Regular CCL seminar

Integrated Satellite-HAP-UAV Network with Hybrid FSO/RF systems

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Contents

1. Context and Motivation

The loss of life and property is huge from disaster [1]

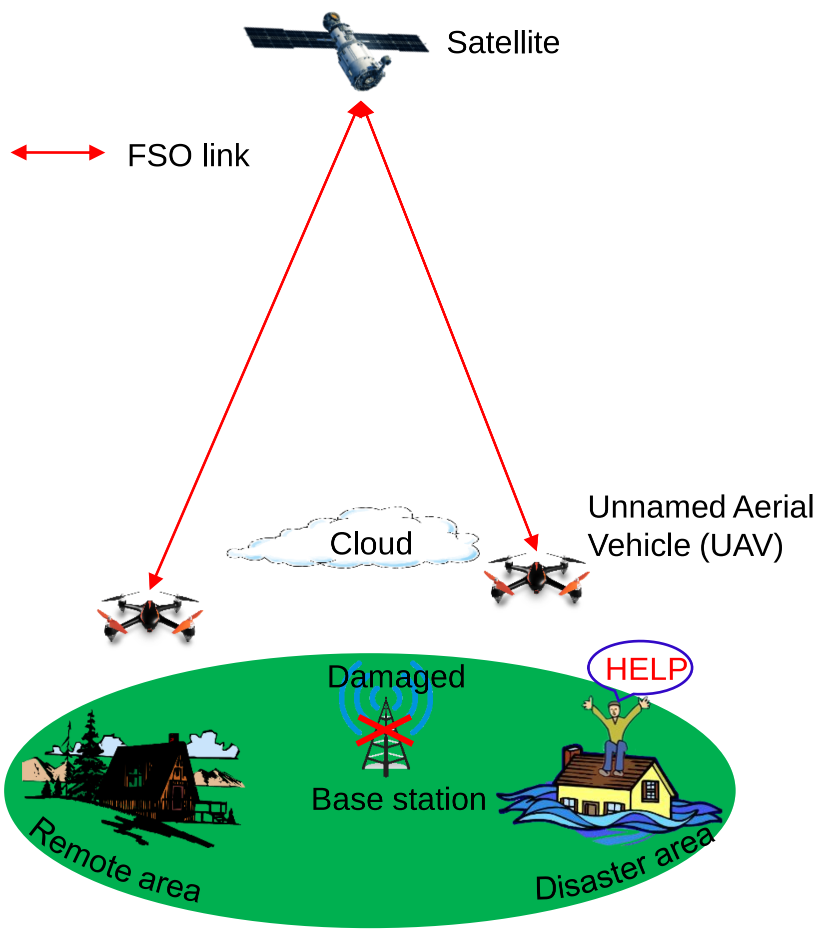
Radio base station vehicle [2]

- Low data rate
- Narrow coverage area
- Difficult to deploy at the inaccessible area

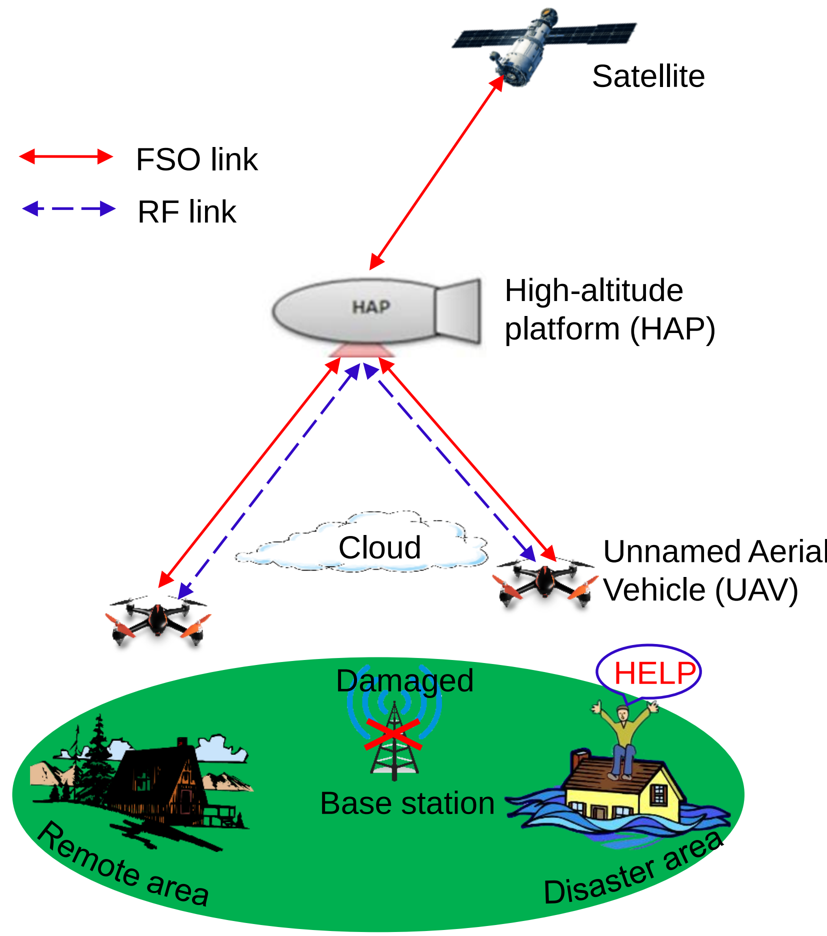
Aims to provide uninterrupted communication in event of tsunamis or earthquakes

[1] “Natural disaster 2019: Now is the time to not give up” CRED 2019.
[2] T. Tokuyasu, et. al., “Wireless Access System for Disaster Recovery Providing Safety and Security to Customers,” NTT Technical Review, vol. 16, no. 1, 2018.

2. Approach



FSO-based satellite communications



FSO-based dual-hop satellite-HAP-UAV with hybrid FSO/RF systems

2. Literature Survey

Ref	Year	Scenarios	FSO link	RF link	Relay	Metrics
[1]	2013	Satellite-GS-GS	GG	Rician	AF	SEP
[2]	2020	Satellite-HAP-GS	GG	Rician	DF	SEP
[3]	2021	GS-HAP-Satellite	GG + PE	Rician	DF	SEP + OP

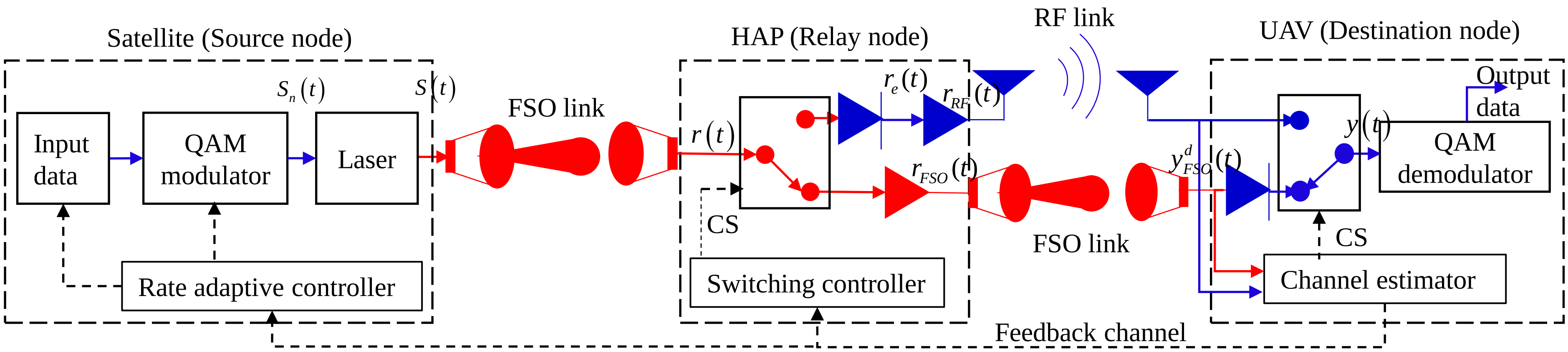
Previous → Focused on the static link (i.e., ground-HAP, ground-satellite)

Our works →

- Investigate the dynamic link since UAV can move within the beam footprint
- Applying two mitigation techniques to counteract the environment effects
  - Relaying technique (AF scheme)
  - Hybrid FSO/RF (adaptive transmission rate)
- Closed-form is derived for all performance metric (average transmission rate, spectrum efficiency, outage probability, and average bit error rate)

[1] Manav R. Bhatnagar, et. al., "Performance analysis of Hybrid satellite-terrestrial FSO cooperative system," **IEEE Photonics Technology Letters**, 2013.
[2] Swaminathan R., et. al., "Performance Analysis of HAPS-based Relaying for Hybrid FSO/RF Downlink Satellite Communication," **VTC2020-Spring**.
[3] Swaminathan R., et. al., "HAPs-based Relaying for Integrated Space-Air-Ground Networks with Hybrid FSO/RF Communication: A Performance Analysis," **IEEE Transactions on Aerospace and Electronic Systems**, 2021.

3. System Description



- - - - CS: control signal
— Electrical signal
— Optical signal

$$S_n(t) = A_{nI}\,g(t)\cos(2\pi f_{RF} t) - A_{nQ}\,g(t)\sin(2\pi f_{RF} t)$$

$$S(t) = P_s\left[1 + mS_n(t)\right]$$

$$r(t) = h_{SR} S(t) + n_{b1}$$

$$r_{FSO}(t) = G_{EDFA}\, r(t)$$

$$y_{FSO}^{d}(t) = h_{FSO} G_{EDFA}\, r(t) + n_{b2}$$

$$y_{FSO}(t) = h_{FSO}\eta G_{EDFA} h_{SR} P_s m S_n(t) + \eta h_{FSO} G_{EDFA} n_{b1} + \eta n_{b2} + n_{rec}$$

$$r_e(t) = \eta h_{SR} P_s m S_n(t) + \eta n_{b1} + n_{re\_hap}$$

$$r_{RF}(t) = G_T\, r_e(t)$$

$$y_{RF}(t) = h_{RF} G_T \eta h_{SR} P_s m S_n(t) + h_{RF} G_T \eta n_{b1} + h_{RF} G_T n_{re\_hap} + n_{re}$$

SNR statistics

- End-to-end instantaneous SNR for FSO-FSO link

$$\gamma_{FSO} = \frac{\left(h_{FSO}\eta G_{EDFA} h_{SR} P_s m\right)^2}{\left(h_{FSO}\eta G_{EDFA}\sigma_{b1}\right)^2 + \left(\eta\sigma_{b2}\right)^2 + \left(\sigma_{rec}\right)^2} = \frac{\frac{\left(P_s m h_{SR}\right)^2}{\sigma_{b1}^2} \frac{\left(\eta h_{FSO}\right)^2}{\left(\eta\sigma_{b2}\right)^2 + \left(\sigma_{rec}\right)^2}}{\frac{\left(\eta h_{FSO}\right)^2}{\left(\eta\sigma_{b2}\right)^2 + \left(\sigma_{rec}\right)^2} + \frac{1}{\left(G_{EDFA}\sigma_{b1}\right)^2}} = \frac{\gamma_1\gamma_{2,FSO}}{\gamma_1 + \gamma_{2,FSO} + 1}$$

- End-to-end instantaneous SNR for FSO-RF link

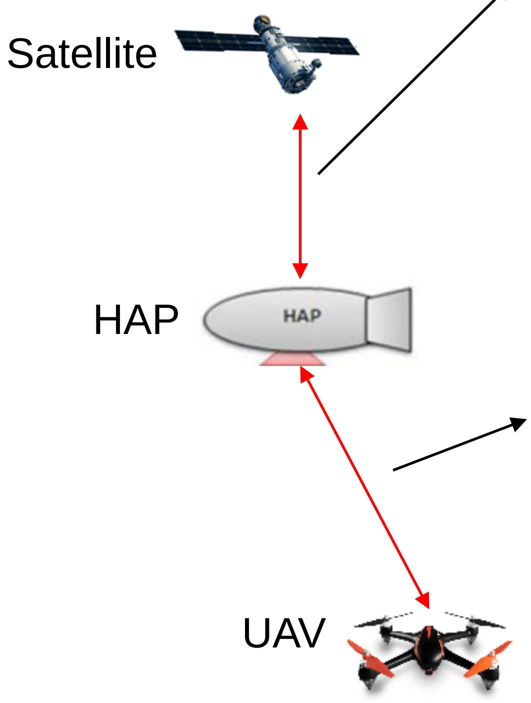
$$\gamma_{RF} = \frac{\left(h_{RF} G_T \eta h_{SR} P_s m\right)^2}{\left(h_{RF} G_T \eta\sigma_{b1}\right)^2 + \left(h_{RF} G_T \sigma_{re\_hap}\right)^2 + \left(\sigma_{re}\right)^2} = \frac{\frac{\left(P_s m h_{SR}\right)^2}{\sigma_{b1}^2} \frac{\left(\eta h_{RF}\right)^2}{\left(h_{RF} G_T \sigma_{re\_hap}\right)^2 + \left(\sigma_{re}\right)^2}}{\frac{\left(\eta h_{RF}\right)^2}{\left(h_{RF} G_T \sigma_{re\_hap}\right)^2 + \left(\sigma_{re}\right)^2} + \frac{1}{\left(G_T\sigma_{b1}\right)^2}} = \frac{\gamma_1\gamma_{2,RF}}{\gamma_1 + \gamma_{2,RF} + 1}$$

$$G_{EDFA}^2 = \frac{1}{P_s m\left(h_{SR}\right)^2 + \left(\sigma_{b1}\right)^2} \qquad \gamma_1 = \frac{\left(P_s m h_{SR}\right)^2}{\left(\sigma_{b1}\right)^2}$$

$$G_T^2 = \frac{1}{P_s m\left(h_{SR}\right)^2 + \left(\sigma_{b1}\right)^2} \qquad \gamma_{2,FSO} = \frac{\left(\eta h_{FSO}\right)^2}{\left(\eta\sigma_{b2}\right)^2 + \left(\sigma_{rec}\right)^2} \qquad \gamma_{2,RF} = \frac{\left(\eta h_{RF}\right)^2}{\left(h_{RF} G_T \sigma_{re\_hap}\right)^2 + \left(\sigma_{re}\right)^2}$$

3. Channel Model

- FSO link (Gaussian beam is assumed to use)



- Beam spreading loss is considered

$$h_{SR} = A_0 \exp\left(-\frac{2\rho_{HAP}^2}{w_{deq}^2}\right)$$

A_0 is the fraction of the collected power at r = 0
ρ_{HAP} is the distance from center of beam to the position of the vehicle (i.e., HAP)
w_{deq} is the equivalent beam waist

- Clouds effect is investigated

$$h_c = \exp(-\alpha_c d_c)$$

α_c is the attenuation coefficient
d_c is the length of clouds

- Gamma-Gamma is used to model atmospheric turbulence

$$f_{h_a}(h_a) = \frac{2(\alpha\beta)^{\frac{\alpha+\beta}{2}}}{\Gamma(\alpha)\Gamma(\beta)} h_a^{\frac{\alpha+\beta}{2}-1} K_{\alpha-\beta}\left(2\sqrt{\alpha\beta h_a}\right), \quad \mathrm{h}_a > 0$$

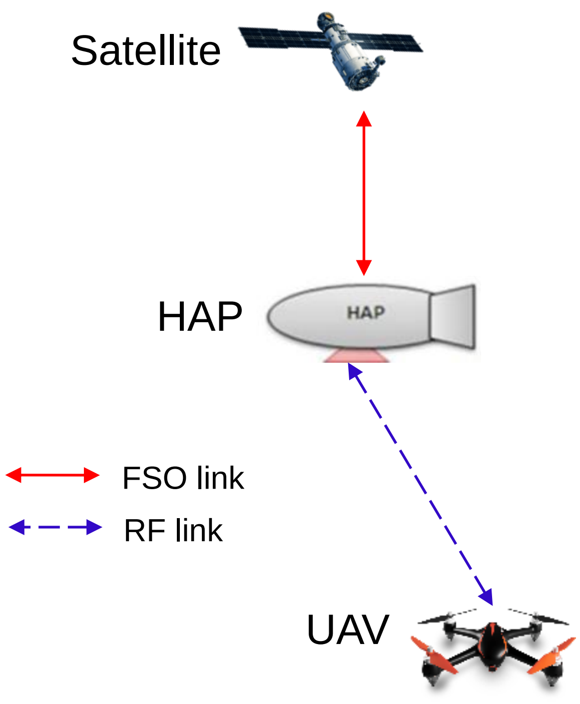
α and β are the small-scale and large-scale eddies

- Pointing error model is studied since dynamic link is considered between HAP and UAV

$$f_{h_{pe}}(h_{pe}) = \frac{w_{Leq}^2}{4A_0\sigma_p^2} \exp\left(-\frac{\rho_{UAV}^2}{2\sigma_p^2}\right)\left(\frac{h_{pe}}{A_0}\right)^{\frac{w_{Leq}^2}{4\sigma_p^2}-1} I_0\left(\frac{\rho_{UAV}}{\sigma_p^2}\sqrt{-\frac{w_{Leq}^2}{2}\ln\left(\frac{h_{pe}}{A_0}\right)}\right)$$

3. Channel model

- RF link



- Rician distribution is used to model the RF channel

$$f_{\gamma_{RF}}(\gamma_{RF}) = \frac{K+1}{\bar{\gamma}_{RF}} \exp\left[-(K+1)\frac{\gamma_{RF}}{\bar{\gamma}_{RF}} - K\right] I_0\left(2\sqrt{K(K+1)\frac{\gamma_{RF}}{\bar{\gamma}_{RF}}}\right)$$

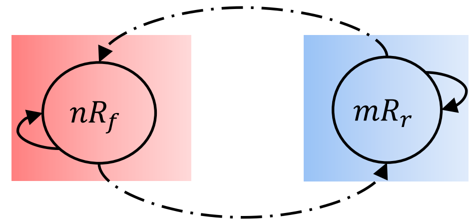
$$\gamma_{RF} = \frac{h_{RD}^2}{\sigma_{D2}^2} \qquad h_{RD} = g_{RF} h_{RF} \qquad L_F = 20\log_{10}\left(\frac{4\pi d_{RD}}{\lambda_{RF}}\right)$$

$$g_{RF} = G_T + G_R - L_F - L_c - L_o \qquad L_c = K_c M_c d_c$$

g_{RF} is the average power gain
h_{RF} is the fading gain
L_F is the free space loss
L_c is the cloud attenuation
L_o is the other loss
d_{RD} is the distance between HAP and UAV
K_c is the specific attenuation within clouds
M_c is the cloud liquid water content

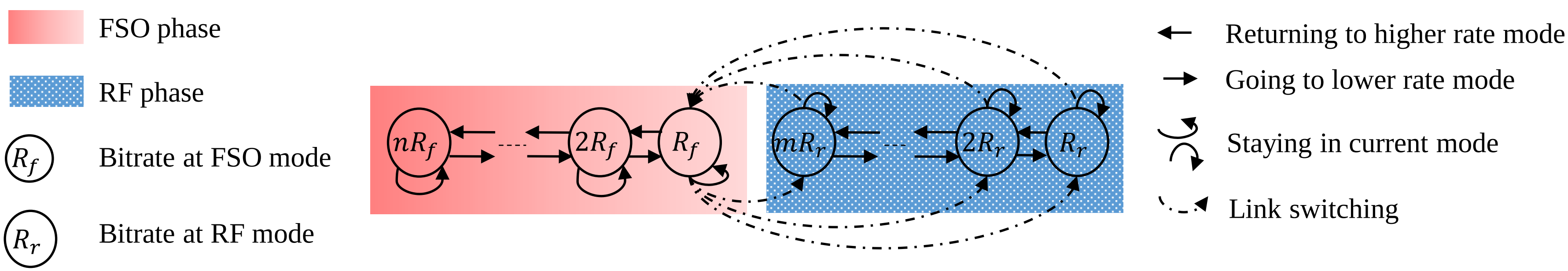
4. Adaptive scheme

- Conventional design



Limitation: frequently switching between FSO and RF link

- Adaptive Multi-rate design



Phase		FSO link					RF link		Outage
Mode		1	2	3	4	5	6	7	8
Transmission Rate		$8R_f$	$7R_f$	$6R_f$	$5R_f$	$4R_f$	$7R_r$	$6R_r$	0
SNR conditions	FSO	$[\gamma_{f5}, \infty)$	$[\gamma_{f4}, \gamma_{f5})$	$[\gamma_{f3}, \gamma_{f4})$	$[\gamma_{f2}, \gamma_{f3})$	$[\gamma_{f2}, \gamma_{f1})$	$[0, \gamma_{f1})$		
	RF	No consideration					$[\gamma_{r2}, \infty)$	$[\gamma_{r1}, \gamma_{r2})$	$[0, \gamma_{r1})$
Modulation		256-QAM	128-QAM	64-QAM	32-QAM	16-QAM	32-QAM	16-QAM	No transmission

5. Performance analysis

- Selected mode probability
  - FSO - FSO link

$$p_f = \int_{\gamma_{f(i)}}^{\gamma_{f(i+1)}} f_{\gamma_f}\left(\gamma_f\right) d\gamma_f = F_{\gamma_f}\left(\gamma_{f(i+1)}\right) - F_{\gamma_f}\left(\gamma_{f(i)}\right)$$

  - FSO - RF link

$$p_r = \int_{\gamma_{r(i)}}^{\gamma_{r(i+1)}} f_{\gamma_r}\left(\gamma_r\right) d\gamma_r = F_{\gamma_r}\left(\gamma_{r(i+1)}\right) - F_{\gamma_r}\left(\gamma_{r(i)}\right)$$

- Average transmission rate

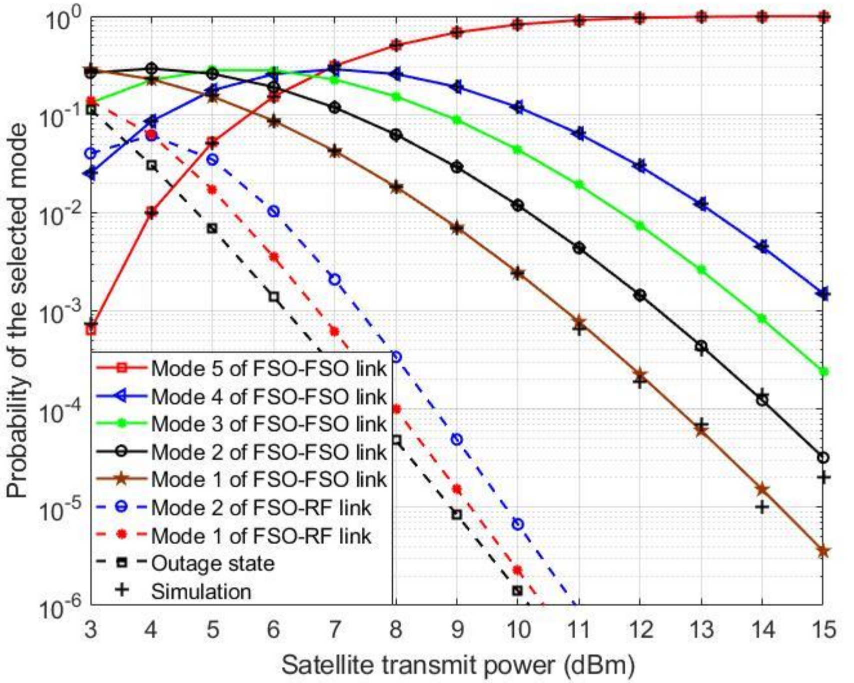
$$\overline{R} = \sum_{k=1}^{N} p_k R_k$$

- Outage probability

$$P_{out} = \int_{0}^{\gamma_{f(1)}} f_{\gamma_f}\left(\gamma_f\right) d\gamma_f \int_{0}^{\gamma_{r(1)}} f_{\gamma_r}\left(\gamma_r\right) d\gamma_r = P_{out}^{FSO} P_{out}^{RF}$$

- Average bit error rate

$$\text{ABER} = \frac{\text{Total errorroneous bits}}{\text{Total transmitted bits}} = \frac{\sum_{k=1}^{N} R_k p_k \text{BER}_k}{\sum_{k=1}^{N} R_k p_k}$$



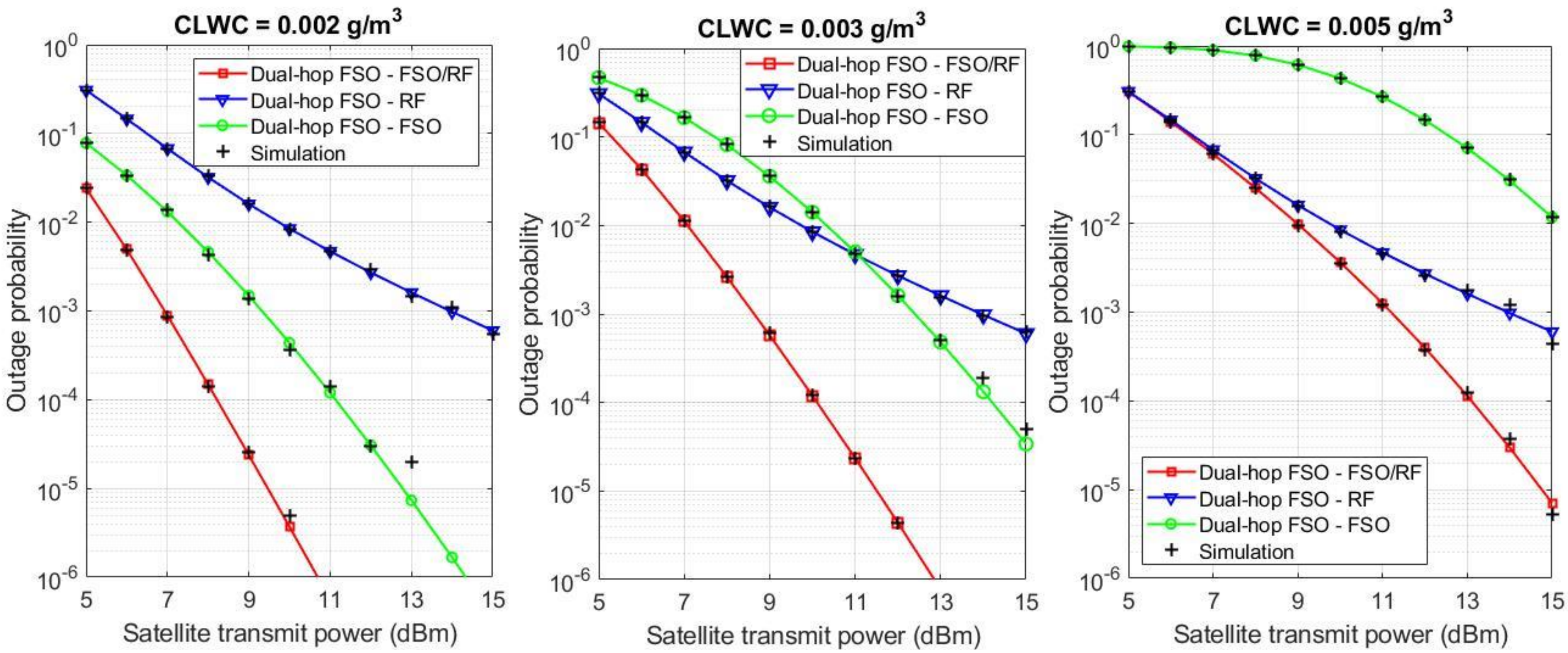
6. Numerical results

- System parameters

Name	Value
LEO satellite	
Altitude	530 km
Divergence angle	50 μm
Optical wavelength	1550 nm
RF frequency	26 GHz
FSO symbol rate	625 Msps
RF symbol rate	160 Msps
High-Altitude Platform (HAP)	
Altitude	20 km
Aperture radius	5 cm
Photodetector eff.	0.9
Background light power	250 μW

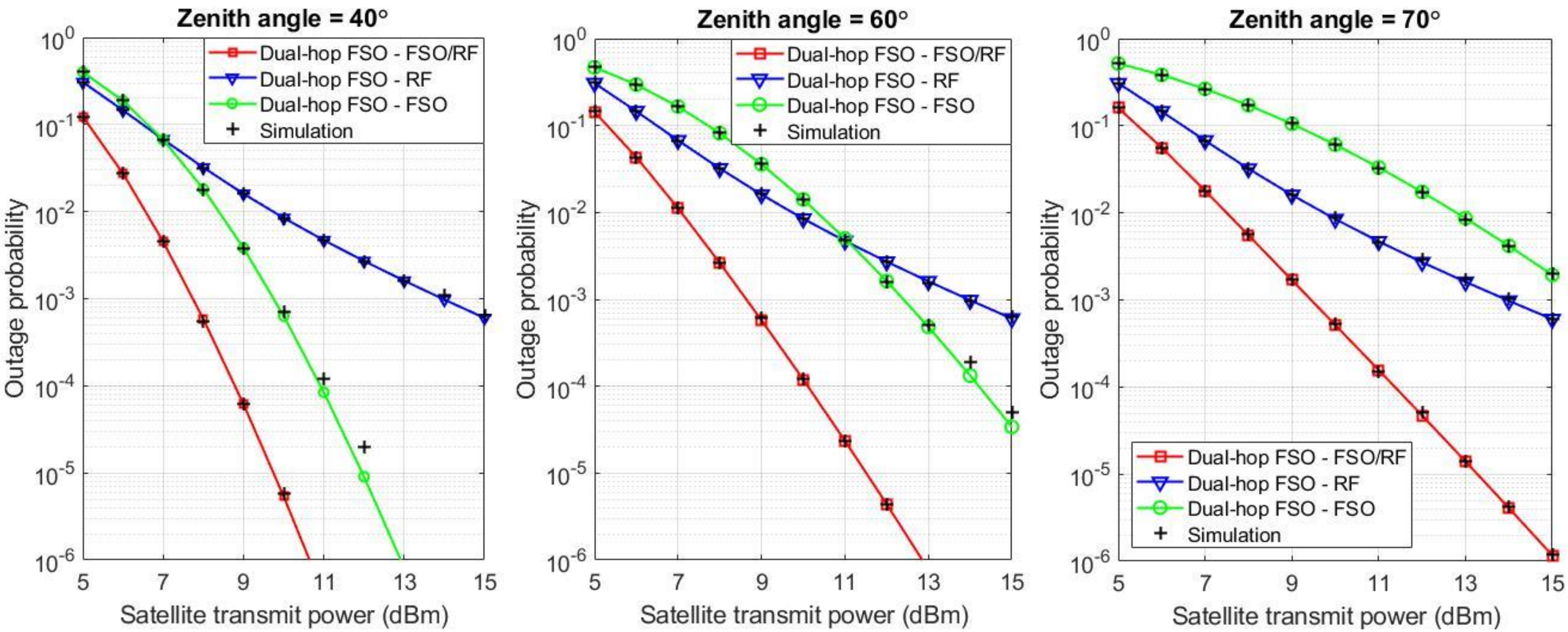
Name	Value
Unmanned Aerial Vehicle (UAV)	
Altitude	100 m
Hovering jitter variance	0.9 m
Aperture radius	5 cm
Background light power	10 μW
Photodetector eff.	0.9
The other parameters	
Wind speed	21 m/s
BER target	10^{-6}
Rician factor	6 dB
Number of concentration	250 cm^{-3}

6. Numerical results



Zenith angle = 60 degree
Divergence angle (HAP) = 2.5 mm
Distance from UAV to beam = 20 m

6. Numerical results

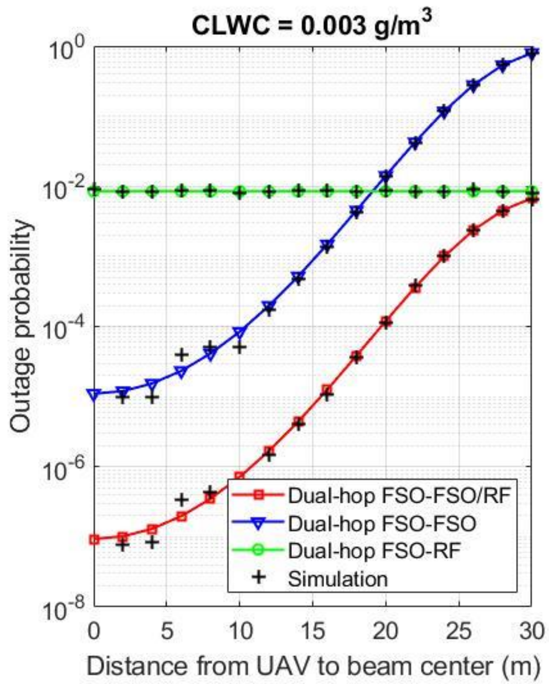


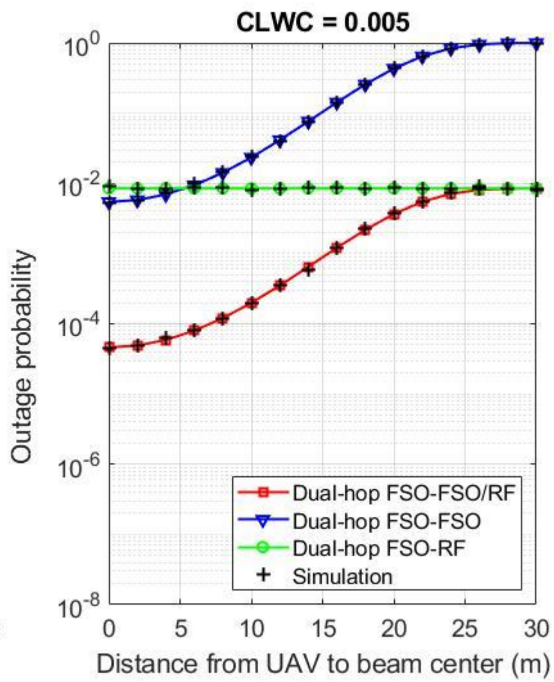
CLWC = 0.003 g/m^3

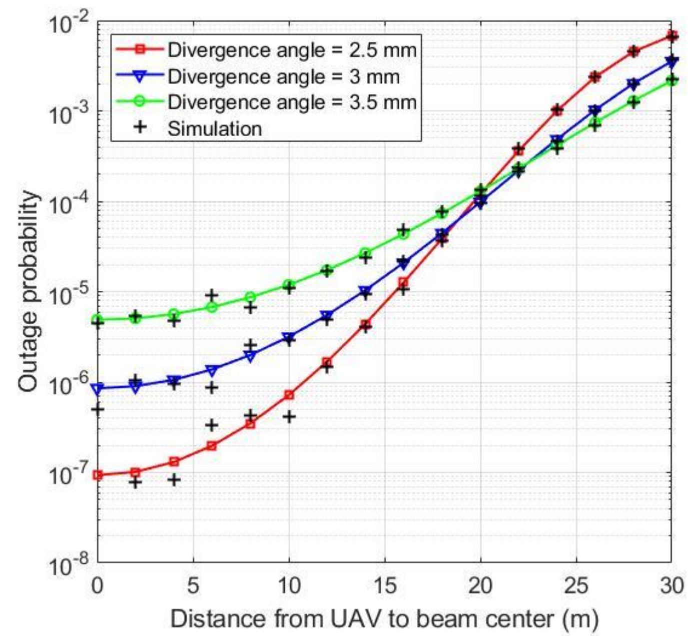
Divergence angle (HAP) = 2.5 mm

Distance from UAV to beam = 20 m

6. Numerical results



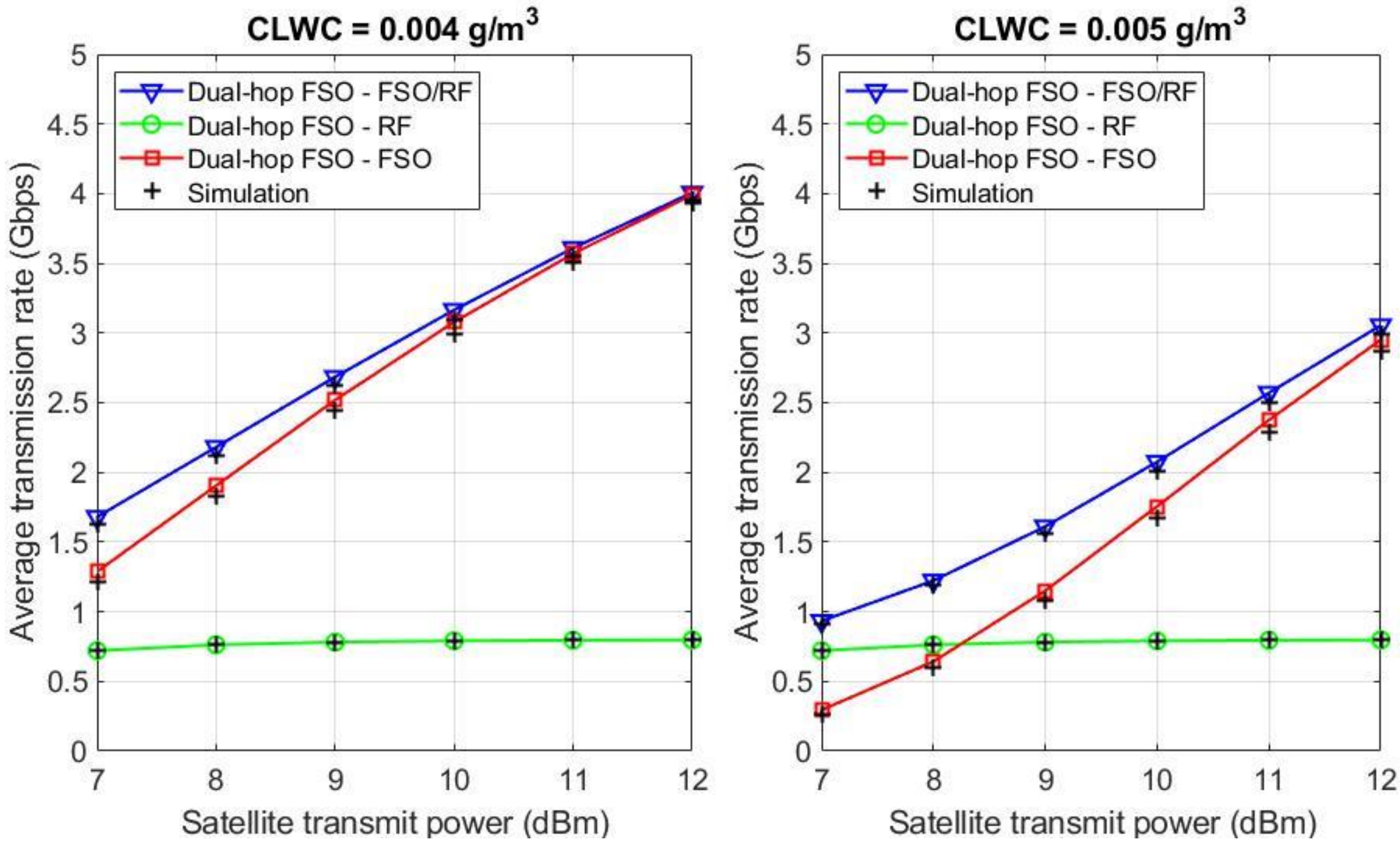




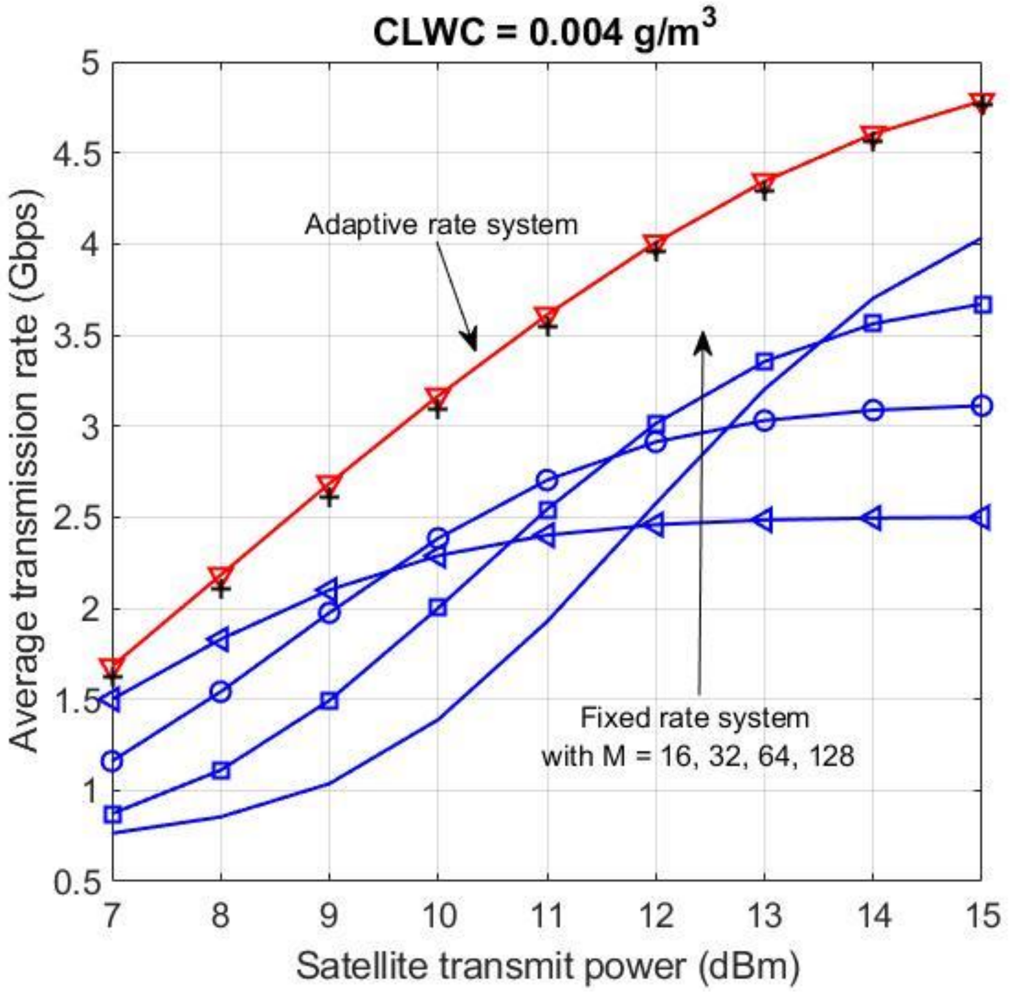
Zenith angle = 60 degree
Divergence angle (HAP) = 2.5 mm
Satellite transmit power = 10 dBm

Dual-hop FSO-FSO/RF system
Zenith angle = 60 degree
Satellite transmit power = 10 dBm

6. Numerical results



6. Numerical results



7. Conclusions

- I studied the adaptive transmission rate for integrated satellite-HAP-UAV with dual-hop FSO/RF system
  - Applying two mitigation technique to counteract the environment effects
    - Relaying technique (AF scheme)
    - Hybrid FSO/RF (Adaptive transmission rate

Thank you for your listening!

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5. Performance analysis

- SNR statistics
  - End-to-end instantaneous SNR for FSO-FSO link

$$\gamma_{FSO} = \frac{\left(h_{FSO} G_{EDFA} h_{SR} P_s m\right)^2}{\left(h_{FSO} G_{EDFA} h_{SR} P_s m \sigma_f\right)^2 + \left(\sigma_{D1}\right)^2} = \frac{\dfrac{\left(P_s m h_{SR}\right)^2}{\sigma_f^2} \dfrac{h_{FSO}^2}{\sigma_{D1}^2}}{\dfrac{h_{FSO}^2}{\sigma_{D1}^2} + \dfrac{1}{\left(G_{EDFA}\sigma_f\right)^2}} = \frac{\gamma_1 \gamma_{2,FSO}}{\gamma_1 + \gamma_{2,FSO} + 1}$$

  - End-to-end instantaneous SNR for FSO-RF link

$$\gamma_{RF} = \frac{\left(h_{RF} G_T h_{SR} P_s m\right)^2}{\left(h_{RF} G_T h_{SR} P_s m \sigma_r\right)^2 + \left(\sigma_{D2}\right)^2} = \frac{\dfrac{\left(P_s m h_{SR}\right)^2}{\sigma_f^2} \dfrac{\eta^2 h_{RF}^2}{\sigma_{D2}^2}}{\dfrac{\eta^2 h_{RF}^2}{\sigma_{D2}^2} + \dfrac{1}{\left(G_T \sigma_r\right)^2}} = \frac{\gamma_1 \gamma_{2,RF}}{\gamma_1 + \gamma_{2,RF} + 1}$$

- Cumulative distribution function (CDF)

$$\gamma = \frac{\gamma_1 \gamma_2}{\gamma_1 + \gamma_2 + 1} \cong \min\left(\gamma_1, \gamma_2\right)$$

  - The CDF of $\min\left(\gamma_1, \gamma_2\right)$ can be expressed as

$$F_\gamma\left(\gamma\right) = \Pr\left(\min\left(\gamma_1, \gamma_2\right) < \gamma\right)$$
$$= F_{\gamma_1}\left(\gamma_1\right) + F_{\gamma_2}\left(\gamma_2\right) - F_{\gamma_1}\left(\gamma_1\right) F_{\gamma_2}\left(\gamma_2\right)$$

$$\gamma_1 = \frac{\left(P_s m h_{SR}\right)^2}{\sigma_f^2}$$

$$\gamma_{2,FSO} = \frac{h_{FSO}^2}{\sigma_{D1}^2}$$

$$\gamma_{2,RF} = \frac{\eta^2 h_{RF}^2}{\sigma_{D2}^2}$$

$$G_{EDFA} = \frac{1}{\left(P_s m h_{SR}\right)^2 + \sigma_r^2}$$

$$G_T = \frac{1}{\left(P_s m h_{SR}\right)^2 + \sigma_r^2}$$

$$S_n(t) = A_{nI} g(t) \cos(2\pi f_{RF} t) - A_{nQ} g(t) \sin(2\pi f_{RF} t)$$

$$S(t) = P_s [1 + m S_n(t)]$$

$$r(t) = h_{SR} S(t) + n_{b1}$$

$$r_{FSO}(t) = G_{EDFA} r(t)$$

$$y_{FSO}^{d}(t) = h_{FSO} G_{EDFA} r(t) + n_{b2}$$

$$y_{FSO}(t) = h_{FSO} \eta G_{EDFA} h_{SR} P_s m S_n(t) + \eta h_{FSO} G_{EDFA} n_{b1} + \eta n_{b2} + n_{rec}$$

$$r_e(t) = \eta h_{SR} P_s m S_n(t) + \eta n_{b1} + n_{re\_hap}$$

$$r_{RF}(t) = G_T r_e(t)$$

$$y_{RF}(t) = h_{RF} G_T \eta h_{SR} P_s m S_n(t) + h_{RF} G_T \eta n_{b1} + h_{RF} G_T n_{re\_hap} + n_{re}$$

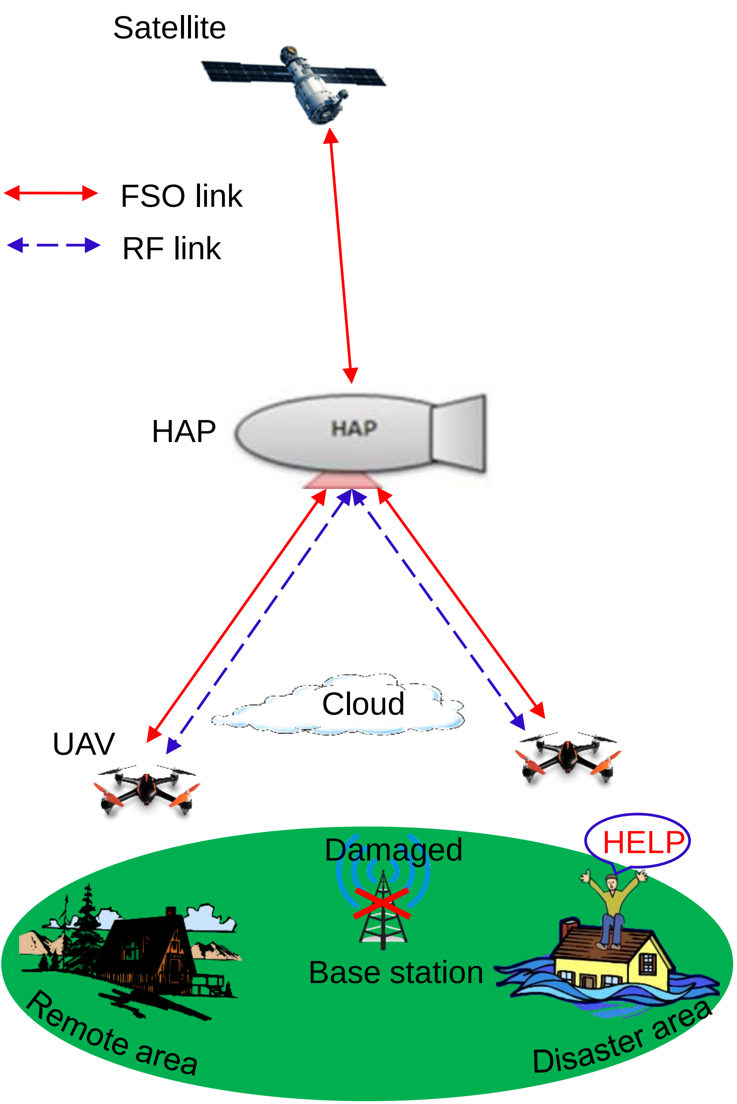
1. Context and Motivation

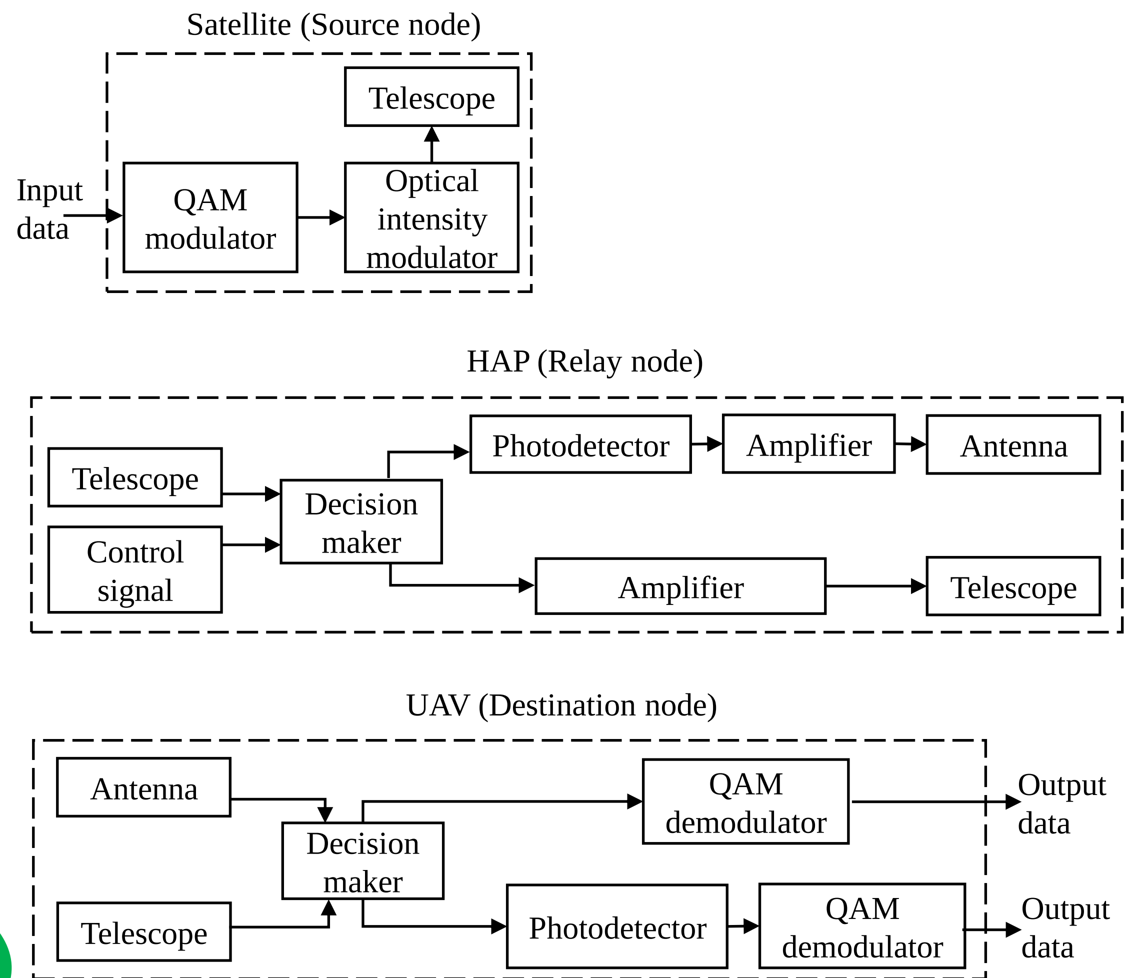
Half of the world's population has no internet access [softbank]

↓

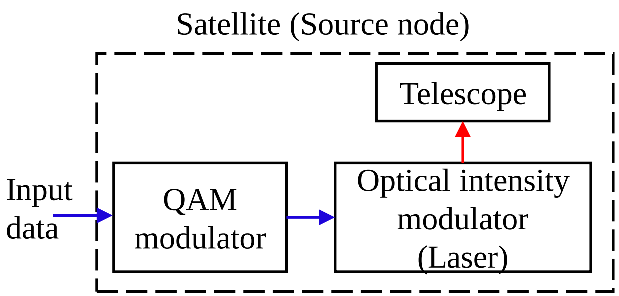
We want to create environment of equal access for all

System Model



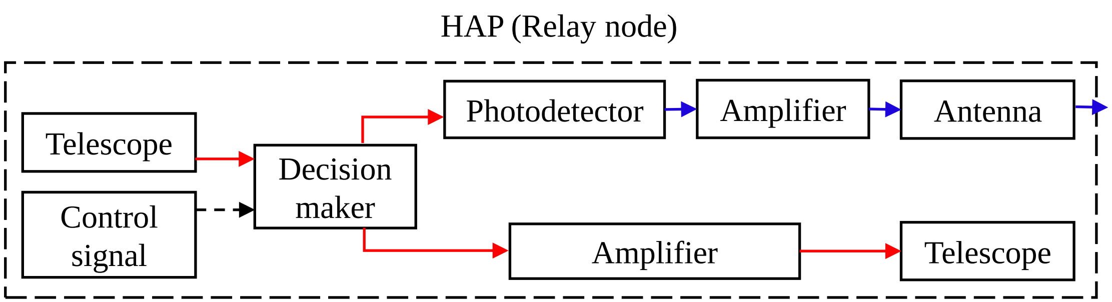


System Model



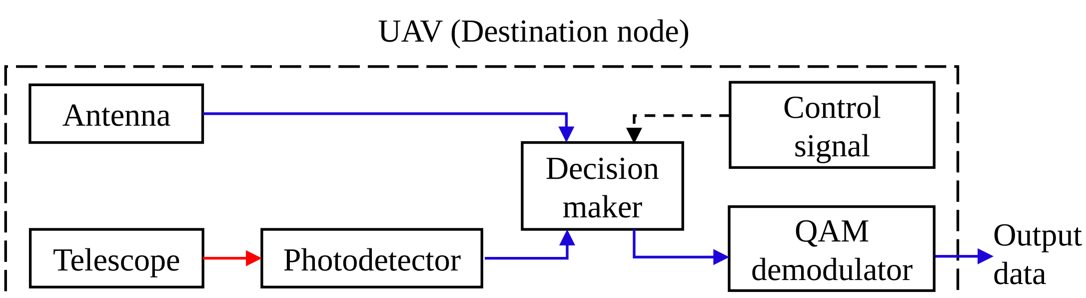
$$S_n(t) = A_{nI}\, g(t)\cos(2\pi f_{RF} t) - A_{nQ}\, g(t)\sin(2\pi f_{RF} t)$$

$$S(t) = P_s\left[1 + mS_n(t)\right]$$



$$r_{RF}(t) = G_T \eta P_R^{RF}\left[h_{SR} P_s\left(1 + mS_n(t)\right) + n_R^{RF}\right]$$

$$r_{FSO}(t) = G_{EDFA} P_R^{FSO}\left[h_{SR} P_s\left(1 + mS_n(t)\right) + n_R^{FSO}\right]$$



$$y_{RF}(t) = h_{RF} G_T \eta P_R^{FSO} h_{SR} P_s m S_n(t) + h_{RF} G_T \eta P_R^{FSO} n_R^{RF} + n_D^{RF}$$

$$y_{FSO}(t) = h_{FSO} G_{EDFA} P_R^{FSO} h_{SR} P_s m S_n(t) + h_{FSO} G_{EDFA} P_R^{FSO} n_R^{FSO} + n_D^{FSO}$$