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Message Scheduling Optimization with Energy Constraints and Uncertain Demands in a Store-and-Forward Nanosatellite Communications Architecture

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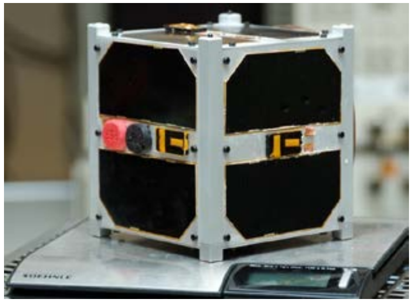
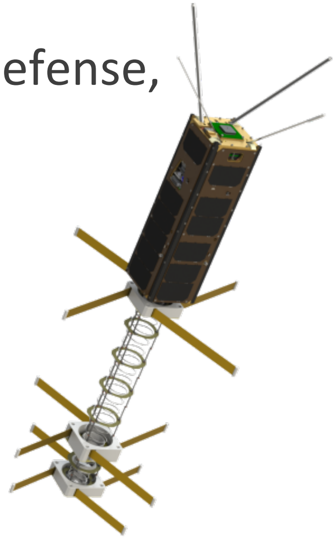
Nanosatellites

Low earth orbit nanosatellites (nanosats) have applications in defense, public and commercial services

- Remote sensing
- Weather monitoring
- Science
- Communications





Advantages

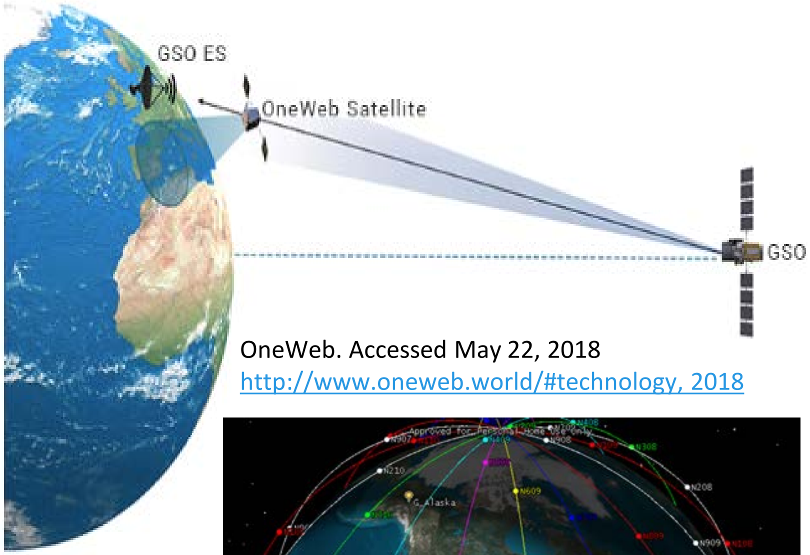
- Low size, weight, and power
- Modular
- Adaptable
- Affordable

Research Motivation

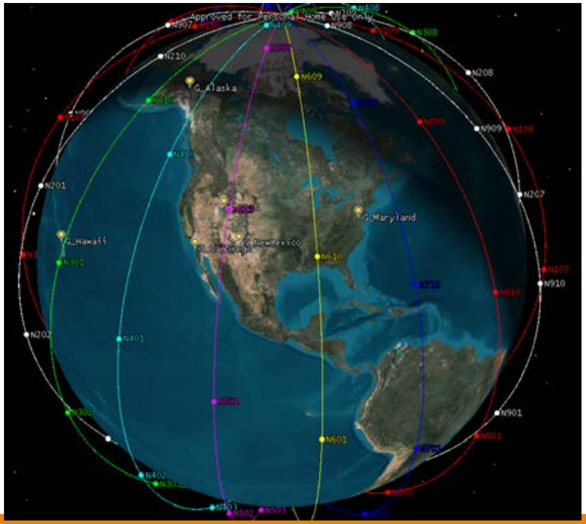
Constellations of nanosats may be used to relay messages between ground nodes

Challenges:

- Short contact time intervals with ground nodes
- Limited available energy due to their small sizes
- Uncertainty in the stability of the connection between nanosats and ground nodes



OneWeb. Accessed May 22, 2018 [http://www.oneweb.world/#technology, 2018](http://www.oneweb.world/#technology)



Develop and analyze scheduling optimization methods to assist with the timely delivery of messages using nanosats

Network Architecture

Nanosats

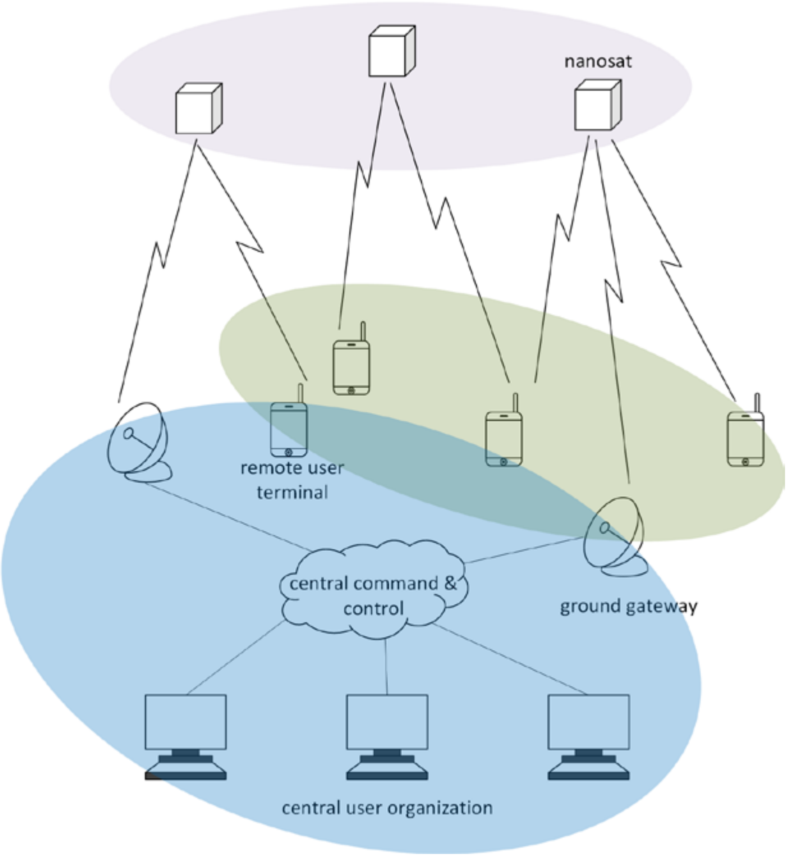
- "Store-and-forward" – no communication between nanosats

Central Command and Control (CCC)

- Centralized system with access to large power supplies and readily available internet connectivity
- Decides message route and schedule

Ground nodes

- Gateways and Remote Users



Outline

- Problem Description
- Optimization Models
    - Deterministic Model without Energy (P1)
    - Deterministic Model with Energy (P2)
    - Probabilistic Demand with Energy (P3)
- Example, Simulation and Policies Comparison
- Summary and Future Work

Problem Description

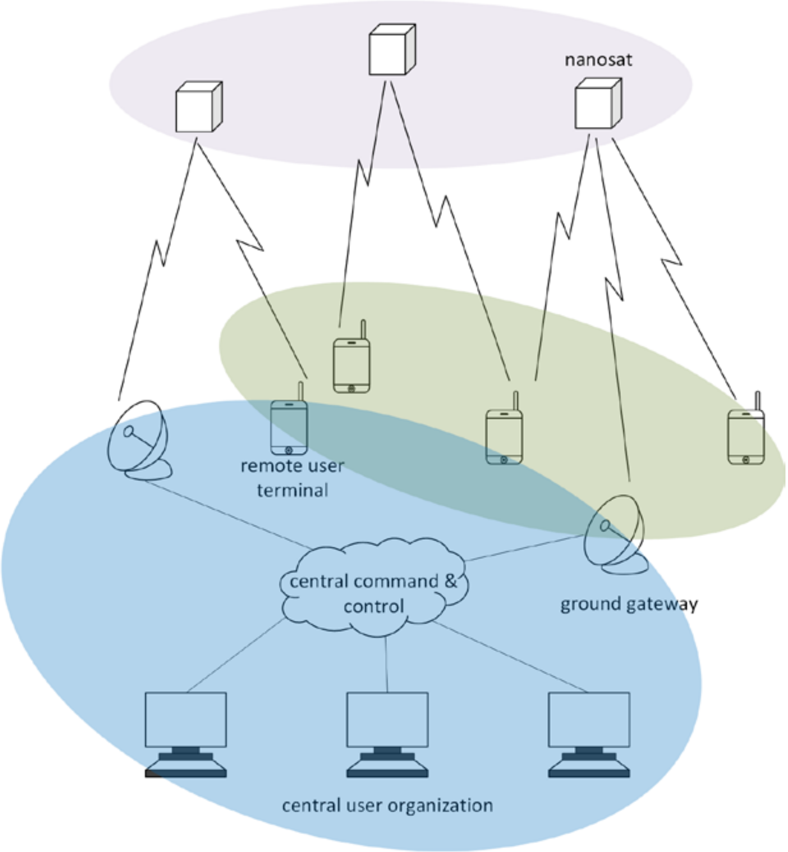
Problem: Deliver messages from CCC to gateways to nanosats to remote users

Objective: Select an optimal route (ground node and nanosatellite) and schedule (message transmit time) to minimize total message delivery times

Constraints:

- Nanosats have limited energy capacity
- Uncertainty of connection stability between nanosats and remote users

Solution Approach: Solve large binary optimization problems quickly



Assumptions

- Nanosats can simultaneously receive and send messages
- Nanosat memory capacity is not considered a constraint
- All messages are in queue at the CCC at time zero
- Remote users’ movements are negligible relative to nanosats and are considered stationary

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Deterministic Model without Energy (P1): Network Representation

Decision Variables:

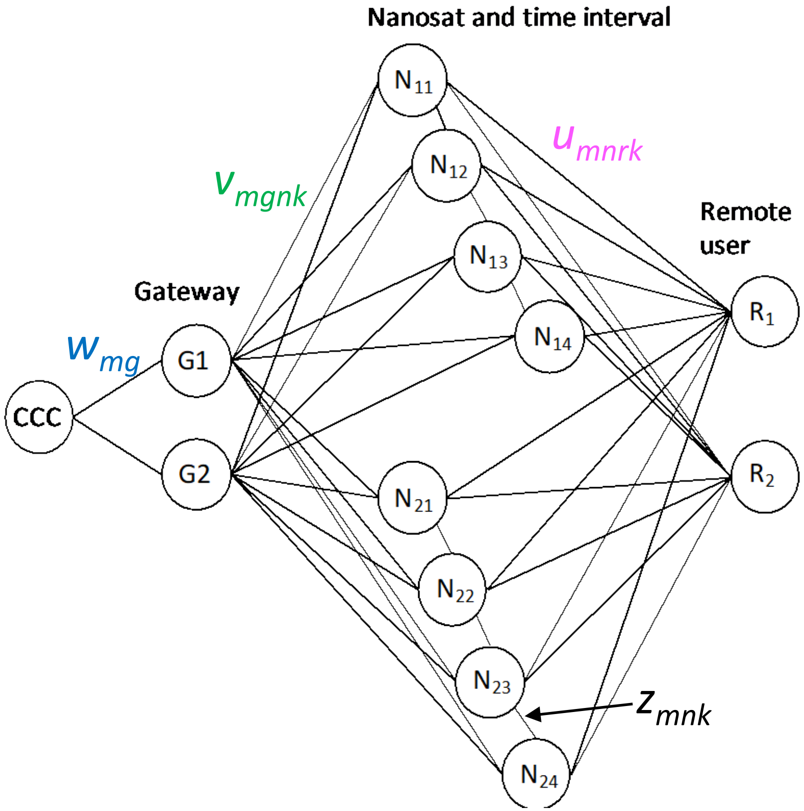
w_{mg} : indicates message *m* is delivered from CCC to gateway *g* in time interval *k*

v_{mgnk} : indicates message *m* is delivered from gateway g to nanosat n in time interval k

u_{mnrk} : indicates message *m* is delivered from nanosat *n* to remote user *r* in time interval *k*

z_{mnk} : indicates message *m* is stored in nanosat *n* between time interval *k* and (*k*+1)

g: gateways	$g = 1, 2, \ldots, G$
n: nanosats	$n = 1, 2, \ldots, N$
r: remote users	$r = 1, 2, \ldots, R$
m: messages	$m = 1, 2, \ldots, M$
k: time intervals	$k = 1, 2, \ldots, K$



Deterministic Model without Energy (P1): Formulation

min $\sum_m \sum_n \sum_r \sum_k (\tau_k * u_{mnrk})$

Minimize the sum of message delivery times

$$w_{mg} = \sum_n \sum_k v_{mgnk} \qquad \forall (m, g)$$

Flow in = Flow out

$$\left(\sum_g v_{mgnk} \right) = z_{mnk} + \sum_r u_{mnrk} \qquad \forall (m, n, k = 1)$$

$$\left(\sum_g v_{mgnk} \right) + z_{mn(k-1)} = z_{mnk} + \sum_r u_{mnrk} \qquad \forall (m, n, k = 2, ..., K - 1)$$

$$\left(\sum_g v_{mgnk} \right) + z_{mn(k-1)} = \sum_r u_{mnrk} \qquad \forall (m, n, k = K)$$

Deterministic Model without Energy (P1): Formulation continued

At most 1 message per time interval *k*

$$\sum_m \sum_n u_{mnrk} \leq 1 \qquad \forall (r,k)$$

$$\sum_m \sum_r u_{mnrk} \leq 1 \qquad \forall (n,k)$$

$$\sum_m \sum_g v_{mgnk} \leq 1 \qquad \forall (n,k)$$

$$\sum_m \sum_n v_{mgnk} \leq 1 \qquad \forall (g,k)$$

Each message sent one time; Meet demand

$$\sum_g w_{mg} = 1 \qquad \forall m$$

$$\sum_n \sum_r \sum_k u_{mnrk} = 1 \qquad \forall m$$

$$\sum_g \sum_n \sum_k v_{mgnk} = 1 \qquad \forall m$$

$$\sum_m \sum_n \sum_k u_{mnrk} = d_r \qquad \forall r$$

$$v_{mgnk}, u_{mnrk}, w_{mg}, z_{mnk} \in \{0,1\}$$

Small Example

2 gateways

2 nanosats

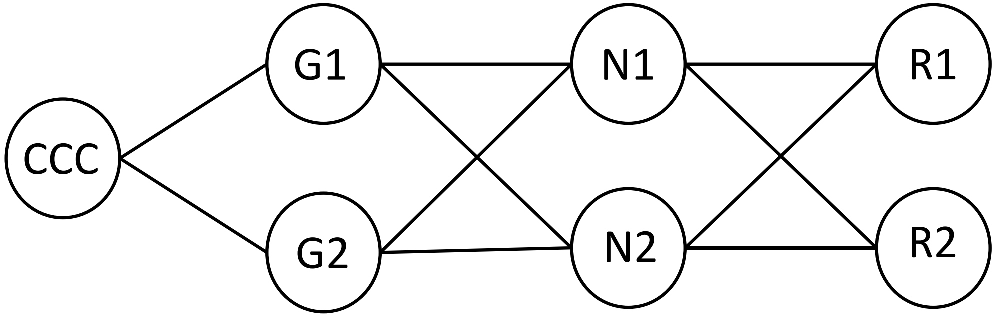
2 remote users

6 messages

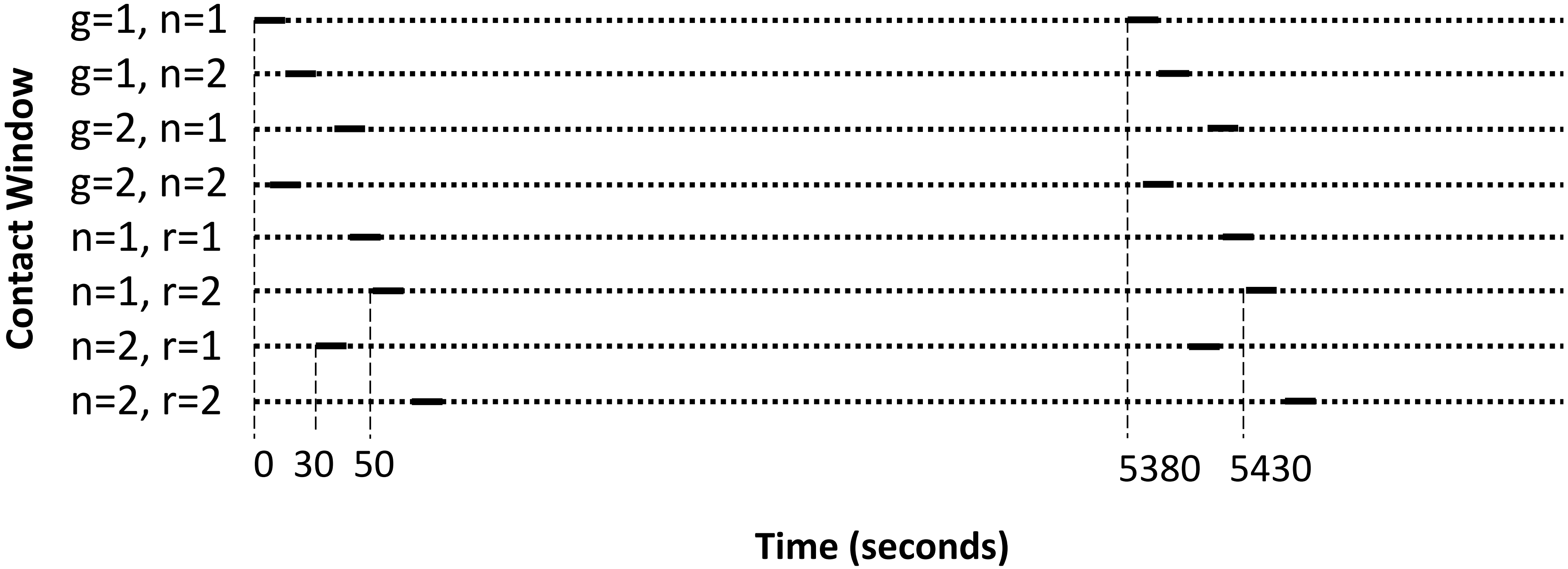
18 time intervals

Remote User	1	2
Demand	3	3

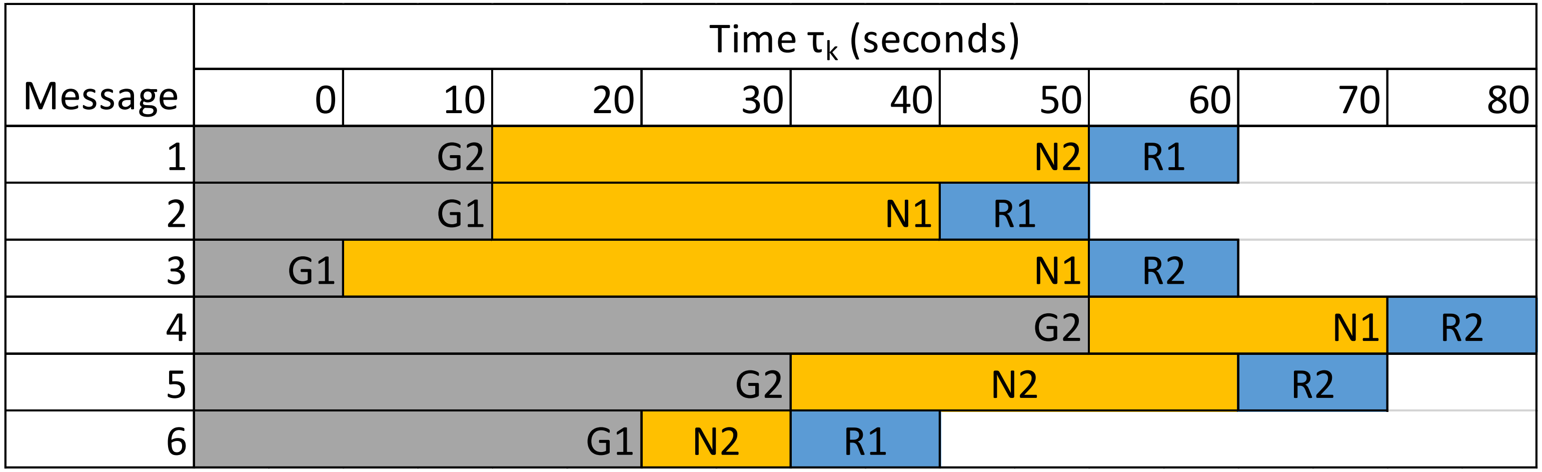
Message	1	2	3	4	5	6
Destination	1	1	2	2	2	1



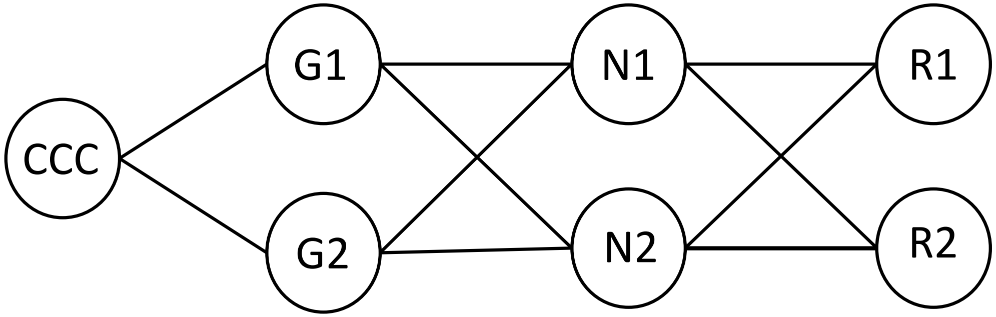
Contact Time Window



(P1) Small Example Results

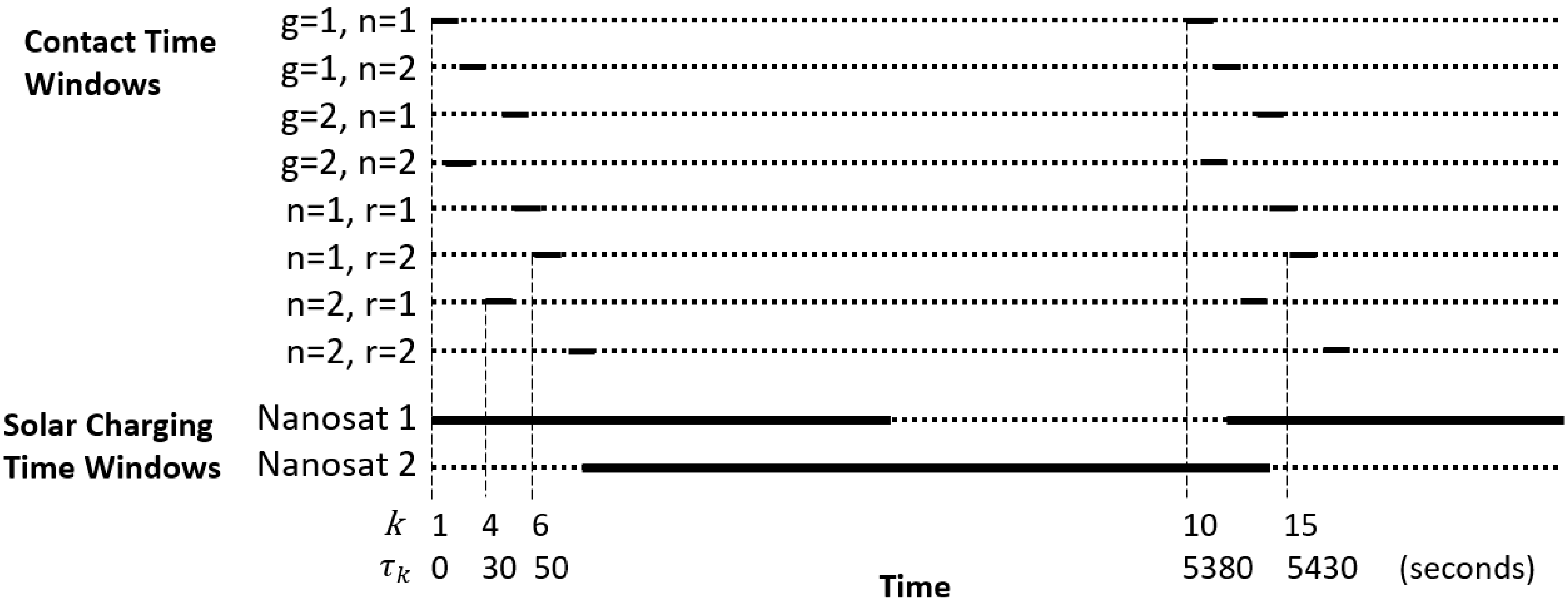


Message	Time τ_k (seconds)								
	0	10	20	30	40	50	60	70	80
1		G2				N2	R1		
2		G1			N1	R1			
3	G1					N1	R2		
4						G2		N1	R2
5				G2		N2		R2	
6			G1	N2	R1				



Solar Charging Time Windows

Nanosats charge batteries when in sunlight



Deterministic Model with Energy Constraints (P2): Network Representation

Additional Decision Variables:

e_{nk} : indicates energy in nanosat *n* is stored between time interval k and (k+1)

h_{nk} : captures spilled energy or extra energy not needed

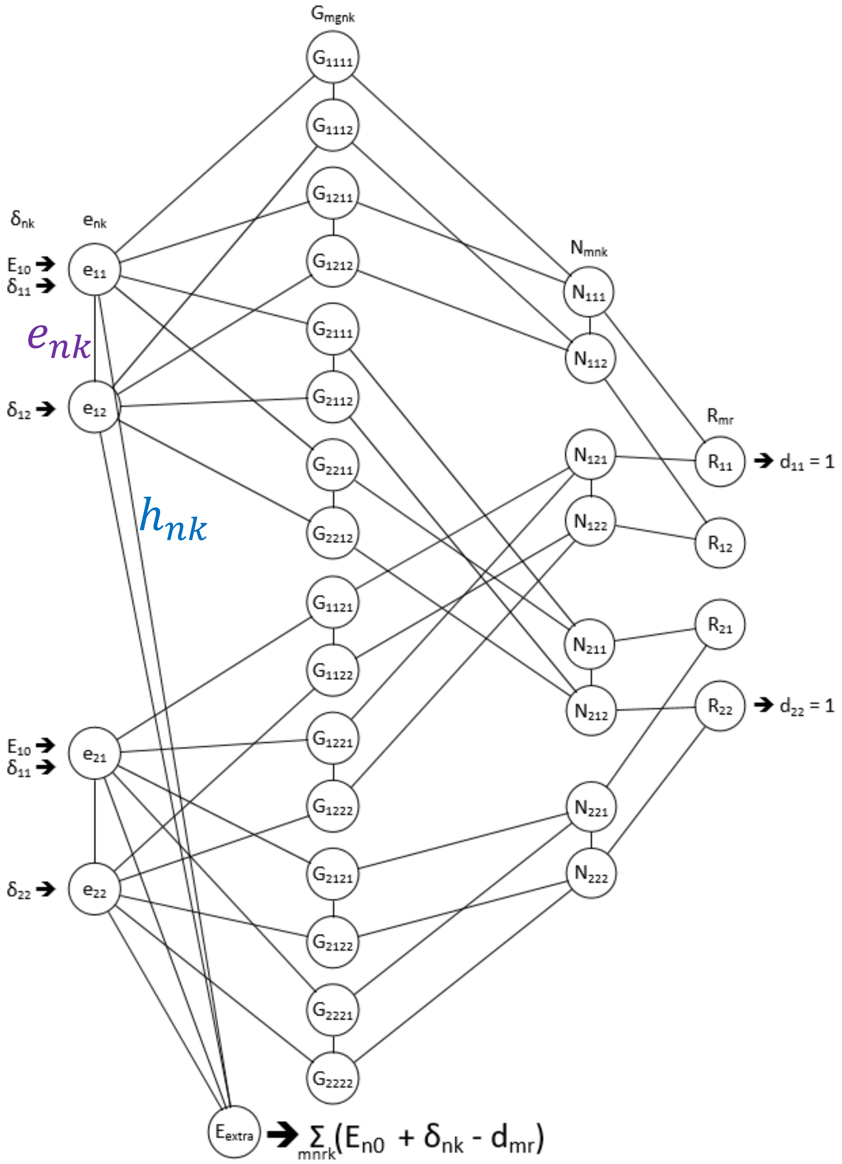
Additional Parameters:

e_{min} : minimum energy capacity for nanosats

e_{max} : maximum energy capacity for nanosats

E_{n0} : remaining energy for nanosats at τ_0

δ_{nk} : energy harvested during time interval k



Deterministic Model with Energy Constraints (P2): Formulation

Additional Energy Constraints:

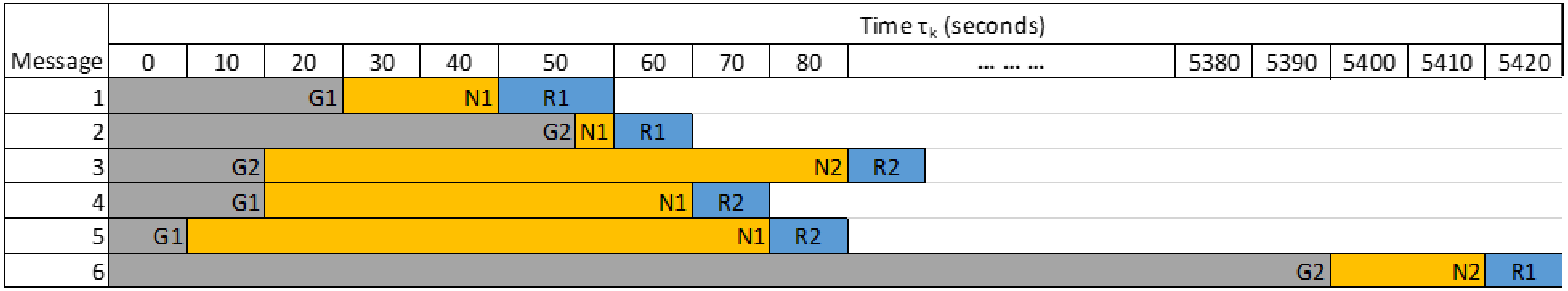
$$e_{nk} = E_{n0} - \sum_m \sum_r u_{mnrk} + \delta_{nk} - h_{n,k-1} \qquad \forall (n, k = 1)$$

$$e_{nk} = e_{n(k-1)} - \sum_m \sum_r u_{mnrk} + \delta_{nk} - h_{n,k-1} \qquad \forall (n, k = 2, ...K)$$

$$e_{min} \leq e_{nk} \leq e_{max}$$

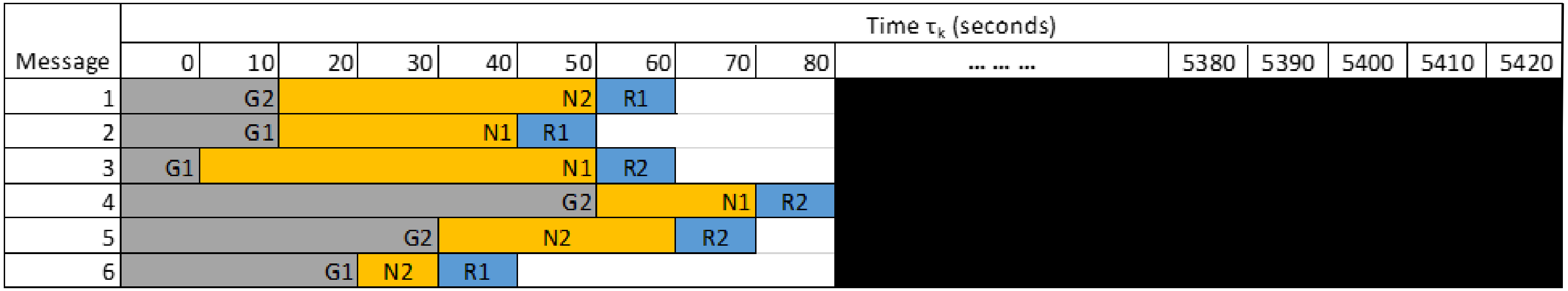
$$h_{nk} \geq 0$$

Small Example Results (P2)



Message	Time τ_k (seconds)													
	0	10	20	30	40	50	60	70	80	... ...	5380	5390	5400	5410	5420
1			G1		N1	R1									
2						G2 N1	R1								
3		G2							N2	R2					
4		G1					N1	R2							
5	G1							N1	R2						
6												G2		N2	R1

Small Example Results (P1)



Message	Time τ_k (seconds)													
	0	10	20	30	40	50	60	70	80	... ...	5380	5390	5400	5410	5420
1		G2				N2	R1								
2		G1			N1	R1									
3	G1					N1	R2								
4						G2		N1	R2						
5				G2		N2		R2							
6			G1	N2	R1										

Probabilistic Model with Energy Constraints (P3)

Message delivery may not be successful due to noise in the environment and noisy nanosat connection

Messages may need multiple delivery attempts

Demand now a random variable

New chance constraint to capture probability of meeting demand:

$$P\left(\sum_{m}\sum_{n}\sum_{k} u_{mnrk} \geq D_r\right) \geq 1-\alpha \quad \forall r$$

where $0 \leq \alpha \leq 1$

Linearizing Chance Constraint

Multinomial distribution where p_i is the probability of success on i^{th} attempt

$$p_i = \begin{cases} 0.7 & i = 1 \\ 0.2 & i = 2 \\ 0.1 & i = 3 \end{cases}$$

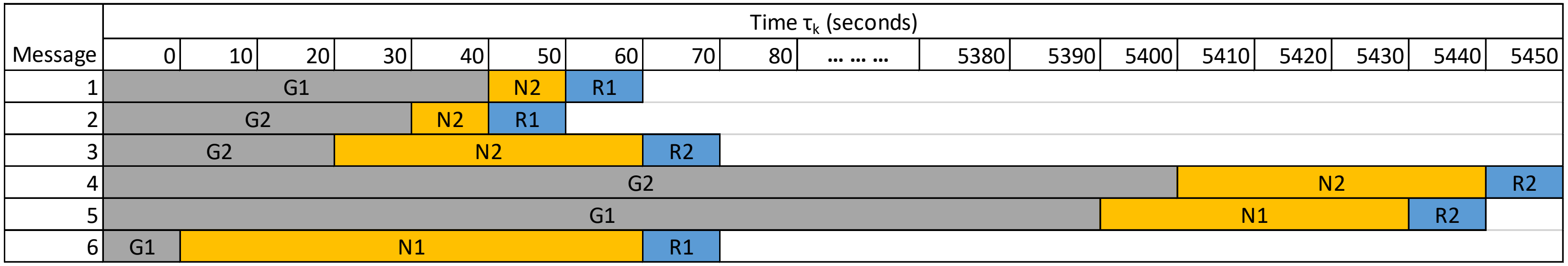
$$P\left(\sum_m \sum_n \sum_k u_{mnrk} \geq D_r\right) \geq 1 - \alpha \qquad \forall r$$

$$\sum_m \sum_n \sum_k u_{mnrk} \geq F_{D_r}^{-1}(1 - \alpha) \qquad \forall r$$

$\alpha = 0.1, \quad 1 - \alpha = 0.9$

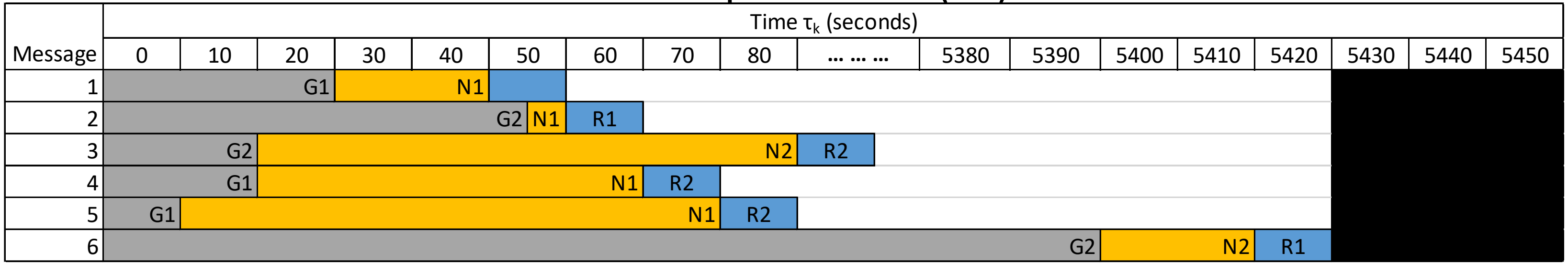
Find the smallest integer value for inverse cdf ($F_{D_r}^{-1}$) that ensures that D_r is met at least 90% of the time

Small Example Results (P3)



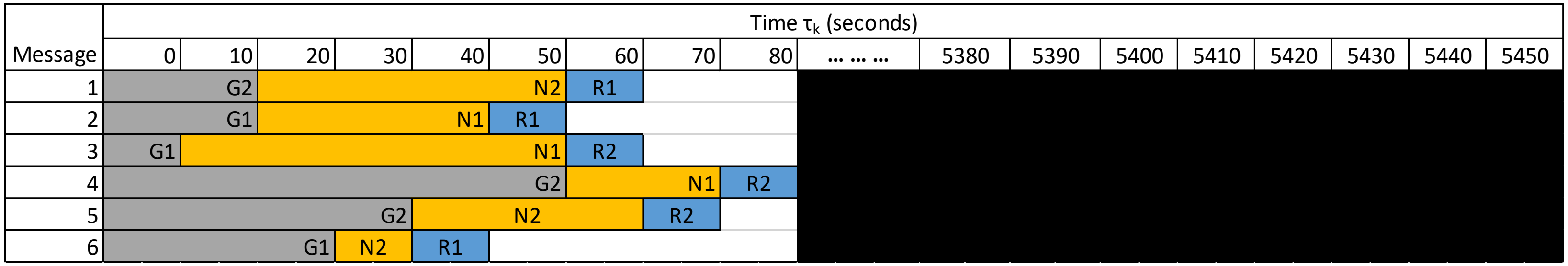
Message	Time τ_k (seconds)																
	0	10	20	30	40	50	60	70	80	… … …	5380	5390	5400	5410	5420	5430	5440	5450
1	G1					N2	R1											
2	G2				N2	R1												
3	G2			N2				R2										
4	G2													N2				R2
5	G1												N1				R2	
6	G1	N1						R1										

Small Example Results (P2)



Message	Time τ_k (seconds)																
	0	10	20	30	40	50	60	70	80	… … …	5380	5390	5400	5410	5420	5430	5440	5450
1	G1			N1												■	■	■
2	G2					N1	R1									■	■	■
3	G2		N2							R2						■	■	■
4	G1		N1					R2								■	■	■
5	G1	N1							R2							■	■	■
6	G2												N2		R1	■	■	■

Small Example Results (P1)



Message	Time τ_k (seconds)																
	0	10	20	30	40	50	60	70	80	… … …	5380	5390	5400	5410	5420	5430	5440	5450
1	G2		N2				R1			■	■	■	■	■	■	■	■	■
2	G1		N1			R1				■	■	■	■	■	■	■	■	■
3	G1	N1					R2			■	■	■	■	■	■	■	■	■
4	G2						N1		R2	■	■	■	■	■	■	■	■	■
5	G2				N2			R2		■	■	■	■	■	■	■	■	■
6	G1			N2	R1					■	■	■	■	■	■	■	■	■

Three Optimization Models

- (P1) provides an optimistic schedule, where all messages are delivered the first time and there is plenty of energy
- (P2) incorporates energy constraints, but still assumes all messages are delivered the first time
- (P3) incorporates energy constraints and also builds in some “slack” to allow for messages needing to be transmitted multiple times

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A Larger Example Description

2 gateways

5 nanosats

6 remote users

21 total messages, 39 message delivery attempts for (P3)

Remote User	1	2	3	4	5	6
Demand	3	7	3	5	1	2

12 hour time window, discretized into 335 time intervals $(k = 335)$

Energy parameters $(e_{min} = 1,\ e_{max} = 4,\ E_{n0} = 1)$

Simulator

Discrete event simulator more detailed than optimization models

Probabilistic message delivery simulation
- Messages may not be successfully delivered on the first attempt
- 10 trials

Energy dynamics are simulated

Message queue and path based on different policies:
- Greedy policy
- Message path solutions from (P1), (P2), and (P3)

Time-ordered event list based on beginning of contact time windows between ground nodes and nanosats

Policies

Greedy

- Quickest path from CCC to a remote user
- Use this path for every message to that remote user

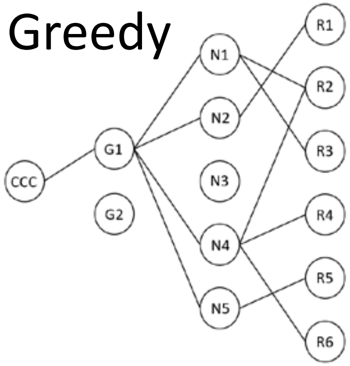
(P1): Deterministic demand without energy

(P2): Deterministic demand with energy

(P3): Probabilistic demand with energy

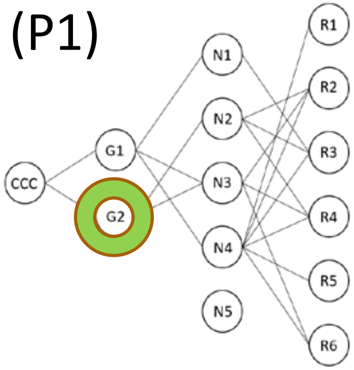
Result Routes for Greedy, (P1), (P2) and (P3)

Greedy



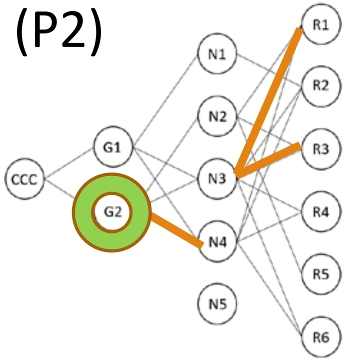
Greedy policy only uses one gateway and four nanosats

(P1)



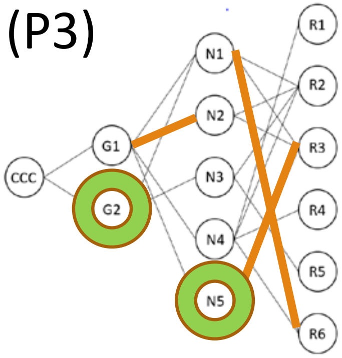
(P1) uses both gateways and four nanosats

(P2)



(P2) uses both gateways, four nanosats, and more routes than (P1)

(P3)



(P3) uses both gateways, five nanosats, almost all routes, and is more evenly balanced

Simulation Results for Four Policies with Probabilistic Demand

Average results from 10 runs

(P3) gives the best results

- (P3) is more evenly distributed so can accommodate random events better

	Greedy	**Simulated (P1)**	**Simulated (P2)**	**Simulated (P3)**
Average Total Delivery Time (seconds)	1,999,760	2,078,320	1,998,210	1,925,410
Average Minimum Delivery Time (seconds)	72,830	75,690	72,850	73,510
Average Maximum Delivery Time (seconds)	129,520	133,410	135,660	126,270

Summary and Future Work

Summary:

- Deterministic models (P1) and (P2) are quickly computed
- Probabilistic model (P3) provides a more balanced use of resources
- Simulation results and policies comparison shows that (P3) message paths give best results

Future Work:

- Message preemption and priority
- Nanosat cross-links
- Constellation optimization