

TOWARDS A DISASTER RESPONSE SYSTEM BASED ON CUBESAT CONSTELLATIONS

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AGENDA

- Introduction
- Problem formulation
- Proposed intelligent and resilient communication infrastructure
- Simulation results
- Conclusions

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INTRODUCTION

- One critical challenge of disaster response management during long-lasting natural disasters and pandemics is to have a reliable communication infrastructure.
 - In typical disaster situations such as tornadoes and floods, communication mechanisms are necessary for facilitating disaster relief operations.
 - In persistent disasters such as the recent pandemic, where people need to work remotely, resilient networking infrastructure is demanding to deliver dynamic traffic streams to unprecedented geographical reaches while meeting the requirements of the associated applications.

INTRODUCTION

- Amongst different established communication technologies, satellite communication has provided a promising communication solution in disaster situations.
 - There are existing satellite-based solutions that are capable of providing low latency and high throughput communication to remote geographical areas, such as Starlink and Amazon's Project Kuiper.

INTRODUCTION

- CubeSats are a breed of satellites that can provide telecommunication services at a much lower cost due to their standardized construction and lower weight.
 - The coverage area of a CubeSat can be significantly improved by using CubeSat constellations.
 - ✓ CubeSat constellations have a great potential to serve as a networking infrastructure for disaster situations given its low cost of deployment.

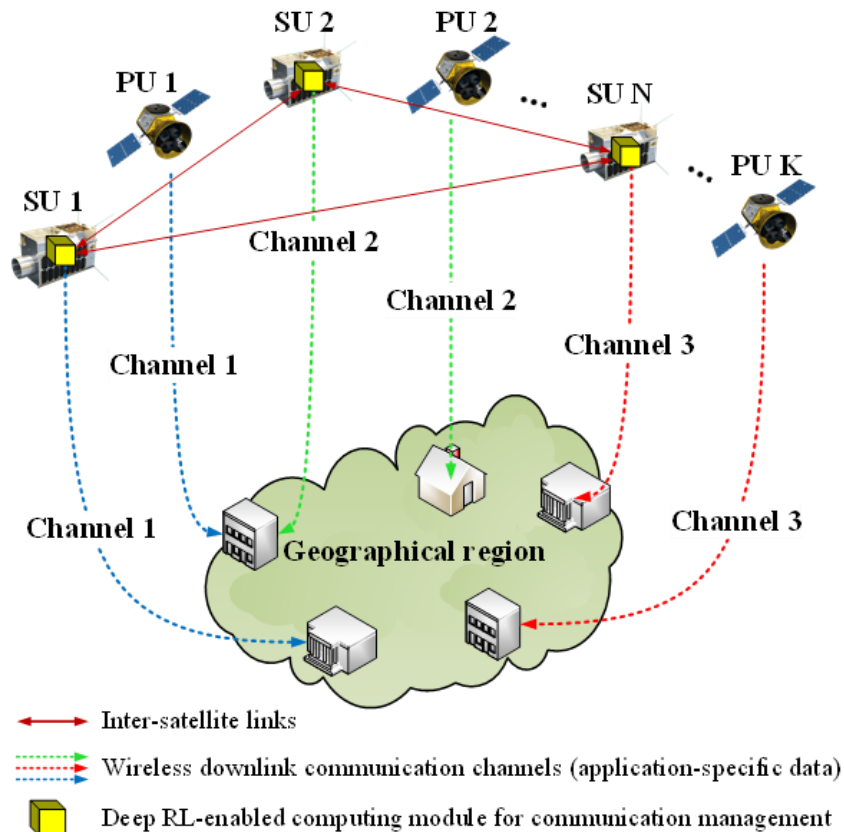
INTRODUCTION

- In our work, we exploit the CubeSat, cognitive radio (CR), and deep reinforcement learning (RL) technologies to develop a CR-powered CubeSat Internet constellation-enabled intelligent and resilient communication infrastructure as a disaster response system.

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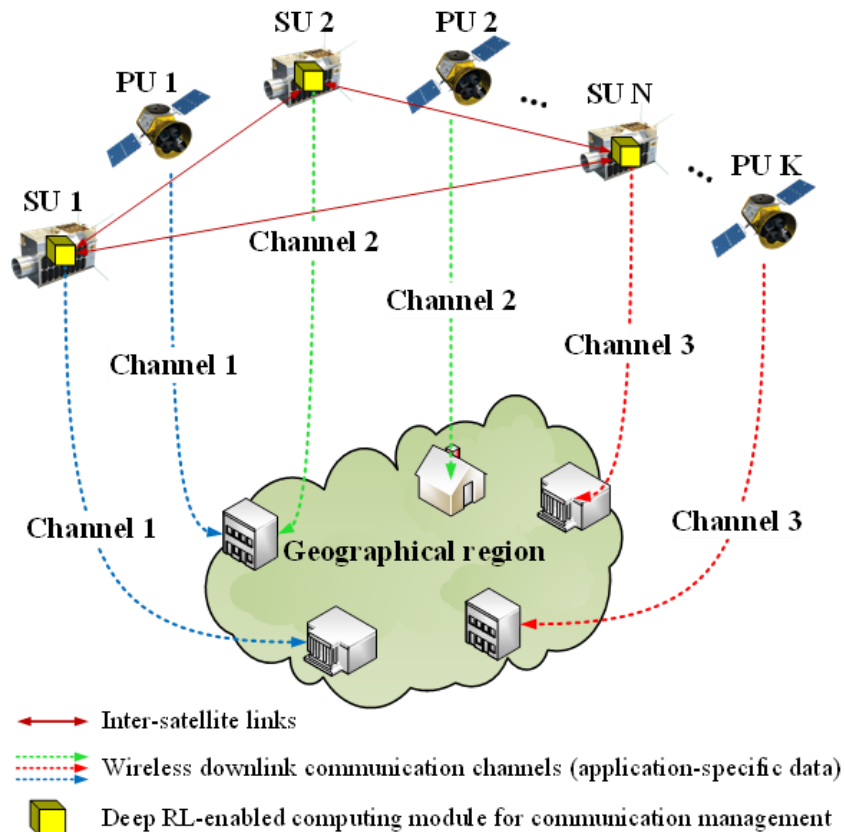
PROBLEM FORMULATION



- In our CR-powered CubeSat Internet constellation-enabled intelligent and resilient communication infrastructure:

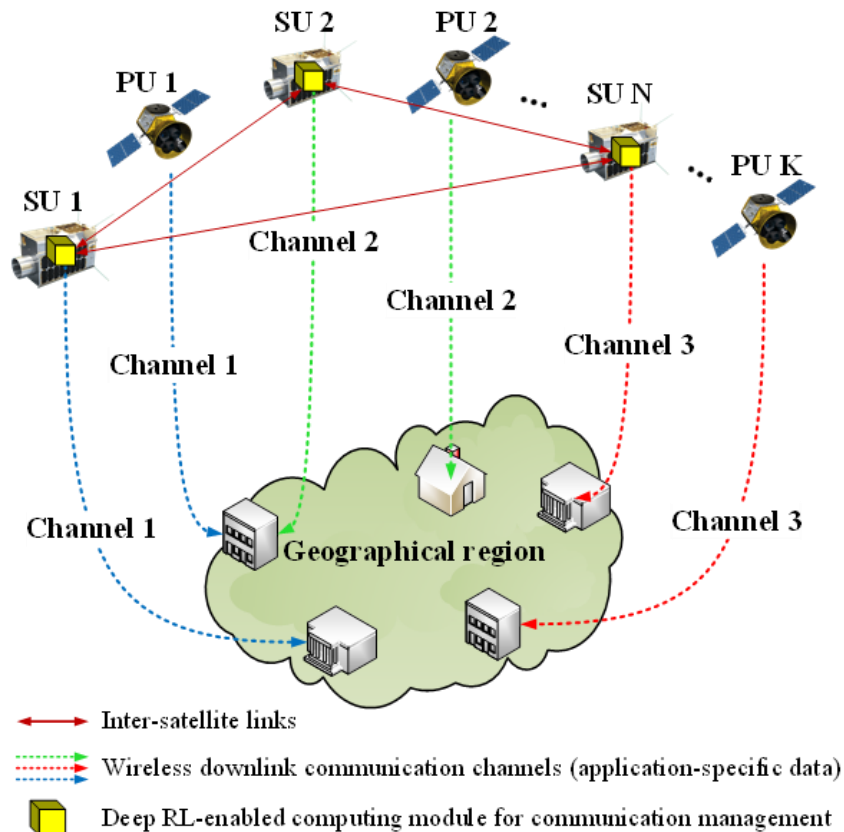
- Each CubeSat agent in the constellation acts as a Secondary User (SU).
- Primary Users (PUs) in our work can be satellites that have been launched for applications, such as meteorological observation, earth observation, and communication.

PROBLEM FORMULATION



- We consider that N SUs cooperate in a decentralized and secure manner to exploit K licensed channels belonging to K PUs, where each channel is occupied by a single PU.
 - The cooperation between the SUs is designed to minimize the interference to PUs and the disruption to other SUs.

PROBLEM FORMULATION



- In this work, the proposed communication infrastructure focuses on supporting the delivery of Video on Demand (VoD) and file transfer traffic streams to ground-based end users.
- For simplicity, we assume that the end users are in closer proximity to each other, and thus frequency reuse is not possible.

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PROPOSED INTELLIGENT AND RESILIENT COMMUNICATION INFRASTRUCTURE

- To fulfill the communication requirements of different applications and ensure satisfactory experiences of the end users, our communication infrastructure is developed to realize QoE-aware traffic management optimization in cognitive communications.
 - The ground-based end users constantly interact with the QoE-aware traffic management mechanism to provide application-driven QoE-related information for traffic management.
 - The SUs in the constellation also communicate with each other to exchange spectrum sensing information.

PROPOSED INTELLIGENT AND RESILIENT COMMUNICATION INFRASTRUCTURE

- To fulfill the communication requirements of different applications and ensure satisfactory experiences of the end users, our proposed communication infrastructure is developed to realize QoE-aware traffic management optimization in cognitive communications.
 - The inter-satellite communication is provided by a Software-Defined Network (SDN) deployed in the CubeSat Internet constellation.
 - The SDN controller in this work is realized via one of the SUs.

PROPOSED INTELLIGENT AND RESILIENT COMMUNICATION INFRASTRUCTURE

- We assume that M number of secondary users choose to transmit on the same channel. For SU j , where $j \in M$, we denote its transmission channel as \mathcal{C}_j .
- By using the FRIIS transmission equation and assuming a unit gain at the receiver end, we formulate the received signal power from SU j at the ground-based receiver as follows:

$$P_r^{SU_j} = \frac{P_t^{SU_j} G_t^{SU_j}}{\left(\frac{4\pi D_t^{SU_j}}{\lambda}\right)^2} \quad (1)$$

PROPOSED INTELLIGENT AND RESILIENT COMMUNICATION INFRASTRUCTURE

- We assume that M number of secondary users choose to transmit on the same channel. For SU j , where $j \in M$, we denote its transmission channel as \mathcal{C}_j .
- Similarly, we can formulate the received signal power from the PU operating on \mathcal{C}_j at the same receiver as:

$$P_r^{PUc_j} = \frac{P_t^{PUc_j} G_t^{PUc_j}}{\left(\frac{4\pi D_t^{PUc_j}}{\lambda} \right)^2} \quad (2)$$

PROPOSED INTELLIGENT AND RESILIENT COMMUNICATION INFRASTRUCTURE

- We consider that a transmitted traffic stream from a SU consists of VoD traffic and file transfer traffic. For file transfer traffic, the end user communicates the size of the file required, $size_j^{ft}$, with SU j , so that SU j can deliver a file equal to the size of the requested payload.
- We also consider that receiving end of a VoD traffic stream sent from SU j has a buffer size of \max_j^B .

PROPOSED INTELLIGENT AND RESILIENT COMMUNICATION INFRASTRUCTURE

- At the beginning of each time slot, a SU decides on the percentage of file transfer traffic to transmit out of total file transfer and VoD traffic.
- If the total received bit rate from SU j is $rate_j^{SU}$, we can define the total received file-transfer traffic and VoD traffic, \mathcal{T}_j^{VOD} and \mathcal{T}_j^{ft} , from SU j at a given time slot as follows.

$$\mathcal{T}_j^{ft} = \mathcal{P}_j^{ft} \cdot rate_j^{SU} \quad (3)$$

$$\mathcal{T}_j^{VOD} = \left(1 - \mathcal{P}_j^{ft}\right) \cdot rate_j^{SU} \quad (4)$$

PROPOSED INTELLIGENT AND RESILIENT COMMUNICATION INFRASTRUCTURE

$$\mathcal{J}_j^{ft} = \mathcal{P}_j^{ft} \cdot rate_j^{SU} \quad (3)$$

$$\mathcal{J}_j^{VOD} = \left(1 - \mathcal{P}_j^{ft}\right) \cdot rate_j^{SU} \quad (4)$$

- \mathcal{P}_j^{ft} denotes the percentage of file transfer traffic.
- $rate_j^{SU}$ can be calculated based on the Shannon-Hartley theorem as follows:

$$rate_j^{SU} = B \cdot \log_2 \left(1 + SINR_j^{SU}\right) \quad (5)$$

➤ $SINR_j^{SU}$ is the SINR of SU j at the receiver:

$$SINR_j^{SU} = \frac{P_r^{SU_j}}{N_0 + P_r^{PUc_j} + \sum_{i=1, i \neq j}^M P_r^{SU_i}} \quad (6)$$

PROPOSED INTELLIGENT AND RESILIENT COMMUNICATION INFRASTRUCTURE

- We next formulate the QoE-aware CR-powered communication management with an optimization model.
 - In our optimization model, we aim to maximize \mathcal{J}_j^{VOD} to satisfy the buffer constraints of the end user while ensuring \mathcal{J}_j^{ft} matches the required file size of the end user.
 - We aim to maximize $SINR_{\mathcal{C}_j}^{PU}$ to ensure that the PU in \mathcal{C}_j experiences a minimum disruption from SU j .
- The objective of our optimization model can be stated as

$$\max_{P_t^{SU_j}, G_t^{SU_j}, D_t^{SU_j}, \mathcal{P}_j^{ft}, \mathcal{C}_j} \left[SINR_{\mathcal{C}_j}^{PU} + \mathcal{J}_j^{VOD} - \left(\mathcal{J}_j^{ft} - size_j^{ft} \right)^2 \right] \quad (8)$$

PROPOSED INTELLIGENT AND RESILIENT COMMUNICATION INFRASTRUCTURE

- For the practical optimization constraints, we consider that
 - The SINR of PUs in their operating channels should be maintained above a certain threshold γ_{min} .
 - The received VoD traffic at the end of each time slot should not overload the buffer, i.e. $\mathcal{B}'_j + \mathcal{T}_j^{VOD} \leq \max_j^{\mathcal{B}}$.
 - The total VoD traffic in the buffer after the received traffic (\mathcal{B}''_j) should be large enough, to give a seamless experience to the end user, i.e. $\mathcal{B}''_j \geq abr_j$.

PROPOSED INTELLIGENT AND RESILIENT COMMUNICATION INFRASTRUCTURE

- For the practical optimization constraints, we consider that
 - \mathcal{T}_j^{ft} should not be less than the requested file size at that time step, i.e. $\mathcal{T}_j^{ft} \geq size_j^{ft}$.
 - $P_t^{SU_j}$, $G_t^{SU_j}$ and $D_t^{SU_j}$ satisfy the operating constraints of the associated CubeSat.

PROPOSED INTELLIGENT AND RESILIENT COMMUNICATION INFRASTRUCTURE

- By combining the optimization objective and practical constraints, we obtain the optimization model as:

$$\max_{P_t^{SU_j}, G_t^{SU_j}, D_t^{SU_j}, \mathcal{P}_j^{ft}, C_j} \left[SINR_{C_j}^{PU} + \mathcal{J}_j^{VOD} - \left(\mathcal{J}_j^{ft} - size_j^{ft} \right)^2 \right] \quad (9)$$

$$\text{subject to} \quad SINR_{C_j}^{PU} \geq \gamma_{min}, \mathcal{J}_j^{ft} \geq size_j^{ft},$$

$$\mathcal{B}_j' + \mathcal{J}_j^{VOD} \leq \max_j^{\mathcal{B}}, \mathcal{B}_j'' \geq abr_j,$$

$$P_t^{max} \geq P_t^{SU_j} \geq P_t^{min}$$

$$G_t^{max} \geq G_t^{SU_j} \geq G_t^{min}$$

$$D_t^{max} \geq D_t^{SU_j} \geq D_t^{min}$$

PROPOSED INTELLIGENT AND RESILIENT COMMUNICATION INFRASTRUCTURE

- To deploy the optimization model for our CubeSat Internet constellation, we propose to model the procedure of determining the transmission parameters based on end users' states and spectrum sensing data as a Markov Decision Process (MDP).
- Considering that RL techniques have been successfully applied in solving optimization problems in MDPs, in our work, we exploit the deep RL technique to solve our optimization model.

PROPOSED INTELLIGENT AND RESILIENT COMMUNICATION INFRASTRUCTURE

- Considering our optimization model involves a continuous action space, we leverage one type of deep RL technique, the Deep Deterministic Policy Gradient (DDPG) RL method, in our work.
- The states and the actions used in our context for the RL method is defined as follows.

$$s_t^j = \left[abr_j, size_j^{ft}, \mathcal{B}'_j, \overline{P^{PU}} \right] \quad (10)$$

$$a_t^j = \left[P_t^{SU_j}, G_t^{SU_j}, D_t^{SU_j}, \mathcal{P}_j^{ft}, \mathcal{C}_j \right] \quad (11)$$

Where $\overline{P^{PU}}$ is the vector consisting of spectrum sensing results $\overline{P^{PU}} = [P_t^{PU_1} \cdot G_t^{PU_1}, P_t^{PU_2} \cdot G_t^{PU_2}, \dots, P_t^{PU_K} \cdot G_t^{PU_K}]$.

PROPOSED INTELLIGENT AND RESILIENT COMMUNICATION INFRASTRUCTURE

- We formulate the reward function in DDPG method to realize our optimization model and design an appropriate penalty mechanism to enforce the practical constraints:

PROPOSED INTELLIGENT AND RESILIENT COMMUNICATION INFRASTRUCTURE

Algorithm 1: Reward function formulation for SU j

$r \leftarrow SINR_{C_j}^{PU} + \mathcal{T}_j^{VOD} - (\mathcal{T}_j^{ft} - size_j^{ft})^2$

if $\mathcal{T}_j^{ft} < size_j^{ft}$ **then**

| $r \leftarrow r - \alpha;$

end

if $\mathcal{B}'_j + \mathcal{T}_j^{VOD} \leq max_j^{\mathcal{B}}$ **then**

| $\mathcal{B}''_j \leftarrow \mathcal{B}'_j + \mathcal{T}_j^{VOD};$

else

| $r \leftarrow r - \beta;$

end

if $\mathcal{B}''_j \geq abr_j$ **then**

| $\mathcal{B}''_j \leftarrow \mathcal{B}''_j - abr_j;$

else

| $r \leftarrow r - \rho;$

end

if $SINR_{C_j}^{PU} < \gamma_{min}$ **then**

| $r \leftarrow r - \delta;$

end

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SIMULATION RESULTS

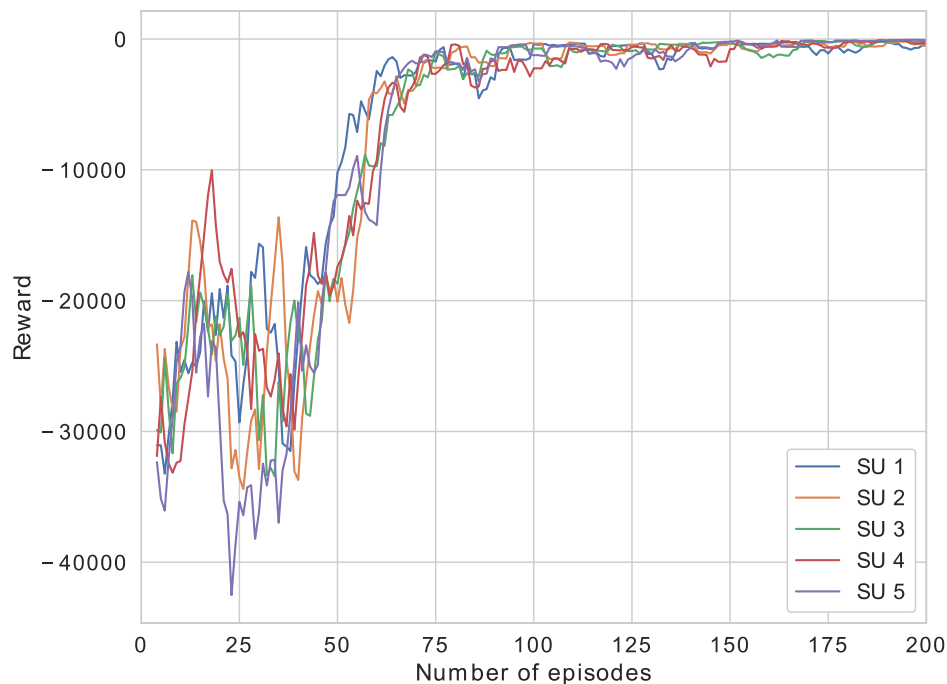
- In our simulation scenarios, we consider 5 CubeSats acting as SUs and operating on four channels with the indices 0, 1, 2, and 3. The operating channels for CubeSats are as follows:
 - CubeSat 1: channels 1, 2, 3
 - CubeSat 2: channels 0, 2, 3
 - CubeSat 3: channels 0, 1, 2, 3
 - CubeSat 4: channels 0, 1, 2, 3
 - CubeSat 5: channels 0, 2

SIMULATION RESULTS

- At the beginning of each episode, an end user requests an adaptive bit rate (ABR) based on their reception quality.
- At each step in an episode, the end user continues to communicate the file transfer size requirement corresponding to that step to the associated SU.
- We consider that the ABR can only be changed at the beginning of each episode.

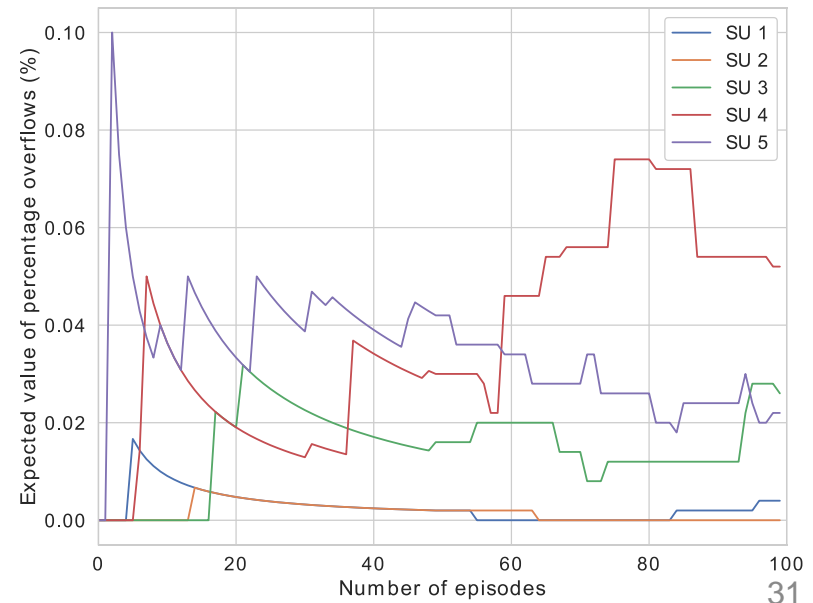
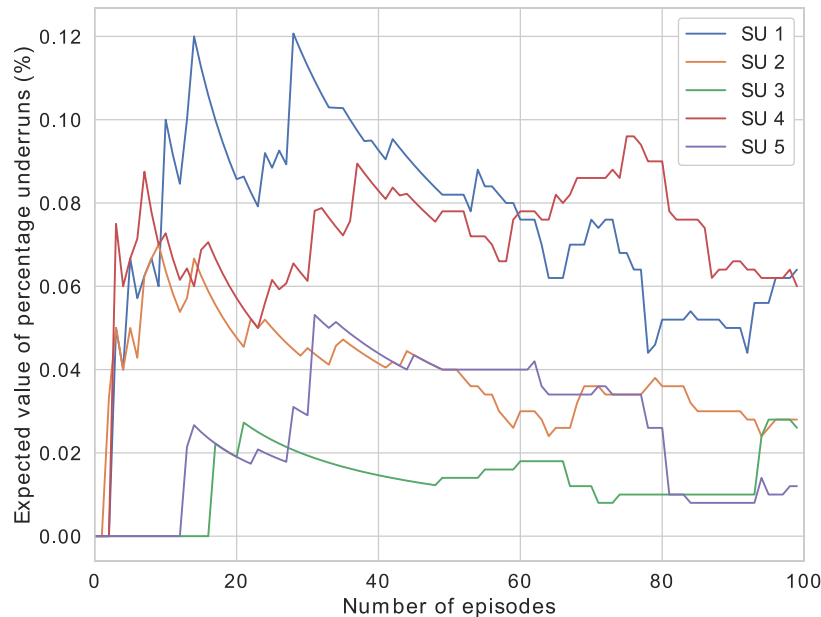
SIMULATION RESULTS

- The reward function quantitatively evaluates the traffic optimization of each CubeSat. From the following plot, we can observe that the value of the reward function for each of the five CubeSats converges to an optimal value after 200 episodes.



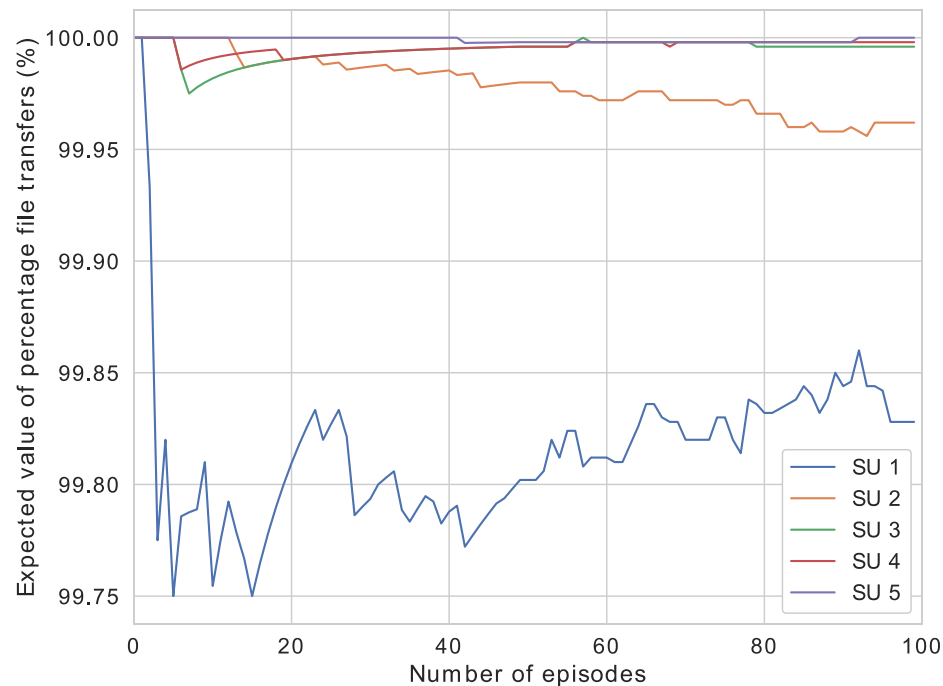
SIMULATION RESULTS

- In our QoE-aware traffic management mechanism, buffer performance is considered as one critical QoE metric. The percentage of buffer underrun incidents and overflow incidents are measured to evaluate the buffer performance. We can observe that each CubeSat can effectively maintain a low level of buffer underrun and overflow incidents in each episode.



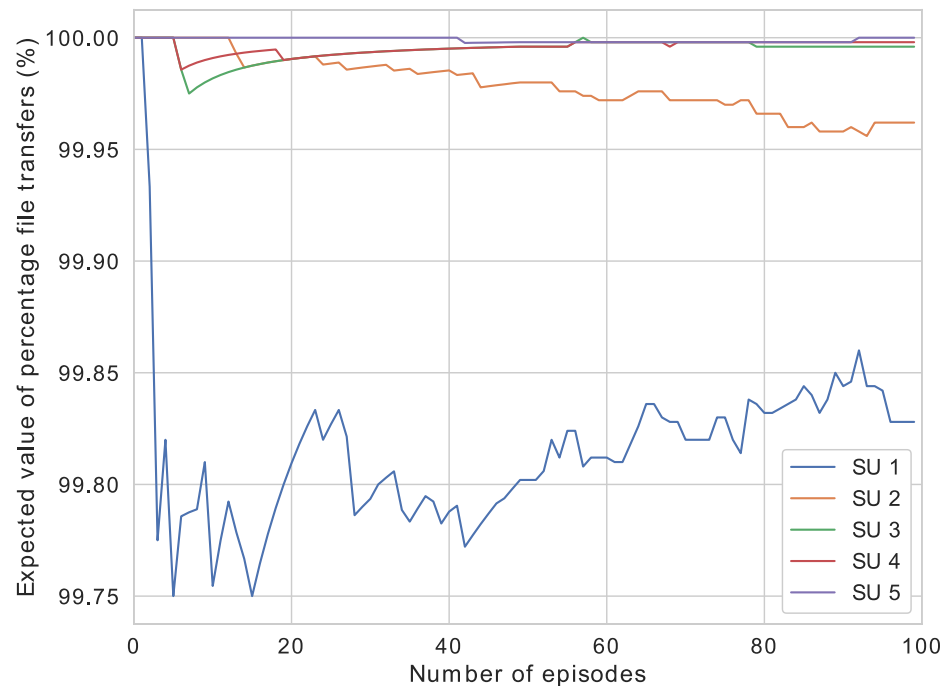
SIMULATION RESULTS

- We further evaluate the performance by measuring the percentage of successful file transfers for each SU. We can observe from the following plot that all the five CubeSat SUs can maintain nearly the maximum file transfer percentage.



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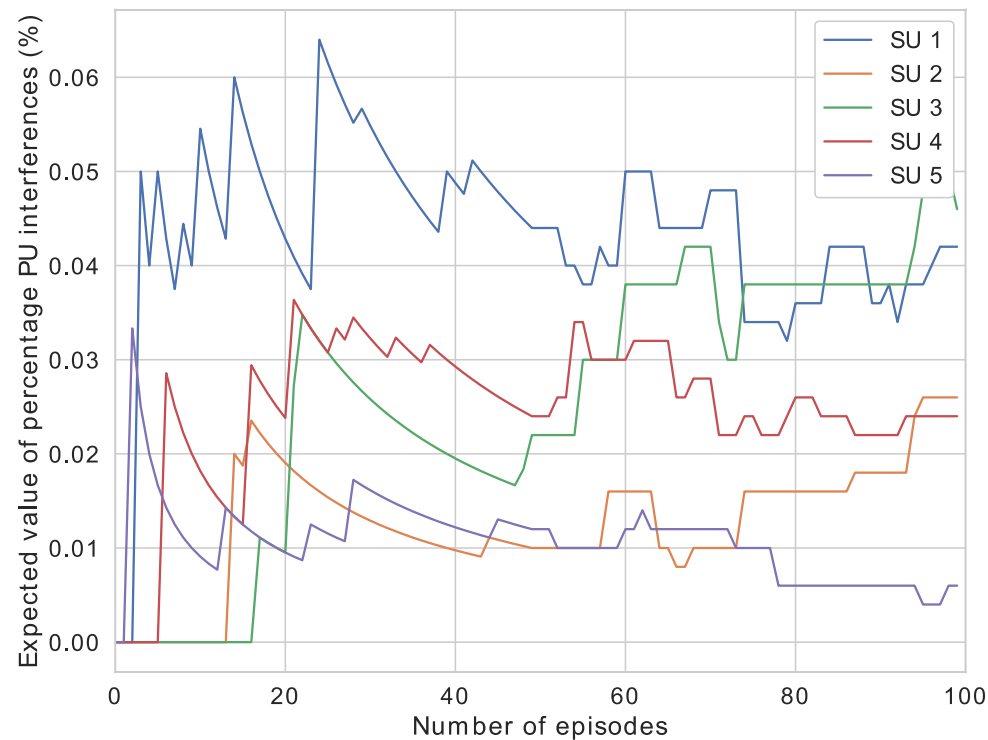


SIMULATION RESULTS

- We also evaluate our proposed traffic management mechanism by considering the potential interference on PUs introduced by each CubeSat SU.
- To achieve this goal, we calculate the PU interference caused by a SU by measuring the percentage of instances where SINR associated with the PU decreases below a certain threshold γ_{min} out of total instances where the SU transmits while a PU is active.

SIMULATION RESULTS

- As shown in the following plot, our proposed traffic management layer enables the minimization of PU interferences for each SU.



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CONCLUSIONS

- In this paper, we have developed a CubeSat Internet constellation-enabled communication infrastructure for disaster management, which has a deep RL-enabled CR-powered traffic optimization mechanism.
 - This traffic optimization mechanism provides cooperative delivery of QoE-aware traffic in a shared medium.
 - The cooperative traffic delivery is performed in such a way by minimizing the disruptions to the PUs operating on the shared bandwidth.

CONCLUSIONS

- We believe that our proposed work will enable a contextual and generalized platform to deliver heterogeneous application traffic geographically amidst varying wireless environmental dynamics.
- In our ongoing work, we are validating our proposed method in a hardware-in-the-loop (HIL) testbed that emulates the actual wireless channel conditions.
- In our future work, we plan to use realistic CubeSat hardware or CubeSat emulators in our HIL setting.

THANK YOU!

QUESTIONS?

BACKUP SLIDES

LIST OF VARIABLES AND THEIR DEFINITIONS

Variables	Definitions
abr_j	Adaptive bit rate at a given time slot corresponding to SU j (bits per second)
B'_j	Buffer size of the customer end at the beginning of a time slot corresponding to SU j (bit)
B''_j	Buffer size of the customer end at the end of a time slot corresponding to SU j (bit)
B	Channel bandwidth (hertz)
$D_t^{PU_k}$	Distance between PU k and the receiver (meter)
$D_t^{SU_j}$	Distance between SU j and the receiver (meter)
P_t^{min}, P_t^{max}	Minimum and maximum transmission power of a SU (watt)
G_t^{min}, G_t^{max}	Minimum and maximum transmission gains of a SU
D_t^{min}, D_t^{max}	Minimum and maximum distances between a SU and a receiver (meter)
γ_{min}	Minimum PU SINR threshold
max_j^B	Maximum buffer size of the customer end corresponding to SU j (bit)

LIST OF VARIABLES AND THEIR DEFINITIONS

Variables	Definitions
N_0	Noise power at the receiver (watt)
\mathcal{P}_j^{ft}	Percentage of file transfer traffic out of total file transfer and VoD traffic for SU j
$\alpha, \beta, \rho, \delta$	Penalty values for optimization function constraints
$size_j^{ft}$	Required size of a file at a given time slot corresponding to SU j (bit)
r	Reward of SU at the end of a certain time slot
λ	Receiver antenna wavelength (meter)
P_t^{SUj}	Transmission power of SU j (watt)
G_t^{SUj}	Transmission gain of SU j
P_t^{PUk}	Transmission power of PU k (watt)
G_t^{PUk}	Transmission gain of PU k
\mathcal{C}_j	Transmission channel of SU j

LIST OF VARIABLES AND THEIR DEFINITIONS

Parameters	Settings
ABR values	235, 375, 560, 750, 1050, 1750, 2350, 3000 kbps
File transfer sizes	256, 512, 1024, 2048 kbits
Maximum buffer size	10000 kbits
Channel bandwidth	20 Mhz
$P_t^{SU_j}$	[0, 5] W
$G_t^{SU_j}$	[0, 5]
$P_t^{PU_k} \cdot G_t^{PU_k}$	0, 10, 20, 30 W
$D_t^{SU_j}$	[449, 451] km
$D_t^{PU_k}$	[500, 600] km
λ	2 m
γ_{min}	0.8
$\alpha, \beta, \rho, \delta$	$\alpha = 600, \beta = 500, \rho = 500, \delta = 100$