Ground System Architectures Workshop 2018
Feb 26 – Mar 1, 2018
Los Angeles, CA

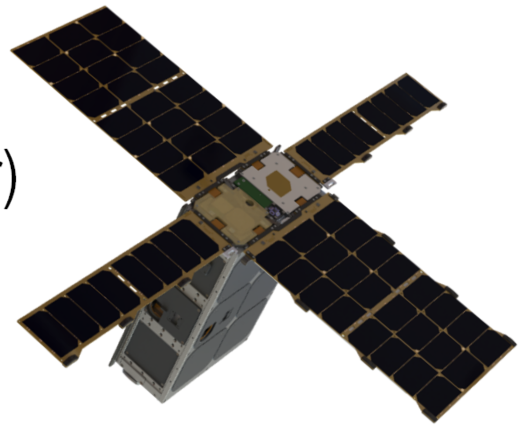
Dynamic Autonomous Message Delivery Scheduling in a Nanosatellite Store-and-Forward Communication Architecture

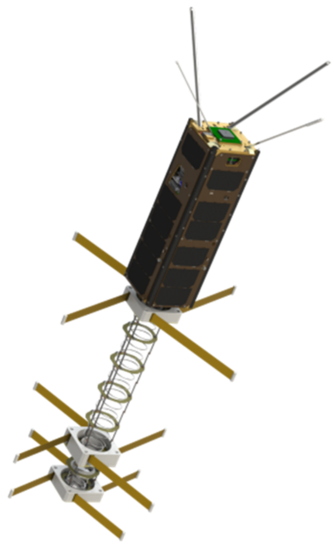
February 28, 2018

Cherry Wakayama (SPAWAR Systems Center Pacific)
Zelda B. Zabinsky (University of Washington)
Michelle Song (University of Washington)
Kimberly Witke (University of South Florida)

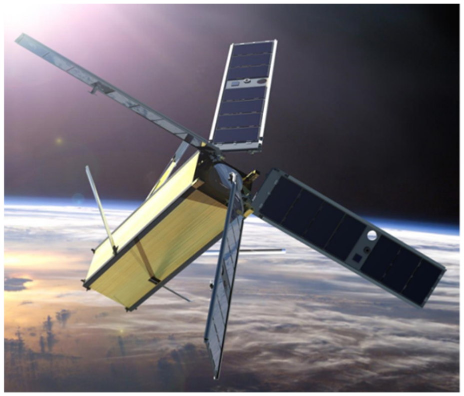
Background

- **Nanosatellites**
  - Low SWAPs
    (Size, Weight, and Power)
  - Modular
  - Adaptable
  - Affordable





- **Applications**
  - Remote sensing
  - Weather monitoring
  - Science
  - Communications



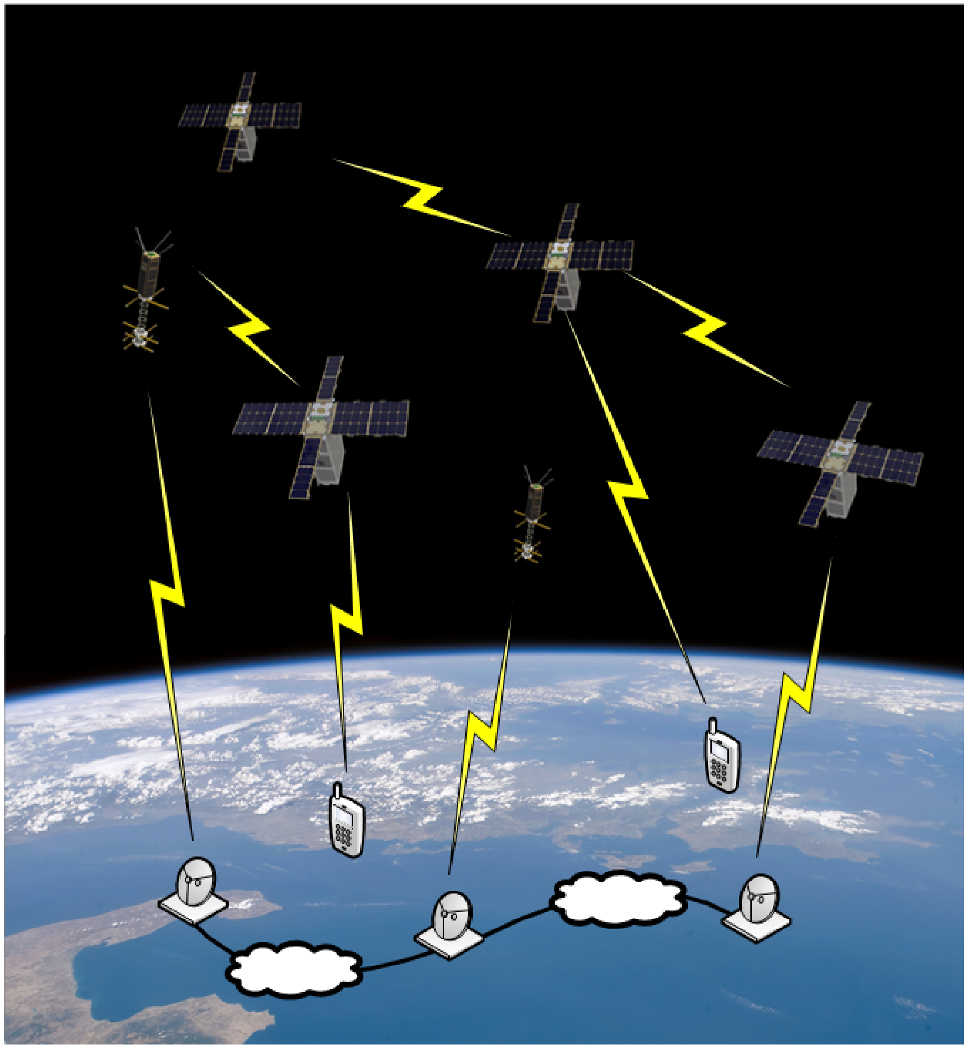
Problem Statement

Goal:

Provide reliable and timely communications in remote and hard-to-reach areas using a constellation of nanosatellites

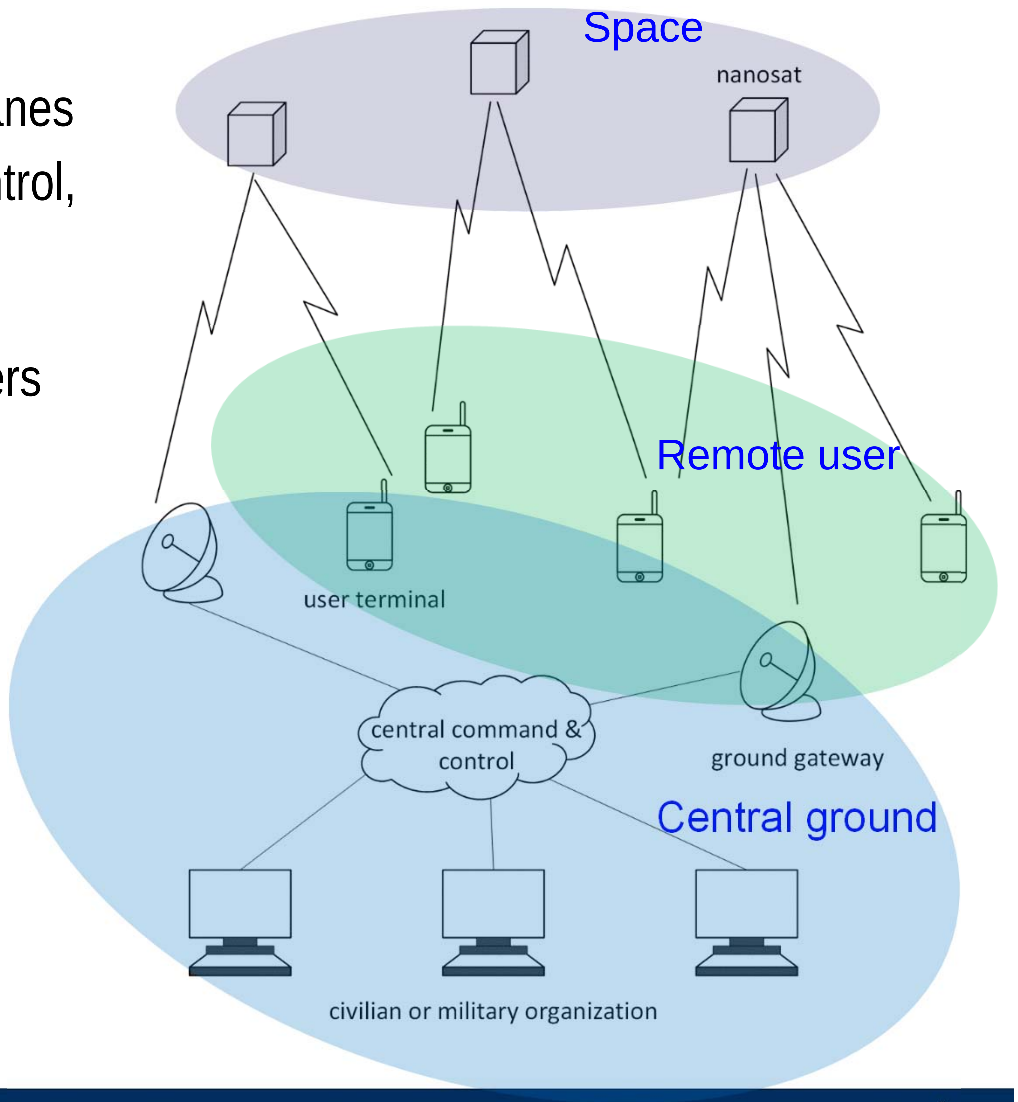
Problem Definition:

How to effectively schedule upload- and download-events within the resource constraints (time, bandwidth, energy)?



Store-and-forward Nanosatellite Communication Architecture

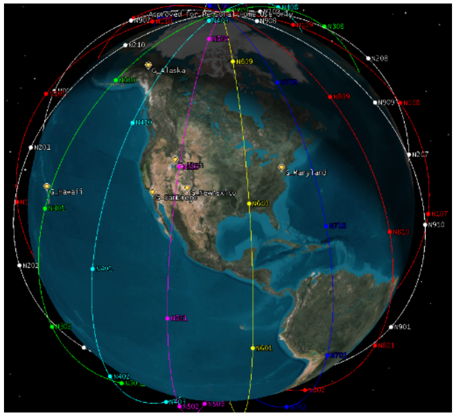
- Three main segments
  - Space: nanosats in LEO orbital planes
  - Central ground: command and control, users, and fixed ground nodes as gateways
  - Remote user: fixed and mobile users without direct access to terrestrial networks
- Without crosslinks, connectivity between a remote user and a central user is achieved with a "store-and-forward approach"



Scheduling Problems

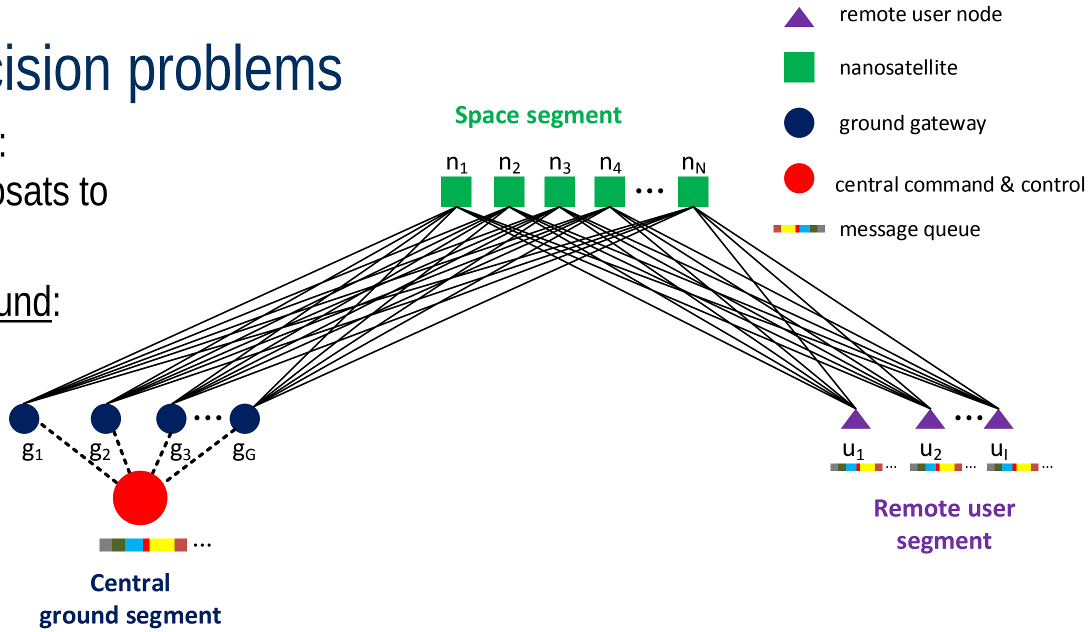
Message flow description

- Messages are collected at central command and control
- Messages are to be scheduled at ground gateways and nanosats during selected contact time windows to be delivered to remote user nodes
- Remote users can also send messages to central users using nanosats
- Some messages are time-sensitive or high-priority
- Network users want the messages as soon as possible



Distributed scheduling decision problems

1) Local Decision making at nanosats: Scheduling of messages from nanosats to gateways and remote users
2) Centralized decision making at ground: Scheduling of messages at central command and control to gateways and nanosats

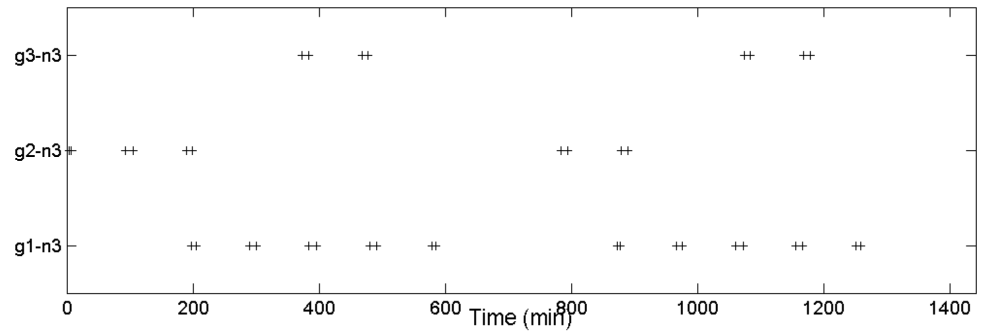


Technical Challenges

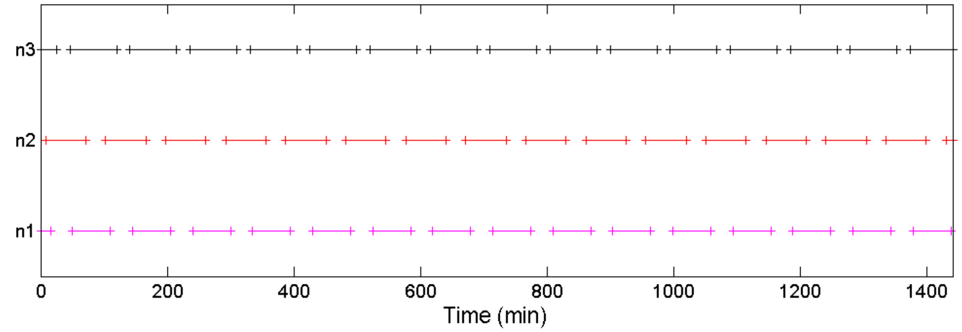
- Conventional large satellites
  - Kilowatt-level power budget
  - High data rate
- Nanosats
  - Watt-level power budget
  - Low data rate
- LEO (low-earth orbit)
  - Short access time window
- Dynamic user priorities
- Coordination among multiple nanosats, ground nodes and users

Require energy efficient and reliable scheduling algorithms

Access Time Windows

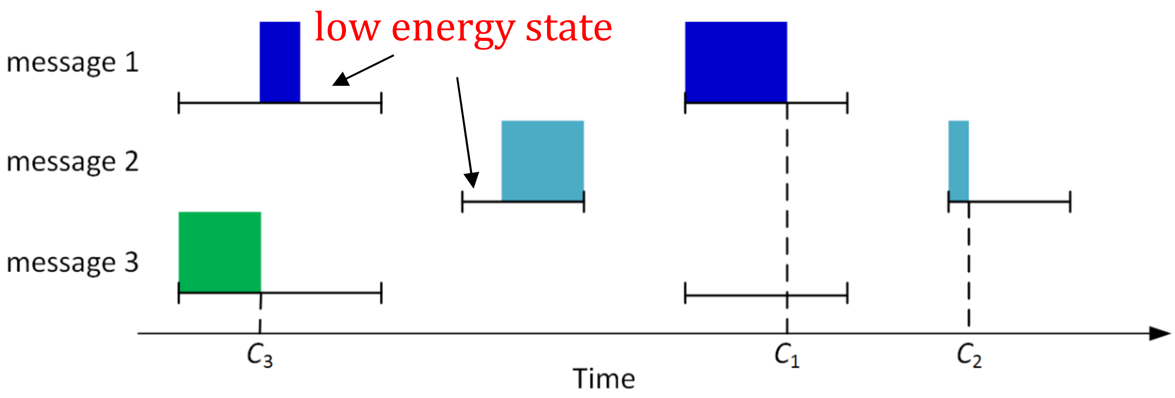


Solar Charging Time Windows



Local Decision Making at Nanosats

- Remote users can initiate and receive messages, and therefore a decentralized nanosat onboard decision making is necessary to reduce overhead delays
- Each nanosat is a decision maker and determines its own message delivery scheduling policy
- Minimize weighted completion time rather than maximizing data download
- Contact windows, charging windows & limited energy storage
- Preemptive scheduling – messages may be forwarded in multiple passes



Nanosat Message Delivery Decision Making

- Autonomous single satellite scheduling with energy and contact time window constraints

(P1) Weighted completion time — **BIP**

$$\min \quad \sum_{j=1}^{J} w_j C_j \quad (1)$$

subject to

$$C_j \geq \tau_{k+1} u_{jk} \text{ for } j = 1, \dots, J, k = 0, \dots, K-1 \quad (2)$$

$$\sum_{j=1}^{J} u_{jk} \leq 1 \text{ for } k = 0, \dots, K-1 \quad (3)$$

$$\sum_{k=0}^{K-1} u_{jk} = s_j, \text{ for } j = 1, \dots, J \quad (4)$$

$$e_{k+1} = e_k + \delta_k - \sum_{j=1}^{J} u_{jk} - h_k \text{ for } k = 0, \dots, K-1 \text{ and } e_0 \text{ is given} \quad (5)$$

$$e_{min} \leq e_k \leq e_{max} \text{ for } k = 0, \dots, K \quad (6)$$

$$h_k \geq 0 \text{ for } k = 0, \dots, K-1 \quad (7)$$

$$C_j \geq 0 \text{ for } j = 0, \dots, J \quad (8)$$

$$u_{jk} = \{0,1\} \text{ for } j = 1, \dots, J, k = 0, \dots, K-1 \quad (9)$$

(P2) Weighted mean busy time — **LP**

$$\min \quad \sum_{j=1}^{J} \sum_{k=0}^{K-1} \frac{w_j}{s_j} \left(\tau_k + \frac{1}{2}\right) u_{jk} \quad (11)$$

subject to

$$\sum_{j=1}^{J} u_{jk} \leq 1 \text{ for } k = 0, \dots, K-1 \quad (12)$$

$$\sum_{k=0}^{K-1} u_{jk} = s_j \text{ for } j = 1, \dots, J \quad (13)$$

$$e_{k+1} = e_k + \delta_k - \sum_{j=1}^{J} u_{jk} - h_k \text{ for } k = 0, \dots, K-1 \text{ and } e_0 \text{ is given} \quad (14)$$

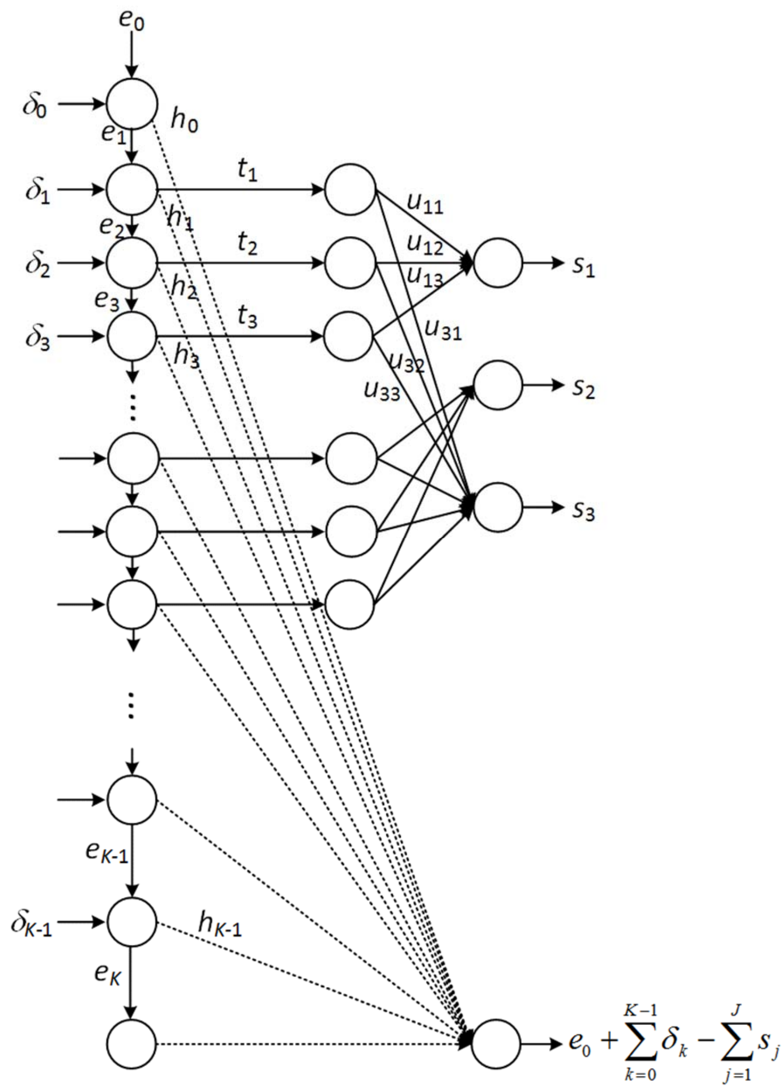
$$e_{min} \leq e_k \leq e_{max} \text{ for } k = 0, \dots, K \quad (15)$$

$$h_k \geq 0, \text{ for } k = 0, \dots, K \quad (16)$$

$$0 \leq u_{jk} \leq 1 \text{ for } j = 1, \dots, J, k = 0, \dots, K-1 \quad (17)$$

Network Flow Model Representation for (P2)

- We make mean busy time approximation such that the resulting problem is a minimum-cost network flow problem
- Constraints
  - No more than one job per time interval
  - Message delivery completion
  - Energy dynamics
- Network flow property
  - Feasibility
  - Integrality
  - Efficient network algorithms exist

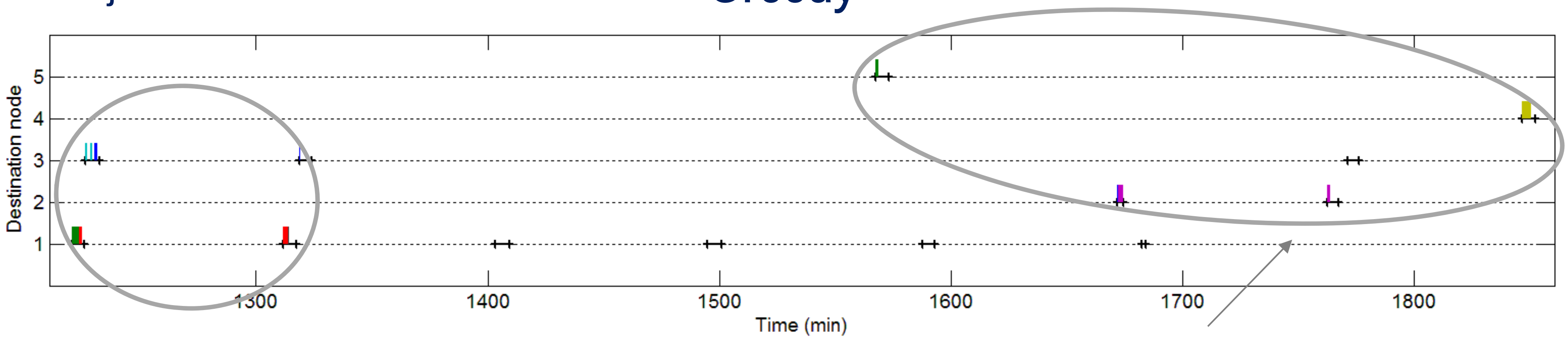


Simulation Results

(P2) outperforms Greedy by 3 hours in total delivery time.

obj function value = 1732693

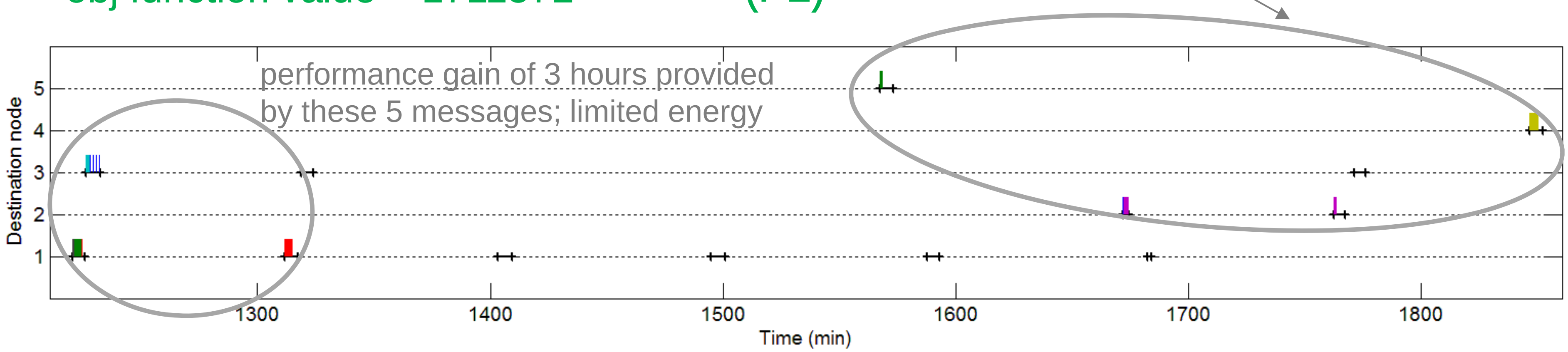
Greedy



same C_j; not limited by energy

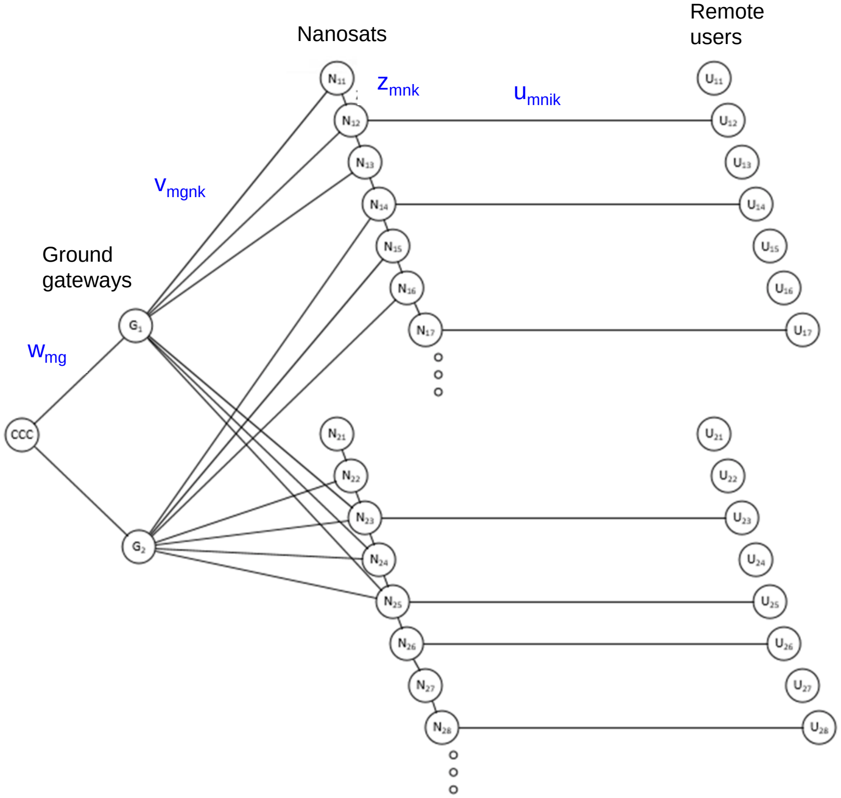
obj function value = 1711572

(P2)



Centralized Decision Making at Ground

- Messages are to be scheduled on certain gateway nodes and nanosat during contact time windows to be delivered to the remote user nodes
- Network management center serves as a central decision maker
- Minimize total message delivery completion time
- Contact windows, charging windows & limited energy storage at nanosats



Scheduling for Ground Gateways and Nanosats

$\min \sum_m \sum_n \sum_i \sum_k (\tau_k * u_{mnik})$	Minimize average total message delivery time to remote users
subject to	
$w_{mg} = \sum_n \sum_k v_{mgnk} \quad \forall (m,g)$	Messages entering each ground node leaves the node
$\left(\sum_g v_{mgnk}\right) + z_{mn(k-1)} = z_{mnk} + \sum_i u_{mnik} \quad \forall (m,n,k)$ $u_{mnik} \leq z_{mn(k-1)} \quad \forall (m,n,i,k)$	Flow constraint for each nanosat in each interval
$\sum_m \sum_n u_{mnik} \leq 1 \quad \forall (i,k)$	Remote user receives at most one message unit in each interval
$\sum_m \sum_g v_{mgnk} \leq 1 \quad \forall (n,k)$	Nanosat receives at most one message unit in each interval
$\sum_m \sum_n v_{mgnk} \leq 1 \quad \forall (g,k)$	Ground node sends at most one message unit in each interval
$\sum_g w_{mg} = 1 \quad \forall m$	Each message is delivered to ground nodes once
$\sum_n \sum_i \sum_k u_{mnik} = 1 \quad \forall m$	Each message is delivered to users once
$\sum_g \sum_n \sum_k v_{mgnk} = 1 \quad \forall m$	Each message is delivered to nanosats once
$\sum_m \sum_n \sum_k u_{mnik} = d_i \quad \forall i$	User demands are met
$v_{mgnk}, u_{mnik}, w_{mg}, z_{mnk} \in \{0,1\}$	Binary decision variables
$e_{nk} = e_{n(k-1)} - \sum_m \sum_i u_{mnik} + (\tau_k - \tau_{k-1}) * \delta_{nk} - h_{n,k-1} \quad \forall (n,k)$	Nanosat energy dynamic at each interval
$e_{min} \leq e_{nk} \leq e_{max}$ $h_{nk} \geq 0$	Decision variables to model nanosat energy stays within appropriate levels

Ongoing & Future Work

- Minimum cost multicommodity dynamic flow problems
- Modeling uncertainty due to link quality by representing the demand to each user with a random variable
- System-level modeling and simulation tool for distributed decision demonstration and performance evaluation
- Architecture considering crosslinks
- Constellation design