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

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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)?
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”
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
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.

![Diagram showing low energy state and message delivery scheduling]

message 1
message 2
message 3

low energy state

C3
C1
C2

Time
Nanosat Message Delivery Decision Making

Autonomous single satellite scheduling with energy and contact time window constraints

(P1) Weighted completion time

\[
\begin{align*}
\text{min} & \quad \sum_{j=1}^{J} w_j C_j \\
\text{subject to} & \quad C_j \geq \tau_{k+1} u_{jk} \text{ for } j = 1, \ldots, J, k = 0, \ldots, K - 1 \quad (2) \\
& \quad \sum_{j=1}^{J} u_{jk} \leq 1 \text{ for } k = 0, \ldots, K - 1 \quad (3) \\
& \quad \sum_{k=0}^{K-1} u_{jk} = s_j \text{ for } j = 1, \ldots, J \quad (4) \\
& \quad e_{k+1} = e_k + \delta_k - \sum_{j=1}^{J} u_{jk} - h_k \\
& \quad \text{for } k = 0, \ldots, K - 1 \text{ and } e_0 \text{ is given} \quad (5) \\
& \quad e_{\text{min}} \leq e_k \leq e_{\text{max}} \text{ for } k = 0, \ldots, K \quad (6) \\
& \quad h_k \geq 0 \text{ for } k = 0, \ldots, K - 1 \quad (7) \\
& \quad C_j \geq 0 \text{ for } j = 0, \ldots, J \quad (8) \\
& \quad u_{jk} \in \{0,1\} \text{ for } j = 1, \ldots, J, k = 0, \ldots, K - 1 \quad (9)
\end{align*}
\]

(BIP)

(P2) Weighted mean busy time

\[
\begin{align*}
\text{min} & \quad \sum_{j=1}^{J} \sum_{k=0}^{K-1} \frac{w_j}{s_j} (T_k + \frac{1}{2}) u_{jk} \\
\text{subject to} & \quad \sum_{j=1}^{J} u_{jk} \leq 1 \text{ for } k = 0, \ldots, K - 1 \quad (12) \\
& \quad \sum_{k=0}^{K-1} u_{jk} = s_j \text{ for } j = 1, \ldots, J \quad (13) \\
& \quad e_{k+1} = e_k + \delta_k - \sum_{j=1}^{J} u_{jk} - h_k \\
& \quad \text{for } k = 0, \ldots, K - 1 \text{ and } e_0 \text{ is given} \quad (14) \\
& \quad e_{\text{min}} \leq e_k \leq e_{\text{max}} \text{ for } k = 0, \ldots, K \quad (15) \\
& \quad h_k \geq 0, \text{ for } k = 0, \ldots, K \quad (16) \\
& \quad 0 \leq u_{jk} \leq 1 \text{ for } j = 1, \ldots, J, k = 0, \ldots, K - 1 \quad (17)
\end{align*}
\]

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

obj function value = 1732693

Greedy

obj function value = 1711572

(P2)

Same $C_j$; not limited by energy

Performance gain of 3 hours provided by these 5 messages; limited energy
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

**Minimize average total message delivery time to remote users**

**Messages entering each ground node leaves the node**

**Flow constraint for each nanosat in each interval**

**Remote user receives at most one message unit in each interval**

**Nanosat receives at most one message unit in each interval**

**Ground node sends at most one message unit in each interval**

**Each message is delivered to ground nodes once**

**Each message is delivered to users once**

**Each message is delivered to nanosats once**

**User demands are met**

**Binary decision variables**

**Nanosat energy dynamic at each interval**

**Decision variables to model nanosat energy stays within appropriate levels**

\[
\begin{align*}
\min & \quad \sum_m \sum_n \sum_i \sum_k (c_{nk} \cdot w_{mnik}) \\
\text{subject to} & \\
& w_{mg} = \sum_n \sum_k u_{mgnk} \quad \forall (m, g) \\
& \left( \sum_g u_{mgnk} \right) + z_{mn(k-1)} = z_{mnk} + \sum_i u_{mnik} \quad \forall (m, n, k) \\
& \sum_i u_{mnik} \leq z_{mn(k-1)} \quad \forall (m, n, i, k) \\
& \sum_m \sum_n u_{mnik} \leq 1 \quad \forall (i, k) \\
& \sum_m \sum_g u_{mgnk} \leq 1 \quad \forall (n, k) \\
& \sum_m \sum_u u_{mnik} \leq 1 \quad \forall (g, k) \\
& \sum_g w_{mg} = 1 \quad \forall m \\
& \sum_n \sum_i \sum_k u_{mnik} = 1 \quad \forall m \\
& \sum_g \sum_n \sum_k u_{mgnk} = 1 \quad \forall m \\
& \sum_m \sum_n \sum_k u_{mnik} = d_i \quad \forall i \\
& u_{mgnk}, u_{mnik}, w_{mg}, z_{mnk} \in \{0, 1\} \\
& e_{nk} = e_{n(k-1)} - \sum_m \sum_i u_{mnik} + (c_{nk} - c_{n(k-1)} \cdot \delta_{nk} - h_{n,k-1}) \quad \forall (n, k) \\
& e_{\min} \leq e_{nk} \leq e_{\max} \\
& h_{nk} \geq 0
\end{align*}
\]
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