

RF/FSO Switching Method for LEO-HAPS Downlink Using Deep Reinforcement Learning

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Abstract—Low Earth orbit (LEO) satellite to high-altitude platform station (HAPS) backhaul links have been actively studied to provide high capacity and reliable connectivity in sixth-generation (6G) non-terrestrial networks (NTN). Hybrid radio-frequency (RF) and free-space optical (FSO) communication can meet these requirements by jointly leveraging the high capacity of FSO and the robustness of RF. However, determining the optimal RF/FSO link is difficult due to stochastic FSO channel fluctuations caused by atmospheric turbulence and pointing errors. This paper proposes a deep Q-network (DQN)-based RF/FSO switching method for LEO-HAPS downlink backhaul networks. The link selection problem is formulated as a partially observable Markov decision process (POMDP). Consequently, the proposed method balances throughput maximization and outage reduction under a fixed switching penalty.

Index Terms—Low Earth orbit (LEO) satellite, high-altitude platform station (HAPS), radio-frequency (RF), free-space optical (FSO), deep Q-network (DQN)

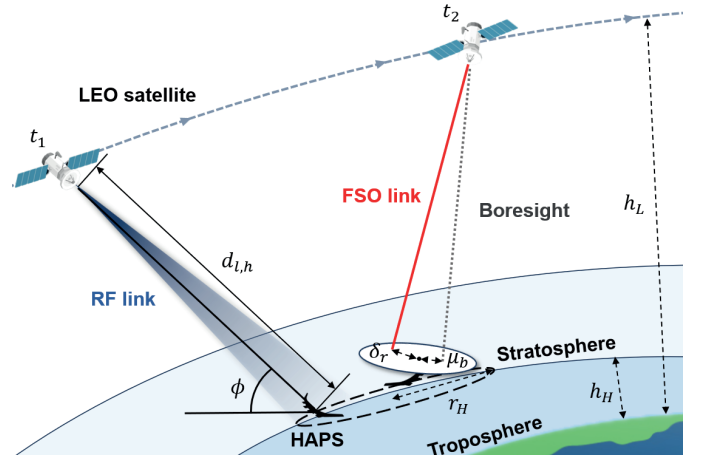


Fig. 1: Hybrid RF/FSO backhaul network scenario between the LEO satellite and the HAPS.

I. INTRODUCTION

Low Earth orbit (LEO) satellites and high-altitude platform stations (HAPS) are emerging as key components of sixth-generation (6G) non-terrestrial networks (NTN), where reliable LEO-HAPS backhaul links are necessary for high capacity [1]. Free-space optical (FSO) communication is attractive for such links owing to its large bandwidth, high directivity, and high data rate. However, FSO links are highly vulnerable to pointing errors and atmospheric turbulence, which can cause severe signal degradation and link failure [1]–[3]. In contrast, radio-frequency (RF) communication can provide higher link reliability but suffers from limited bandwidth and lower data rates [1], [4]. Therefore, hybrid RF/FSO communication can be a solution for the LEO-HAPS backhaul by combining the high capacity advantage of FSO links with the reliability of RF links [1], [5]. Nevertheless, in hybrid RF/FSO communication, link selection requires balancing throughput and link reliability under unpredictable stochastic FSO channel conditions, while avoiding unnecessary link switching. Therefore, this paper proposes a deep Q-network (DQN)-based RF/FSO link switching method that formulates the link selection problem as a partially observable Markov decision process (POMDP) to control the throughput–reliability tradeoff under a fixed switching penalty.

II. SYSTEM MODEL

We consider a hybrid RF/FSO downlink scenario as illustrated in Fig. 1. The LEO satellite set is defined as $\mathcal{L} = \{l_1, l_2, \dots, l_M\}$, where each satellite $l \in \mathcal{L}$ operates in an orbit at an altitude of h_L . Meanwhile, the HAPS H operates at a fixed stratospheric altitude h_H along a circular trajectory with radius r_H . When the elevation angle ϕ between satellite l and HAPS H satisfies the minimum elevation angle ϕ_{th} , satellite l can transmit data to HAPS H over either the RF or FSO link. The connection duration is divided into discrete time slots $\mathcal{T} = \{1, 2, \dots, T\}$ for sequential RF/FSO link selection.

A. RF Channel Model

We adopt the large-scale RF channel model in [4]. The RF path loss L^{RF} is defined as follows:

$$L^{RF} = L_b^{RF} + L_g^{RF} + L_s^{RF} + L_e^{RF}, \quad (1)$$

where L_b^{RF} denotes the basic path loss, L_g^{RF} denotes the atmospheric gas absorption loss, L_s^{RF} denotes the scintillation loss, and L_e^{RF} denotes the building entry loss. For the considered LEO-HAPS link, L_e^{RF} is not considered due to the aerial LoS propagation environment, and L_s^{RF} is negligible at the Ka-band. Moreover, the basic path loss is reduced to the free-

space path loss (FSPL) since shadow fading and clutter loss are negligible for the clear line of sight (LoS) aerial link. Accordingly, L_b^{RF} is defined as follows:

$$L_b^{\text{RF}} = 20 \log_{10} \left(\frac{4\pi d_{l,H}}{\lambda_{\text{RF}}} \right), \quad (2)$$

where λ_{RF} is the RF wavelength, and $d_{l,H}$ is the slant distance between the LEO satellite l and the HAPS H .

B. FSO Channel Model

The received optical signal of the FSO channel y is defined as follows [1]:

$$y = \zeta P^{\text{FSO}} Ix + n_H, \quad (3)$$

where ζ denotes the optical-to-electrical conversion coefficient, P^{FSO} denotes the FSO transmit power of the LEO satellite, x denotes the transmitted signal, and n_H denotes the additive white Gaussian noise (AWGN). The total irradiance gain of the FSO channel I is defined as follows:

$$I = I^a I^p I^t, \quad (4)$$

where I^a is the stratospheric attenuation, I^p is the pointing error, and I^t is the stratospheric turbulence. I^a is modeled by the Beer-Lambert law [1], which is defined as follows:

$$I^a = \exp(-\psi d_s), \quad (5)$$

where d_s is the stratospheric slant distance between the LEO satellite l and the HAPS H , ψ is an attenuation factor for the optical wavelength λ_{FSO} .

I^p can be approximated as follows [2]:

$$I^p(\delta_r; d_{l,H}) \approx A_0 \exp \left(-\frac{2\delta_r^2}{w_{eq}^2} \right), \quad (6)$$

where $A_0 = [\text{erf}(\rho)]^2$, $\rho = a_r \sqrt{\pi/2}/w_d$, and $w_d = \phi_{\text{FSO}} d_{l,H}$, with a_r and ϕ_{FSO} denoting the receiver aperture radius and the FSO beam divergence angle. Assuming that the radial displacement δ_r follows a Rician distribution, the equivalent beamwidth w_{eq} is defined as follows:

$$w_{eq}^2 = \frac{w_d^2 \sqrt{\pi} \text{erf}(\rho)}{2\rho \exp(-\rho^2)}. \quad (7)$$

With Gaussian jitter variance $\sigma_j^2 = \sigma_\theta^2 d_{l,H}^2$ and boresight displacement $\mu_b = \phi_b d_{l,H}$, where σ_θ and ϕ_b denote the jitter angle and boresight angle, the PDF of I^p is defined as follows:

$$f_{I^p}(I) = \frac{g^2 \exp \left(-\frac{\mu_b^2}{2\sigma_j^2} \right)}{A_0 g^2} I^{g^2-1} I_0 \left(\frac{\mu_b}{\sigma_j^2} \sqrt{-\frac{w_{eq}^2}{2} \ln \left(\frac{I}{A_0} \right)} \right), \quad (8)$$

where $g = w_{eq}/(2\sigma_j)$, and $I_0(\cdot)$ denotes the modified Bessel function of the first kind with order zero.

I^t is modeled by the EW fading [3]. The cumulative distribution function (CDF) of I^t is defined as follows:

$$F_{\text{EW}}(I^t; \beta, \eta, \alpha) = \left\{ 1 - \exp \left[-\left(\frac{I^t}{\eta} \right)^\beta \right] \right\}^\alpha, \quad (9)$$

where the shape parameter α , β , and the scale parameter η are defined as follows:

$$\alpha = \frac{7.220 \times \sigma_1^{2/3}}{\Gamma(\sigma_1^{2/6} - 0.104)}, \quad (10)$$

$$\beta = 1.012(\alpha \sigma_1^2)^{-13/25} + 0.142, \quad (11)$$

$$\eta = \frac{1}{\alpha \Gamma \left(1 + \frac{1}{\beta} \right) g_1(\alpha, \beta)}. \quad (12)$$

The shape parameter dependent variable $g_1(\alpha, \beta)$ is defined as follows:

$$g_1(\alpha, \beta) = \sum_{k=0}^{\infty} \frac{(-1)^k \Gamma(\alpha)}{k! (k+1)^{1+\frac{1}{\beta}} \Gamma(\alpha-k)}. \quad (13)$$

The scintillation index σ_I^2 is defined as follows:

$$\sigma_I^2 = \exp \left[\frac{0.49 \sigma_R^2}{\left(1 + 1.11 \sigma_R^{12/5} \right)^{7/6}} + \frac{0.51 \sigma_R^2}{\left(1 + 0.69 \sigma_R^{12/5} \right)^{6/5}} \right] - 1. \quad (14)$$

The Rytov variance σ_R^2 is defined as follows:

$$\sigma_R^2 = 2.25 \left(\frac{2\pi}{\lambda_{\text{FSO}}} \right)^{7/6} \sec^{11/6}(\xi_{l,H}) \int_{h_H}^{h_S} C_n^2(h) (h-h_H)^{5/6} dh, \quad (15)$$

where h_S is the maximum altitude of the stratosphere, $\xi_{l,H}$ is the zenith angle between the satellite l and the HAPS H .

The refractive index parameter $C_n^2(h)$ is defined as follows:

$$C_n^2(h) = 8.148 \times 10^{-56} u^2 h^{10} \exp \left(-\frac{h}{1000} \right) + 2.7 \times 10^{-16} \exp \left(-\frac{h}{1500} \right) + C_0 \exp \left(-\frac{h}{100} \right), \quad (16)$$

where $u = \sqrt{v^2 + 30.69v + 348.91}$ is the root mean square (RMS) of the wind speed, v is the wind speed, and C_0 denotes the nominal value of $C_n^2(h)$ [3].

C. Performance Metrics

The received RF power $P_{\text{rx}}^{\text{RF}}$ is defined as follows:

$$P_{\text{rx}}^{\text{RF}} = P_{\text{tx}}^{\text{RF}} + G_{\text{tx}}^{\text{RF}} + G_{\text{rx}}^{\text{RF}} - L^{\text{RF}}, \quad (17)$$

where $P_{\text{tx}}^{\text{RF}}$ is the RF transmit power, $G_{\text{tx}}^{\text{RF}}$ and $G_{\text{rx}}^{\text{RF}}$ denote the antenna gains of the RF transmitter and the RF receiver, respectively. Then, the RF SNR γ^{RF} is defined as follows:

$$\gamma^{\text{RF}} = P_{\text{rx}}^{\text{RF}} - N_0^{\text{RF}}, \quad (18)$$

where N_0^{RF} denotes the RF noise power.

For the FSO link, the SNR γ^{FSO} is defined as follows [1]:

$$\gamma^{\text{FSO}} = \frac{(\zeta P^{\text{FSO}} I)^2}{N_0^{\text{FSO}}}, \quad (19)$$

where N_0^{FSO} denotes the FSO noise power.

Let $\mathcal{K} = \{\text{RF}, \text{FSO}\}$ denote the set of available links. At each time slot $t \in \mathcal{T}$, the channel capacity of link $k \in \mathcal{K}$ at time slot t is defined as follows:

$$C^k(t) = B^k \log_2(1 + \gamma^k(t)), \quad (20)$$

where B^k and $\gamma^k(t)$ denote the bandwidth and linear-scale SNR of link k , respectively.

D. Problem Formulation

In this paper, we optimize RF/FSO link selection to improve effective throughput, reduce link failures, and suppress unnecessary switching. The RF/FSO link selection problem is formulated as follows:

$$\mathbf{P1:} \quad \max_{x^k(t)} \sum_{t=1}^T C_{\text{eff}}(t) - c_1 N_{\text{out}} - c_2 N_{\text{sw}}, \quad (21)$$

s.t.

$$\mathbf{C1:} \quad x^k(t) \in \{0, 1\}, \quad (22)$$

$$\mathbf{C2:} \quad \sum_{k \in \mathcal{K}} x^k(t) = 1, \quad \forall t \in \mathcal{T}, \quad (23)$$

$$\mathbf{C3:} \quad \phi(t) \geq \phi_{\text{th}}, \quad \forall t \in \mathcal{T}. \quad (24)$$

In **P1**, the link selection indicator $x^k(t)$ represents whether link k is activated at time slot t . N_{out} and N_{sw} denote the outage count and switching count. The parameters c_1 and c_2 denote the scale parameters for outage and switching.

The effective throughput at time slot t is defined as follows:

$$C_{\text{eff}}(t) = \sum_{k \in \mathcal{K}} x^k(t) C^k(t) \mathcal{X}^k(t), \quad (25)$$

where $\mathcal{X}^k(t)$ denotes the link availability indicator, defined as

$$\mathcal{X}^k(t) = \mathbb{I}[\gamma^k(t) \geq \gamma_{\text{th}}]. \quad (26)$$

Constraints **C1** and **C2** ensure hard switching between the RF and FSO links by defining a binary link selection indicator and allowing only one link to be selected at each time slot. Constraint **C3** ensures that the elevation angle between the LEO satellite and the HAPS is greater than or equal to the minimum elevation angle.

In practical LEO-HAPS backhaul links, instantaneous channel information is not available at the time of link selection because transmission feedback is obtained only after the decision is made. In addition, stochastic FSO channel fluctuations make delayed feedback insufficient to accurately capture the current link condition. Therefore, the RF/FSO link selection problem is formulated as a POMDP. Since the RF/FSO switching problem has a discrete action space and an unknown state transition probability, DQN is adopted to learn the switching policy from delayed observations and rewards.

III. DYNAMIC RF/FSO LINK SWITCHING FRAMEWORK USING DEEP REINFORCEMENT LEARNING

Fig. 2 illustrates the proposed DQN-based RF/FSO link switching framework. During the connection period, the satellite selects either the RF or FSO link at each time slot t .

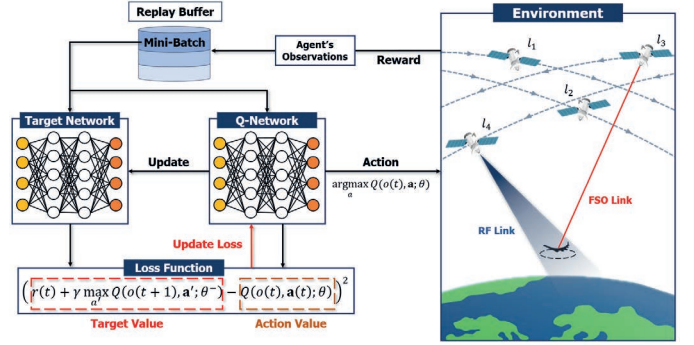


Fig. 2: Proposed DQN-based RF/FSO link switching framework for the hybrid LEO-HAPS backhaul network.

Algorithm 1 DQN-Based RF/FSO Link Switching

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1: Initialize online network  $Q(O, a; \theta)$ , target network  $Q(O, a; \theta^-)$ , and replay buffer  $\mathcal{D}$ , and optimizer with learning rate  $\eta_L$ 
2: Set  $\theta^- \leftarrow \theta$ 
3: for episode = 1, ...,  $N_{\text{ep}}$  do
4:   Reset environment and initialize  $o(1)$ ,  $a(0)$ , and  $i_0^o$ 
5:   for  $t = 1, \dots, T$  do
6:     Select  $a(t) \in \mathcal{A}$  using an  $\epsilon$ -greedy policy
7:     Execute  $a(t)$ , obtain  $r(t)$ ,  $i_t^o$ , and observe  $o(t+1)$ 
8:     Store  $(o(t), a(t), r(t), o(t+1))$  in  $\mathcal{D}$ 
9:     if  $|\mathcal{D}| \geq |\mathcal{D}|_{\min}$  and  $t \bmod N_u = 0$  then
10:      Sample a mini-batch  $(O, a, r, O')$  from  $\mathcal{D}$ 
11:       $G = r + \gamma_D \max_{a' \in \mathcal{A}} Q(O', a'; \theta^-)$ 
12:      Update  $\theta$  by minimizing  $(G - Q(O, a; \theta))^2$ 
13:    end if
14:    Update  $\theta^- \leftarrow \theta$  every  $C$  steps
15:  end for
16:  Decay  $\epsilon$ 
17: end for
18: Output:  $\pi^*(O) = \arg \max_{a \in \mathcal{A}} Q(O, a; \theta)$ 

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The POMDP is characterized by $(\mathcal{S}, \mathcal{A}, O, P, R, \gamma_D)$, where $\mathcal{S}$ is the global state space, $\mathcal{A} = \{a^{\text{RF}}, a^{\text{FSO}}\}$ is the action space, O is the observation space, P is the unknown state transition probability, R is the reward function, and γ_D is the discount factor. The global state $s(t) \in \mathcal{S}$ is defined as follows:

$$s(t) = [o^T(t), \gamma^{\text{RF}}(t), \gamma^{\text{FSO}}(t), C^{\text{RF}}(t), C^{\text{FSO}}(t)]^T, \quad (27)$$

where $o(t)$ denotes the agent observation.

Since the instantaneous channel information in $s(t)$ is not observable before link selection, $o(t)$ is defined as follows:

$$o(t) = [\phi(t), \Delta\phi(t), z(t-1), i_{t-1}^o]^T, \quad o(t) \in O, \quad (28)$$

where $\Delta\phi(t)$ denotes the elevation angle variation. The previous link selection flag $z(t-1)$ and delayed outage feedback i_{t-1}^o are defined as follows:

$$z(t-1) = x^{\text{RF}}(t-1), \quad (29)$$

TABLE I: Simulation and DQN Parameters

Notation	Value	Notation	Value
System & Geometry			
h_L	530 km	h_H	20 km
h_S	50 km	r_H	5 km
ϕ_{th}	25°	γ_{th}	7 dB
RF Link (Ka-band)			
f^{RF}	20 GHz	λ_{RF}	15 mm
B^{RF}	400 MHz	P_{tx}^{RF}	21.52 dBm
G_{tx}^{RF}	38.5 dBi	G_{rx}^{RF}	39.7 dBi
N_0^{RF}	-88.74 dBm	L_g^{RF}	0.5 dB
FSO Link			
λ_{FSO}	1550 nm	B^{FSO}	2.5 GHz
P_{tx}^{FSO}	21.52 dBm	N_0^{FSO}	-78.82 dBm
a_r	0.1 m	ζ	0.6 A/W
ϕ_{FSO}	20 μ rad	ϕ_b	4 μ rad
σ_θ	4 μ rad	ψ	10^{-4} km $^{-1}$
u	65 m/s	C_0	10^{-18} m $^{-2/3}$
DQN			
ω_c	0.3	ω_s	0.3
ω_o	0.9	γ_D	0.98
η_L	5×10^{-4}	$ \mathcal{D} $	100,000
N_B	64	$ \mathcal{D} _{min}$	2,000
N_u	4 steps	C	4,000 steps
N_{ep}	10,000	N_ϵ	5,000 episodes
ϵ_{init}	0.5	ϵ_{final}	0.01

$$i_t^o = \sum_{k \in \mathcal{K}} x^k(t) (1 - \mathcal{X}^k(t)). \quad (30)$$

The reward jointly accounts for effective throughput, link outage, and switching regularization as

$$r(t) = \omega_c \frac{C_{eff}(t)}{C_{max}} - \omega_s \mathbb{I}[z(t) \neq z(t-1)] - \omega_o i_t^o, \quad (31)$$

where C_{max} is the maximum link capacity, and ω_c , ω_s , and ω_o are the weights for throughput, switching penalty, and outage penalty, respectively. The DQN is trained to learn the RF/FSO switching policy according to Algorithm 1.

IV. NUMERICAL RESULTS

A. Simulation Setup

Table I includes the parameters of the designed LEO-HAPS RF/FSO downlink system and the DQN model. The LEO satellite orbit is configured based on the SpaceX Gen2 Starlink system [6]. The HAPS parameters are set based on the configuration in [6]. The RF channel parameters are configured based on the 3rd Generation Partnership Project (3GPP) NTN models [4], [7], while the FSO link parameters are set with reference to the Space Development Agency (SDA) optical communications terminal (OCT) standard [8].

The Q-network takes the four-dimensional state observation as the input layer, and the output layer consists of two neurons for the Q-values of the RF and FSO selection. The network has four hidden layers. Rectified linear unit (ReLU) is used as an activation function, and the network is trained using the Adam optimizer with the mean squared error (MSE) loss

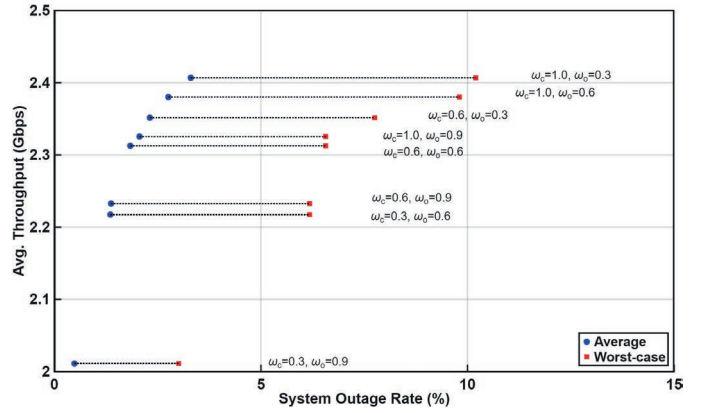


Fig. 3: Selection of throughput and outage reward weights.

between the target Q-value and the predicted Q-value of the online network.

The DQN settings in Table I include the learning rate η_L , replay buffer size $|\mathcal{D}|$, mini-batch size N_B , number of training episodes N_{ep} , online and target network update intervals N_u and C . The ϵ -greedy exploration probability is linearly decayed from ϵ_{init} to ϵ_{final} over N_ϵ episodes.

To evaluate the performance of the proposed DQN, we consider greedy, FSO-only, RF-only, and offline dynamic programming (DP) methods as baselines. The greedy method selects the link with higher SNR observed in the previous slot. The FSO-only method always selects the FSO link regardless of outage feedback, while the RF-only method always selects the RF link as a conservative baseline. The offline DP method serves as an oracle upper bound by assuming full future channel knowledge and determining the optimal link sequence over the entire episode.

B. Performance Comparison

Prior to comparing the proposed DQN-based switching method with the baseline methods, the reward weights ω_c , ω_s , and ω_o must be properly determined. The throughput weight ω_c encourages the agent to select the high-capacity FSO link. In contrast, the outage weight ω_o penalizes outage events and induces a conservative policy that relies on RF link. Thus, ω_c and ω_o mainly determine the RF/FSO selection tendency and the tradeoff between throughput and reliability. Although ω_s also affects throughput and outage by suppressing link transitions and the associated interruption loss, jointly varying all three weights would confound the link-selection tendency with switching stability. Therefore, ω_s is fixed at 0.3 as a stability regularizer, while different (ω_c, ω_o) pairs are evaluated in Fig. 3. Compared with the selected setting of $\omega_c = 0.3$ and $\omega_o = 0.9$, a larger ω_c or smaller ω_o achieves higher throughput through aggressive FSO selection, but it also causes excessive outage. In contrast, a smaller ω_c or larger ω_o tends to converge to an RF-only policy with no switching. Therefore, we adopt $(\omega_c, \omega_s, \omega_o) = (0.3, 0.3, 0.9)$ as the reward weight setting for the proposed method throughout the simulations.

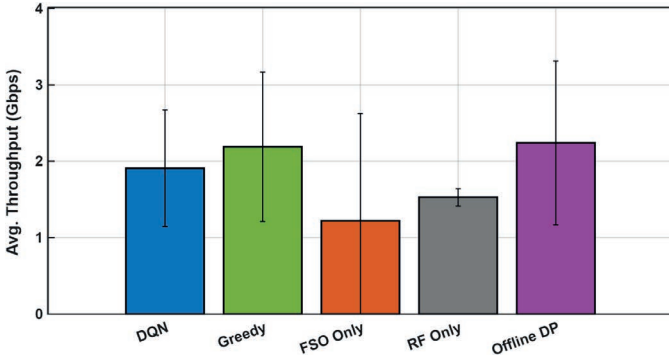


Fig. 4: Average throughput comparison.

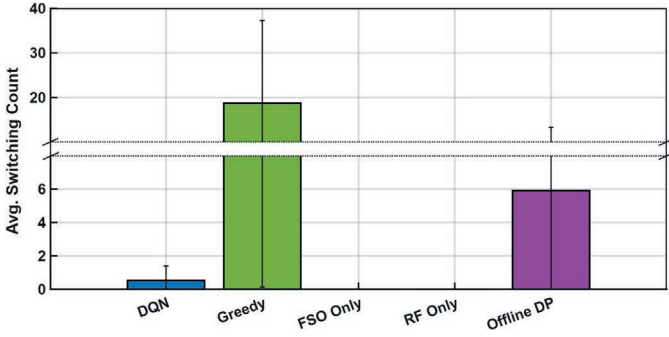


Fig. 5: Average switching count comparison.

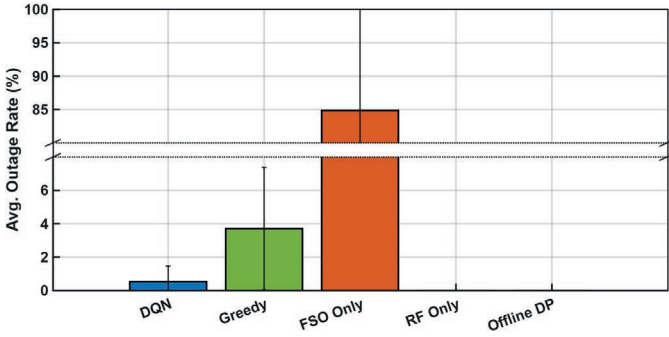


Fig. 6: Average outage rate comparison.

The proposed DQN-based switching method is compared with the baselines in terms of average throughput, switching count, and outage rate. As shown in Fig. 4, the offline DP achieves the highest average throughput of 2.24 Gbps, followed by the greedy method at 2.19 Gbps, while the proposed DQN achieves 1.91 Gbps. In terms of the number of switching events, Fig. 5 shows that the greedy method incurs 18.72 switching events on average, whereas the offline DP and proposed DQN require 5.91 and 0.53 switching events, respectively. In terms of link reliability, Fig. 6 shows that the FSO-only method suffers from a high outage rate of 84.88%, while the greedy method and proposed DQN achieve outage rates of 3.70% and 0.53%, respectively. The offline DP achieves zero outage by using full future channel knowledge. These results indicate that the greedy method maintains

high throughput through myopic SNR-based decisions, but causes frequent switching and residual outage under stochastic FSO channel fluctuations. Compared with the greedy method, the proposed DQN reduces the switching count by 97.2% and the outage rate by 85.7%, with a 12.8% throughput reduction. Relative to the offline DP upper bound, the proposed DQN reduces the switching count by 91.0%, with a 14.8% throughput loss and a small outage rate of 0.53%, indicating that it learns the long-term effects of switching and outage from causal feedback without future channel knowledge. The lower throughput of the proposed DQN results from avoiding frequent switching for short-term throughput gains, thereby substantially reducing both switching count and outage rate.

V. CONCLUSION

This paper proposed a DQN-based RF/FSO switching method for LEO-HAPS downlink backhaul networks. The RF/FSO link selection problem was formulated as a POMDP, where the agent relies on link geometry features and delayed transmission feedback. Simulation results show that the proposed method achieves an average throughput of 1.91 Gbps and an outage rate of 0.53%. The proposed DQN achieves near-oracle reliability with fewer switching events, despite using only causal observations. These results demonstrate that the proposed method provides reliable and stable RF/FSO link selection for LEO-HAPS backhaul networks.

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REFERENCES

- [1] O. B. Yahia, E. Erdogan, G. K. Kurt, I. Altunbas, and H. Yanikomeroglu, "HAPS selection for hybrid RF/FSO satellite networks," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 58, no. 4, pp. 2855–2867, Aug. 2022.
- [2] F. Yang, J. Cheng, and T. A. Tsiftsis, "Free-space optical communication with nonzero boresight pointing errors," *IEEE Transactions on Communications*, vol. 62, no. 2, pp. 713–725, Feb. 2014.
- [3] R. Barrios and F. Dios, "Exponentiated Weibull distribution family under aperture averaging for Gaussian beam waves," *Optics Express*, vol. 20, no. 12, pp. 13 055–13 064, 2012.
- [4] 3GPP TR 38.811 V15.4.0, "Study on new radio (NR) to support non-terrestrial networks (release 15)," Sep. 2020.
- [5] Y. Wang, P. Wang, X. Liu, and T. Cao, "On the performance of dual-hop mixed RF/FSO wireless communication system in urban area over aggregated exponentiated Weibull fading channels with pointing errors," *Optics Communications*, vol. 410, pp. 609–616, 2018.
- [6] Federal Communications Commission, "Space Exploration Holdings, LLC Request for Orbital Deployment and Operating Authority for the SpaceX Gen2 NGSO Satellite System," Order and Authorization, FCC 22-91, Dec. 2022.
- [7] 3GPP TR 38.821 V16.4.0, "Solutions for NR to support non-terrestrial networks (NTN) (release 16)," Mar. 2023.
- [8] Space Development Agency, "Optical communications terminal (OCT) standard," Version 3.2.0, Mar. 2025.