

Traffic Control Analysis in High Altitude Platforms using a Semi-Markov Process Approach

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Abstract—This study uses a cooperative communication approach to propose a traffic model for relay nodes in space-air-ground networks. The proposed model is employed in three-layer networks: low earth satellite (LEO), high altitude platform (HAP), and user devices on the ground. This type of aerial communication network is adopted in most Internet of Things (IoT) networks. The analysis has been carried out by constructing traffic models. The traffic model has been analyzed by applying the semi-Markov process due to the non-exponential behaviour of some of the transitions of states. The network's practical lifetime, the average delay of source/relay packets, and throughput are investigated through the novel traffic model. Finally, through numerical illustrations, the impact of the performance measures is shown by conducting a sensitivity analysis.

Index Terms—Aerial communications & networking, cooperative communication, high altitude platform, low earth orbit, semi-Markov process, and traffic model.

I. INTRODUCTION

Space-air-terrestrial (SAT) networks enable widespread access to the Internet of Things (IoT) and mobile users via 6G technology. High altitude platforms (HAPs) and low earth orbit (LEO) satellites are used to accomplish this purpose. These satellites improve system performance and provide coverage to mobile and IoT users in places where ground-based stations are inadequate [1]. Ensuring quality of service (QoS) and managing traffic are pivotal aims of SAT networks. Sustained operation of HAPs is crucial for maintaining satisfactory QoS for users, underscoring the importance of effective power and energy management strategies for HAPs.

These challenges are tackled by proposing different network architectures and analyzing them using various modeling approaches. This research in aerial communications aims to address these challenges using stochastic modeling methods. Specifically concerning traffic management, we examine a model of the SAT network that is applicable to diverse IoT networks. This approach may increase QoS metrics like transmission probability and packet latency while also extending the life of devices.

A. State of the Art

Researchers have launched a targeted investigation into network modeling involving satellites, HAPs, and IoT users ([2], [3]). One of the primary challenges in IoT networks is efficient data transmission. Therefore, managing energy to sustain network operations without compromising QoS is crucial and challenging. HAPs can act as relay nodes between

satellites and IoT users, ensuring QoS requirements in IoT networks. The authors of [4] investigated the cooperative satellites and HAPs network. Furthermore, [5] evaluated HAP-LEO network performance in a broader sense by taking into account the non-uniform satellite distribution through the use of a non-homogeneous Poisson point process. In [6], a Markov process was employed to model a system where HAP work as a relay node for up-link data transfer. The results obtained from this model were compared with simulated outcomes. The HAP system was modeled in [7] in order to analyze performance while taking into account various arrival and service procedures.

In rural areas without ground base stations or HAP-oriented ground stations, the authors of [8] jointly investigated the usage of HAP-LEO satellite to assist IoT users. They explored the collaborative operation of HAPs and satellites to establish a SAT network in [4]. Reference [9] introduced a constellation design technique for a large network of HAPs aimed at ensuring QoS and meeting user demands. In [10], the utilization of millimeter-wave technology by HAPs to cover under served areas was examined. Several studies have detailed the system's characteristics, including reliability, performance, power management, and energy efficiency, using stochastic modeling approaches.

There isn't much research on SAT networks using stochastic modeling in the scope of current literature. The authors of [11] proposed a stochastic model for the energy saving in HAP-LEO communication network whereas the underlying study focuses on the energy harvesting scenario in SAT network. The study being presented focuses on the performance analysis of a SAT network using a generalized stochastic model, the semi-Markov process (SMP) model. For some system states, general sojourn time has been taken into consideration, and the basic assumptions of exponential distribution have been relaxed.

B. Motivation and Contributions

In this paper, we aim to investigate a network model that consists of three key components: LEO satellites, HAP, and IoT devices. This model shows considerable promise for integration into diverse IoT networks. However, it encounters several challenges, such as traffic management, optimizing throughput, and fulfilling QoS requirements for IoT devices. To tackle these challenges, a novel stochastic model is de-

vised and extensively examined. This paper provides valuable insights into the potential benefits of a cooperative communication approach within the SAT network. The analysis is valid only for uplink data transmission.

The primary contributions of this study are as follows:

- 1) A stochastic model has been crafted to scrutinize the traffic dynamics within this multi-layer architecture. Within this model, certain transition states exhibit behaviour that deviates from exponential distributions.
- 2) We have employed the methodology of SMP to comprehensively analyze this traffic model. Through this model, we derive crucial performance metrics, including transmission probabilities, throughput, and average packet delay.
- 3) The proposed study provides sensitivity analysis for both the stochastic models to describe the behaviour of performance measures.

C. Paper Organization

The proposed study is divided into the following sections. Section II consists of the network topology, traffic model and energy harvesting model. The potential stochastic model for traffic control is described in Section III, followed by key performance indicators. Section IV provides in-depth presentations of important performance measures with respect to the several parameters of the system. Finally, Section V concludes with suggestions for further research.

II. SYSTEM DESCRIPTION

A. Network Topology

We employ a simple model to assess the efficacy of a HAP relay in enhancing uplink UE-LEO communication. This model involves a single HAP positioned at the origin on the x-y plane, elevated to a fixed height of H_H km, and a single LEO also positioned at the origin but elevated to a higher fixed height of H_L km, where $H_H < H_L$. Both the HAP and LEO feature circular coverage areas on the plane, with their centres aligned at the origin. All uplink UEs are situated on the plane within the coverage area of the HAP. There are two types of UEs, one of which uses HAP as a relay (UE_1), and the second type (UE_2), which is the users having high power can communicate directly to LEO satellites. Figure 1 depicts the system architecture of the HAP-LEO system, that has been modelled using the stochastic process.

B. Traffic Control Model

The two user types (UE_1 or UE_2) are characterized based on a delay constraints. UE_2 are more delay sensitive in comparison of UE_1 . For the traffic control model, it has been considered that there are two queues. There are two queues. Queue 1 contains UE_1 which are receiving service at HAP and queue 2 contains UE_1 and UE_2 which are receiving service at LEO. To reduce the complexity of the proposed model, it has been assumed that queue 1 can contain a maximum K number of UE_1 's and queue 2 consists of a maximum M number of UE_1 's and UE_2 's. In queue 2, the service is provided on first

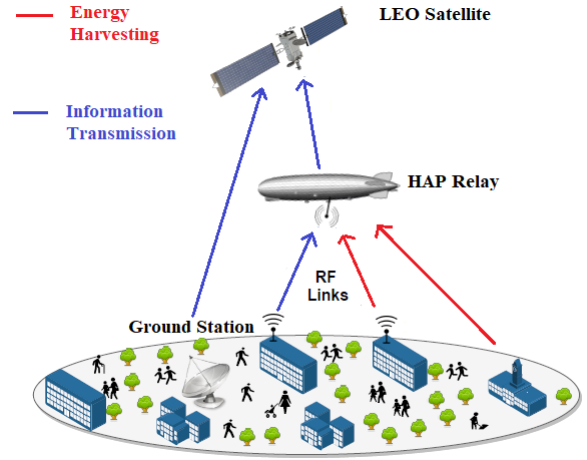


Fig. 1: System architecture of HAP-LEO system

come first serve basis to UE 's. The service of UE_1 will be completed in two phases; in phase 1, it will receive the service from the HAP; in phase 2, it will receive service from LEO. After completing the service from LEO, the UE_1 will exit the system. At the same time, the LEO will directly complete the service of UE_2 . Since UE_1 is a multi-hop model, it is considered that both the queues have concatenation i.e., once UE_1 completes it's service it will exit queue 1 and it will join queue 2 to complete it's service in phase 2.

There is specific information on the system statuses in Table I.

III. SMP MODEL FOR TRAFFIC CONTROL

This section consists of the steady-state analysis of the proposed model. Let $\{X(t), t \in T\}$ denote the state process of the system where $X(t)$ denotes the state of the underlying system at time t . Here, each system state has correspondence to the time instances, e.g., $X = \{(0, 0) \cap (i^H, j) \cap (i^L, j); 1 \leq i^H \leq K, 1 \leq i^L \leq K, 1 \leq j \leq M\}$ corresponds to $T = \{t_0, t_1, t_2, \dots\}$.

The sojourn times for the service processes of the packets follow general distributions where the Markov property is satisfied at time epochs T . Consequently, the most appropriate description of the underlying stochastic process is the semi-Markov process (SMP). Equation (1) represents the state space for the specified stochastic process.

$$\Omega = \{(0, 0) \cap (i^H, j) \cap (i^L, j); 1 \leq i^H, i^L \leq K, 1 \leq j \leq M\}. \quad (1)$$

Table II provides the notations and their description used in the proposed traffic model. Table III denotes the distributions of sojourn times for the SMP model. Figure 2 represents the state transition diagram of the underlying stochastic traffic model. Here, the UE_1 arrives with rate λ_1 and UE_2 arrives with rate λ_2 . The service to UE_1 is provided with rate μ_H in phase 1 and with rate μ_L in phase 2. Similarly, the service to UE_2 is provided with rate μ_2 .

States	Functionalities
Idle state	The system is idle until packets arrive.
Active state of HAP & LEO on the arrival of UE_1	There are two possibilities for the busy states a) if HAP serves to incoming UE_1 packets b) if LEO serves to those UE_1 packets which HAP has served in phase 1.
Active state of LEO on the arrival of UE_2	LEO serves to UE_2 packets

TABLE I: Description of states of traffic control model.

TABLE II: Notations and their description.

Notation	Description
λ_1, λ_2	Arrival of UE_1 , and UE_2 , respectively.
μ_H, μ_L	Service of UE_1 from HAP and LEO, respectively.
μ_2	Service of UE_2 from LEO

The finite capacity of the system defines its stability. The existence and uniqueness of the SMP model's steady-state probability follow. The two-stage method is used to compute the steady-state probabilities. In this method, the entries of kernel matrix $K_{m,n}(t) = P\{X_1 = n, t_1 \leq t \mid X_0 = m\}$ are computed where $m, n \in \Omega$ and $\{(X_n, t_n), n \geq 0\}$.

The cumulative distribution function (CDF) for the transition from state m to n of the state space is defined as $F_{m,n}$. The non-zero elements of the kernel matrix are computed using the methodology described in [11].

$$K_{(0,0),(1^H,0)}(t) = \int_0^t (1 - F_{(0,0),(0,1)}(x)) dF_{(0,0),(1^H,0)}(x),$$

$$= \frac{\lambda_1}{\lambda_1 + \lambda_2} (1 - e^{-(\lambda_1 + \lambda_2)t}). \quad (2)$$

Similarly, following Equation (2), the other entries are computed and are given in Table IV.

TABLE III: Distributions of sojourn times in semi-Markov model for general distributions.

CDF	General Distribution	Mean
$F_{(i^H,j),(i^L,j)}(t)$	Deterministic	$\frac{1}{\mu_H}$
$F_{(i^L,j),((i-1)^L,j)}(t)$	Deterministic	$\frac{1}{\mu_L}$
$F_{(i^H,j),(i^H,j-1)}(t)$	Deterministic	$\frac{1}{\mu_2}$
$F_{(i^H,j),((i+1)^H,j)}(t)$	Exponential	λ_1
$F_{(i^H,j),(i^H,j+1)}(t)$	Exponential	λ_2

A. Steady-State Analysis

The matrix $K(\infty)$ with entries $K_{m,n}(\infty)$ constructs the one step transition probabilities for the model where $K_{m,n}(\infty) = \lim_{t \rightarrow \infty} K_{m,n}(t)$, where $m, n \in \Omega$. The steady-state probabilities of embedded Markov chain (v_{ij}) are obtained by solving Equation (3)

$$v = vK(\infty), \quad \sum_{i,j \in \Omega} v_{ij} = 1, \quad (3)$$

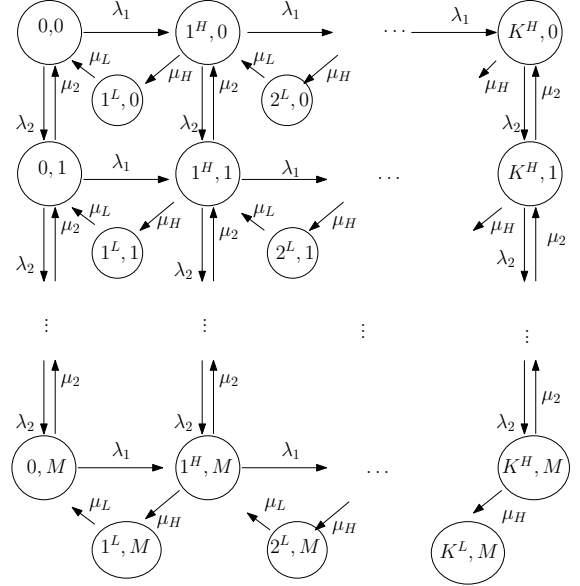


Fig. 2: State transition diagram of traffic model

where, $v = (v_1, v_2, \dots, v_{ij}); i, j \in \Omega$ is the steady-state probability vector. The steady-state probabilities for the proposed SMP model are computed by Equation (4)

$$\pi(i, j) = \frac{v_{ij} h_{ij}}{\sum_{i,j \in \Omega} v_{ij} h_{ij}}, \quad i, j \in \Omega, \quad (4)$$

where h_{ij} is the mean sojourn time spent by the process in each state. The expected sojourn times can be computed as below mentioned.

$$h_{00} = \int_0^\infty (1 - F_{00,01}(t))(1 - F_{00,1^H0}(t)) dt,$$

$$= \frac{1}{\lambda_1 + \lambda_2}, \quad (5)$$

$$h_{0j} = \int_0^\infty \left[(1 - F_{0j,0j+1}(t))(1 - F_{0j,1^Hj}(t)) \right. \\ \left. \times (1 - F_{0j,0j-1}(t)) \right] dt$$

$$= \frac{1 - e^{-(\lambda_1 + \lambda_2)/\mu_2}}{\lambda_1 + \lambda_2}; \quad j = 1, 2, \dots, M-1, \quad (6)$$

TABLE IV: Kernel matrix entries.

Notations	Values	Notations	Values
$K_{(0,0),(0,1)}(t)$	$\frac{\lambda_2}{\lambda_1+\lambda_2}(1 - e^{-(\lambda_1+\lambda_2)t})$	$K_{(i^H,0),((i+1)^H,0)}(t)$	$\begin{cases} \frac{\lambda_1}{\lambda_1+\lambda_2}(1 - e^{-(\lambda_1+\lambda_2)/\mu_H}), & t \geq \frac{1}{\mu_H} \\ \frac{\lambda_1}{\lambda_1+\lambda_2}(1 - e^{-(\lambda_1+\lambda_2)t}), & t < \frac{1}{\mu_H} \end{cases}$
$K_{(i^H,0),(i^H,1)}(t)$	$\begin{cases} \frac{\lambda_2}{\lambda_1+\lambda_2}(1 - e^{-(\lambda_1+\lambda_2)/\mu_H}), & t \geq \frac{1}{\mu_H} \\ \frac{\lambda_2}{\lambda_1+\lambda_2}(1 - e^{-(\lambda_1+\lambda_2)t}), & t < \frac{1}{\mu_H} \end{cases}$	$K_{(i^H,0),(i^L,0)}(t)$	$\begin{cases} e^{-(\lambda_1+\lambda_2)/\mu_H}, & t \geq \frac{1}{\mu_H} \\ 0, & t < \frac{1}{\mu_H} \end{cases}$
$K_{(K^H,0),(K^L,0)}(t)$	$\begin{cases} e^{-\lambda_2/\mu_H}, & t \geq \frac{1}{\mu_H} \\ 0, & t < \frac{1}{\mu_H} \end{cases}$	$K_{(K^H,0),(K^H,1)}(t)$	$\begin{cases} 1 - e^{-\lambda_2/\mu_H}, & t \geq \frac{1}{\mu_H} \\ 1 - e^{-\lambda_2 t}, & t < \frac{1}{\mu_H} \end{cases}$
$K_{(i^L,j),((i-1)^H,j)}(t)$	$\begin{cases} 1, & t \geq \frac{1}{\mu_L} \\ 0, & t < \frac{1}{\mu_L} \end{cases}$	$K_{(i,j),(i,j-1)}(t)$	$\begin{cases} e^{-(\lambda_1+\lambda_2)/\mu_2}, & t \geq \frac{1}{\mu_2} \\ 0, & t < \frac{1}{\mu_2} \end{cases}$
$K_{(i,j),(i,j+1)}(t)$	$\begin{cases} \frac{\lambda_2}{\lambda_1+\lambda_2}(1 - e^{-(\lambda_1+\lambda_2)/\mu_2}), & t \geq \frac{1}{\mu_2} \\ \frac{\lambda_2}{\lambda_1+\lambda_2}(1 - e^{-(\lambda_1+\lambda_2)t}), & t < \frac{1}{\mu_2} \end{cases}$	$K_{(i,j),((i+1)^H,j)}(t)$	$\begin{cases} \frac{\lambda_1}{\lambda_1+\lambda_2}(1 - e^{-(\lambda_1+\lambda_2)/\mu_2}), & t \geq \frac{1}{\mu_2} \\ \frac{\lambda_1}{\lambda_1+\lambda_2}(1 - e^{-(\lambda_1+\lambda_2)t}), & t < \frac{1}{\mu_2} \end{cases}$
$K_{(i^H,j),(i^H,j-1)}(t)$	$\begin{cases} e^{-(\lambda_1+\lambda_2)/\mu_2}, & t \geq \frac{1}{\mu_H} > \frac{1}{\mu_2} \\ e^{-(\lambda_1+\lambda_2)/\mu_H}, & t \geq \frac{1}{\mu_2} > \frac{1}{\mu_H} \\ 0, & \text{otherwise} \end{cases}$	$K_{(i^H,j),((i+1)^H,j)}(t)$	$\begin{cases} \frac{\lambda_1}{\lambda_1+\lambda_2}(1 - e^{-(\lambda_1+\lambda_2)/\mu_H}), & t \geq \frac{1}{\mu_2} > \frac{1}{\mu_H} \\ \frac{\lambda_1}{\lambda_1+\lambda_2}(1 - e^{-(\lambda_1+\lambda_2)/\mu_2}), & t \geq \frac{1}{\mu_H} > \frac{1}{\mu_2} \\ 0, & \text{otherwise} \end{cases}$
$K_{(i^H,j),(i^H,j+1)}(t)$	$\begin{cases} \frac{\lambda_2}{\lambda_1+\lambda_2}(1 - e^{-(\lambda_1+\lambda_2)/\mu_H}), & t \geq \frac{1}{\mu_2} > \frac{1}{\mu_H} \\ \frac{\lambda_2}{\lambda_1+\lambda_2}(1 - e^{-(\lambda_1+\lambda_2)/\mu_2}), & t \geq \frac{1}{\mu_H} > \frac{1}{\mu_2} \\ 0, & \text{otherwise} \end{cases}$	$K_{(0,M),(1^H,M)}(t)$	$\begin{cases} 1 - e^{-\lambda_1/\mu_2}, & t \geq \frac{1}{\mu_2} \\ 1 - e^{-\lambda_1 t}, & t < \frac{1}{\mu_2} \end{cases}$
$K_{(0,M),(0,M-1)}(t)$	$\begin{cases} e^{-\lambda_1/\mu_2}, & t \geq \frac{1}{\mu_2} \\ 0, & t < \frac{1}{\mu_2} \end{cases}$	$K_{(i^H,M),(i^H,M-1)}(t)$	$\begin{cases} (1 - e^{-\lambda_1/\mu_H}), & t \geq \frac{1}{\mu_2} > \frac{1}{\mu_H} \\ (1 - e^{-\lambda_1/\mu_2}), & t \geq \frac{1}{\mu_H} > \frac{1}{\mu_2} \\ 0, & \text{otherwise} \end{cases}$
$K_{(i^H,M),(i^L,M)}(t)$	$\begin{cases} (1 - e^{-\lambda_1/\mu_H}), & t \geq \frac{1}{\mu_2} > \frac{1}{\mu_H} \\ (1 - e^{-\lambda_1/\mu_2}), & t \geq \frac{1}{\mu_H} > \frac{1}{\mu_2} \\ 0, & \text{otherwise} \end{cases}$	$K_{(i^H,M),((i+1)^H,M)}(t)$	$\begin{cases} e^{-\lambda_1/\mu_H}, & t \geq \frac{1}{\mu_2} > \frac{1}{\mu_H} \\ e^{-\lambda_1/\mu_2}, & t \geq \frac{1}{\mu_H} > \frac{1}{\mu_2} \\ 0, & \text{otherwise} \end{cases}$
$K_{(K^H,M),(K^H,M-1)}(t)$	$\begin{cases} 1, & t \geq \frac{1}{\mu_H} > \frac{1}{\mu_2} \\ 0, & \text{otherwise} \end{cases}$	$K_{(K^H,M),(K^L,M)}(t)$	$\begin{cases} 1, & t \geq \frac{1}{\mu_2} > \frac{1}{\mu_H} \\ 0, & \text{otherwise} \end{cases}$

$$h_{0M} = \int_0^\infty \left[(1 - F_{0M,0M-1}(t))(1 - F_{0M,1^H M}(t)) \right. \\ \left. \right] dt = \frac{1 - e^{-\lambda_1/\mu_2}}{\lambda_1}, \quad (7)$$

$$h_{i^H 0} = \int_0^\infty \left[(1 - F_{i^H 0,i^H 1}(t))(1 - F_{i^H 0,(i+1)^H 0}(t)) \right. \\ \left. \times (1 - F_{i^H 0,i^L 0}(t)) \right] dt \\ = \frac{1 - e^{-(\lambda_1+\lambda_2)/\mu_H}}{\lambda_1 + \lambda_2}; \quad i^H = 1, 2, \dots, K-1, \quad (8)$$

$$h_{K^H 0} = \int_0^\infty \left[(1 - F_{K^H 0,K^H 1}(t))(1 - F_{K^H 0,K^L 0}(t)) \right. \\ \left. \right] dt = \frac{1 - e^{-\lambda_2/\mu_H}}{\lambda_2}, \quad (9)$$

$$h_{i^L j} = \int_0^\infty (1 - F_{i^L 0,00}(t)) dt = \frac{1}{\lambda_2}, \quad (10)$$

$$h_{ij} = \int_0^\infty \left[(1 - F_{ij,i^L j}(t))(1 - F_{ij,i^H j+1}(t)) \right]$$

$$\times (1 - F_{ij,i+1 j}(t))(1 - F_{ij,i j-1}(t)) \Big] dt \\ = \begin{cases} \frac{1 - e^{-(\lambda_1+\lambda_2)/\mu_H}}{\lambda_1+\lambda_2}, & \frac{1}{\mu_2} > \frac{1}{\mu_H} \\ \frac{1 - e^{-(\lambda_1+\lambda_2)/\mu_2}}{\lambda_1+\lambda_2}, & \frac{1}{\mu_H} > \frac{1}{\mu_2} \end{cases}. \quad (11)$$

B. Performance Measures

This section provides the performance indicators related to the network traffic model in the expression form.

- Transmission probability of HAP

$$p^t = \sum_{i^H=1}^K \sum_{j=0}^M \pi(i^H, j). \quad (12)$$

- Throughput of the system

$$T = \left[\sum_{i^H=1}^K \sum_{j=0}^M \pi(i^H, j) + \sum_{i^L=1}^K \sum_{j=0}^M \pi(i^L, j) \right. \\ \left. + \sum_{j=1}^M \pi(0, j) \right] \mu. \quad (13)$$

- Average packet delay at HAP and LEO queues

$$D_s = D_H + D_L = \frac{L_H}{\lambda_1} + \frac{L_L}{\lambda_2}$$

$$= \frac{\sum_{i=1}^K \sum_{j=0}^M i^H \pi(i^H, j)}{\lambda_1} \quad (14)$$

$$+ \frac{\sum_{i^H=1}^K \sum_{j=0}^M j \pi(i^H, j)}{\lambda_2}. \quad (15)$$

IV. NUMERICAL ILLUSTRATION

This section provides a sensitivity analysis of the performance measures concerning the system parameters. Estimation of the parameters is out of the scope this study, therefore, the values of some of the parameters have been taken from [11]. Table V denotes the values of parameters considered for the numerical illustration.

TABLE V: Default values of parameters [11].

Parameters	λ_1, λ_2	μ_H, μ_L, μ_2	$M = K$
Possible values	$0.5 - 2/ms$	$0.5 - 3/ms$	100

In this section, the assumption of general distribution is relaxed and exponential distribution is considered instead. The relaxation of assumption converts the underlying SMP model into a continuous time Markov (CTMC) chain model. A comparison of results will also be provided in this section. The behavior of the transmission probability of HAP (p^t) with regard to μ and λ is shown in Figure 3. Figure 4 shows the comparison in the values of p^t if the general assumption is relaxed and converted to exponential one. It signifies that the consideration of different results may affect the estimation of system performance. The behavior of delay (D_s) with regard to μ ($\mu_H + \mu_L + \mu_2$) and λ ($\lambda_1 + \lambda_2$) is shown in Figure 5. The average packet latency will decrease as μ increases but will increase relative to λ . Similarly, Figure 6 shows the difference between the values for SMP case and relaxed case CTMC.

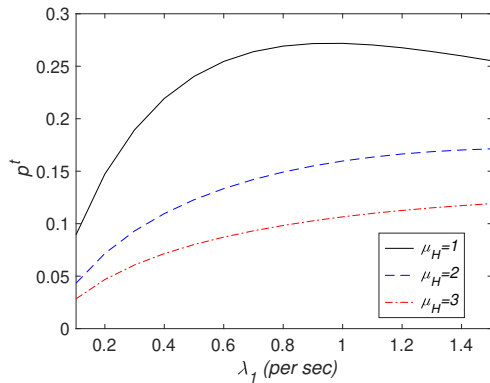


Fig. 3: Transmission probability versus service rate.

The behavior of throughput (T) in relation to μ and λ is depicted in Figure 7. Due to more packets in the system, a greater parameter λ value corresponds to an increased T . It is also observed that T rises as μ increases, indicating that more packets are served and hence, higher throughput.

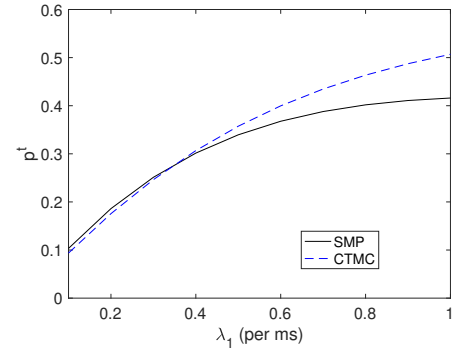


Fig. 4: Transmission probability versus arrival rate of UE_1 with SMP and CTMC case

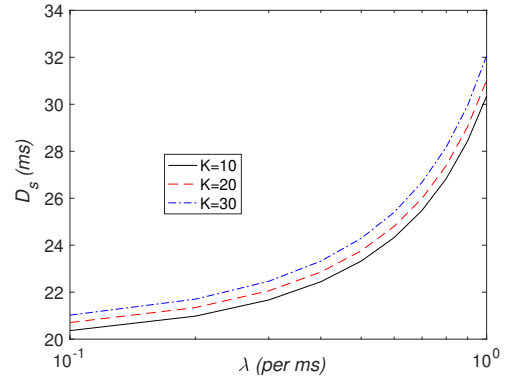


Fig. 5: Delay versus arrival rate.

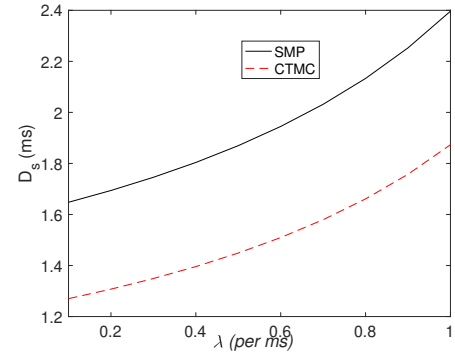


Fig. 6: Delay versus arrival for SMP and CTMC cases

V. CONCLUSIONS & FUTURE DIRECTIONS

This study presents a cooperative SAT communication network tailored for HAP systems. The innovative stochastic model is engineered for implementation across three distinct layers: LEO satellites, HAPs, and ground-based user devices. The research delves into the construction of a detailed traffic model. This model is meticulously analyzed using a SMP to accommodate the non-exponential behavior exhibited in certain state transitions. The traffic model investigates crucial performance metrics, including the practical lifetime of the

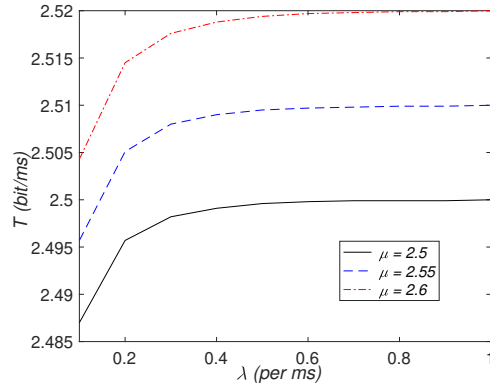


Fig. 7: Throughput versus service rate.

network, the average delay experienced by source and relay packets, and overall throughput. To illustrate the significance of these metrics, the study provides an in-depth numerical analysis, showcasing the effects through a comprehensive sensitivity analysis.

In future, the proposed model can be studied from the energy management perspective for HAP.

VI. ACKNOWLEDGEMENT

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