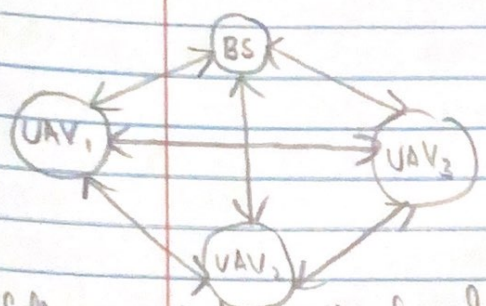
↓

ⓓ Share Control Frame with the BS and all the other UAVs in the swarm.

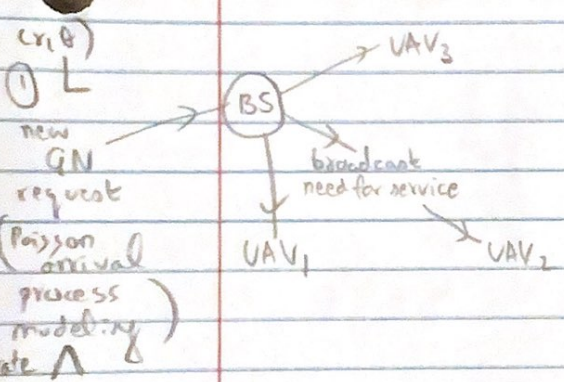
→ argmin channel (from step ⓐ)
→ WAIT_TIME_CHANNEL
→ SERVICE_TIME
→ LAGRANGIAN
→ WAIT_TIME_TRANSCEIVER

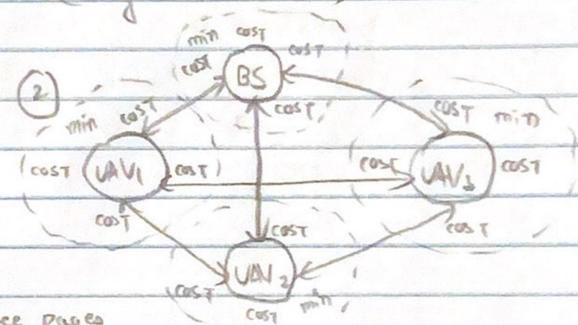
$\text{LAGRANGIAN} + \text{WAIT\_TIME\_TRANSCEIVER} + \text{WAIT\_TIME\_CHANNEL} \rightarrow \oplus \rightarrow \text{COST}$

Consensus-driven conflict resolution

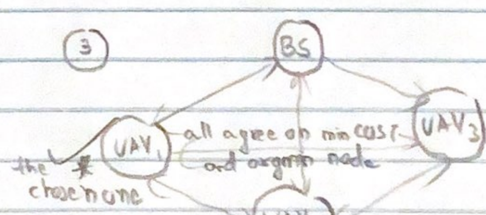


- fully-connected distributed mesh serving as the control network
- control frames are way smaller than data frames : Ignore processing latencies
- control operations happen on a way smaller time-scale than request arrivals
  (typically milliseconds) (1 every minute for 1Mb) (1 every 30 min for 100Mb)





see pages 1-6 for info on how COST is computed & shared



- UAV$_1$ chosen by consensus
- Reserves spot in the previously chosen argmin channel k's queue and the previously chosen argmin transceiver x's queue.

4 UAV$_1$: either available/not and capable/not

Waits WAIT_TIME_CHANNEL : Gets channel k for decode and forward
(0 if channel available)

Waits WAIT_TIME_TRANSCEIVER : Gets transceiver x for decode and forward
(0 if transceiver available)

Starts serving GN-G (primary/piggyback)

DEV SHEET

Channel Assignment

```
                         q_k                              bs
find_wait_time_channel ( queue_state_channel_k , BS/UAV, ) :
                           decode/forward
                               dec
```

all fwd BS & UAV ops do not allow freq reuse

```
if bs or !dec :
    ts = max ( remaining SERVICE_TIME of all requests currently being served
               by this server )

    tqwait = 0 , i = 0
    l = number of requests currently waiting in the queue
    while ( i < l ) :
        s = '0'
                     (i+1, i+2, ..., l-1)
        for j = i+1 : l
            s' = is_reuse (j)
            if s' == '0' : break          # '0' = s
            else : s.join (s')            # "01" = s = "011" = "011...1"
        tqwait += max ( serv_time corresponding to every request in s )
        i = j
    return ts + tqwait
```

[0] [1] [1] [l-1]

note here that the reuse analysis is for prev requests in queue not for current request

– req marked reused can be served at the same time
– so, the server will be free after max (ser_time of these requests)

reuse = 0 | no reuse
~~reuse = 1 | reuse allowed~~

UAV decode freq reuse allowed

```
else :
    serv_reqs = [ array of reqs currently being served by this server ]
    wait_reqs = [ array of reqs currently waiting in the queue ]
    if len(wait_reqs) == 0 :
        reuse = freq_reuse ( serv_reqs )   # Tell me whether I can reuse channel k
                                           # given the reqs currently being served
        if reuse == 0 : return max ( remaining service_time of serv_reqs )
        else : return 0
    ts = max ( remaining service_time of serv_reqs )
    tqwait = 0 , i = 0
    l = len ( wait_reqs )
    while ( i < l ) :
        s = '0'
        for j = i+1 : l
            s' = is_reuse (j)
            if s' == 0 : break
            else : s.join (s')
```

find_wait_time_channel

else

breaks i = l-1

while(i < l)

for

i = j

if i == l-1 and s[-1] == '1':

if freq_reuse ([req corresponding to s]) == '1':

continue

tq_wait += max (serv_time corresponding to every request in s)

return ts + tq_wait

find_wait_time_transceiver (state of transceiver 'x' queue):

return remaining_serv_time of request being served $+ \sum_{\text{req waiting}}$ serv_time

UAV(i)

freq_reuse$_{(k)}$ (array of requests to analyze, current_traj) — array, traj; (k) channel

UAVs = get_indices_of_UAVs (array)

$\mathcal{U}_k$

$\mathbb{E}\left[|g_{GU|i,k}|^2\right] = 1$

for every point x in traj:

$$SINR^{x}_{min|i,k} = \mathbb{E}\left[\frac{\left(\beta_0 d_{GU|i}^{-\alpha} P_{LoS} + x\beta_0 d_{GU|i}^{-\tilde{\alpha}} P_{NLoS}\right) P_{Tx} \underbrace{|g_{GU|i,k}|^2}_{}}{N_0 B_k \Gamma + \sum_{j \in \mathcal{U}_k} \beta_0 \underbrace{d_{min|ij}^{-\alpha}}_{} \underbrace{|g_{ij,k}|}_{K = k_1}^2 P_{Tx}}\right]$$

dist to UAV$_j$ at its closest point in its remaining trajectory to UAV$_i$ (obtained from the trajectory updates shared by UAV$_j$ in its control frame)

$(\because \phi_{ij} = 0)$ purely LoS same height

if $SINR^{x}_{min|i,k}$ < threshold:

return 0 (no reuse)

return 1 (reusing k for decode allowed)

Contributions

1. UAVs equipped with multiple transceivers; can serve multiple users at a time.

2. Frequency reuse enabled to improve spectral efficiency.
   (across UAVs)

3. Waiting optimization for the UAVs.

4. An optimal single-agent policy replicated across a fully-decentralized swarm mitigating the need for complex joint (combined state-and-action) optimization.
   multi-agent

5. Fully distributed deployment; no need for central coordinator or aggregator.

6. Queueing analysis at both the channels $(M/G/N_c)$ as well as at the individual transceiver chains $(M/G/N_x)$.

7. Dynamic traffic arrivals / Poisson arrival process : Adaptive.

no other state-of the-art does any of this!

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 1,2,3
- SCA
- DDQN-PER 1,2,3
- BS only
- ~~MoB~~ CUAV 1,2,3,5,10
- CSCA-ADMM 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, 1 BS with PB, FR

30 GHz, 10,000 requests

for each policy for NC

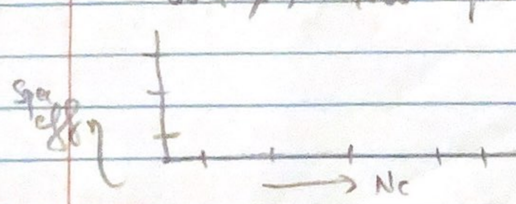
5 MAESTRO runs
- N_c = 1
- N_c = 2
- N_c = 4
- N_c = 8
- N_c = 10

L = 10 Mb

1 req every 5 mins

30 GHz, 1BS, 1UAV

Pavg = 1.2 kW



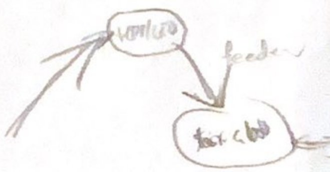
Use V_I V values of N_c=2 to train N_c = 4

N_c = 8

N_c = 10

what time book?

tput 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)
- HAP (with feeder)
- LEO (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 channels
- $B_k = 2.5$ 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 TRO-X
- DDPG
- PDQN-PER