VTC2019-Fall
HAWAII
Intelligent Connection & Transportation

Throughput Analysis of Incremental Redundancy Hybrid ARQ for FSO-based Satellite Systems

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Hawaii-USA, Sept. 25, 2019

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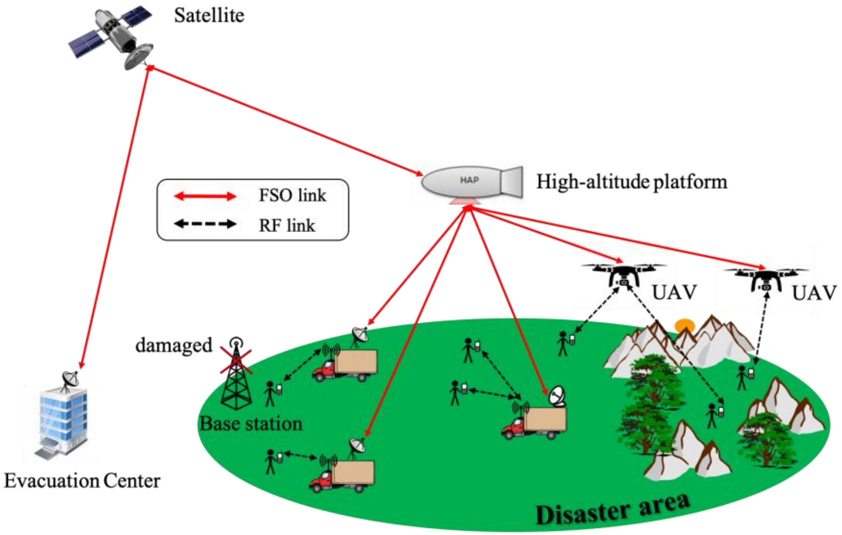
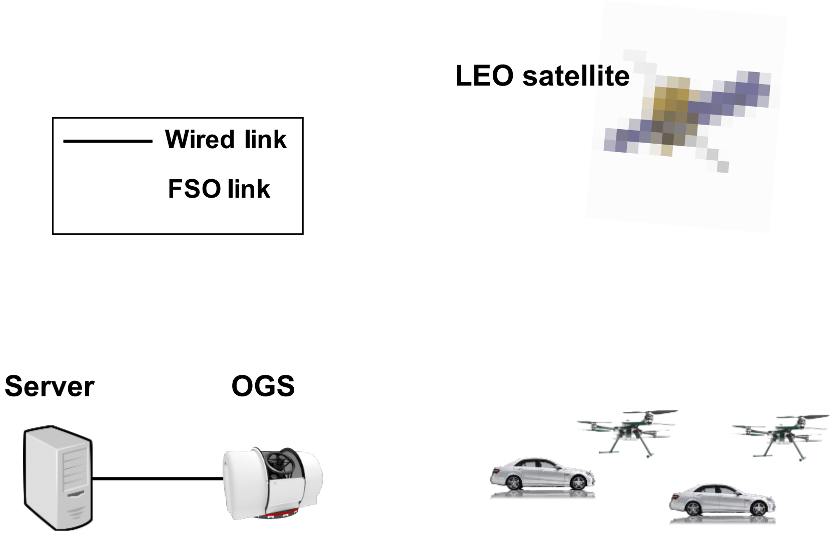
Free Space Optical (FSO)-based Satellite

FSO-based satellite communications:

- Availability of vast unlicensed bandwidth (using laser to provide ~ Gbps of data rate)
- Flexible deployment and wide coverage area (could be deployed for rural and remote areas)



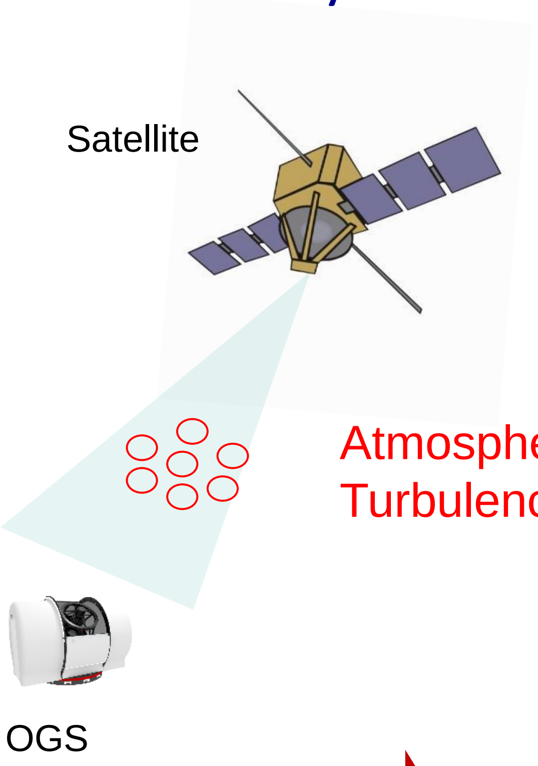
(1) Disaster recovery



(2) Internet-based access

Challenge in FSO-based Satellite System

- One of the main challenging issues in the design of FSO-based satellite systems is the <u>uncertainty of atmospheric channels</u>



Atmospheric Turbulence → **Degrade the system performance (cause the bit error)**

→ **Proper error control methods are required**

Error Control Solutions

- Automatic repeat request (ARQ) and forward error correction (FEC) are the most popular error-control protocols [1]-[2].

[1]. DLR group, “Channel Modelling for Free-Space Optical Inter-HAP Links Using Adaptive ARQ Transmission,” SPIE 2014

[2]. Eiji Okamoto, et al., “A Markov-Based Satellite-to-Ground Optical Channel Model and Its Effective Coding Scheme,” IEICE Trans. Com., 2012

- For FSO-based satellite:
  - ARQ may **not efficient** in high-latency networks when channel becomes noisy (**requires many retransmissions**)
  - FEC always **requires redundancy** and may **reduce system throughput** (more redundancy, more reliable, but reduce throughput)

The solution (combine FEC and ARQ): retransmit only redundancy for erroneous frame and combine with previous received ones to correct that frame

Incremental redundancy hybrid ARQ (IR-HARQ) protocol
which has not been investigated for FSO-based satellite systems

What’s Our Goal?

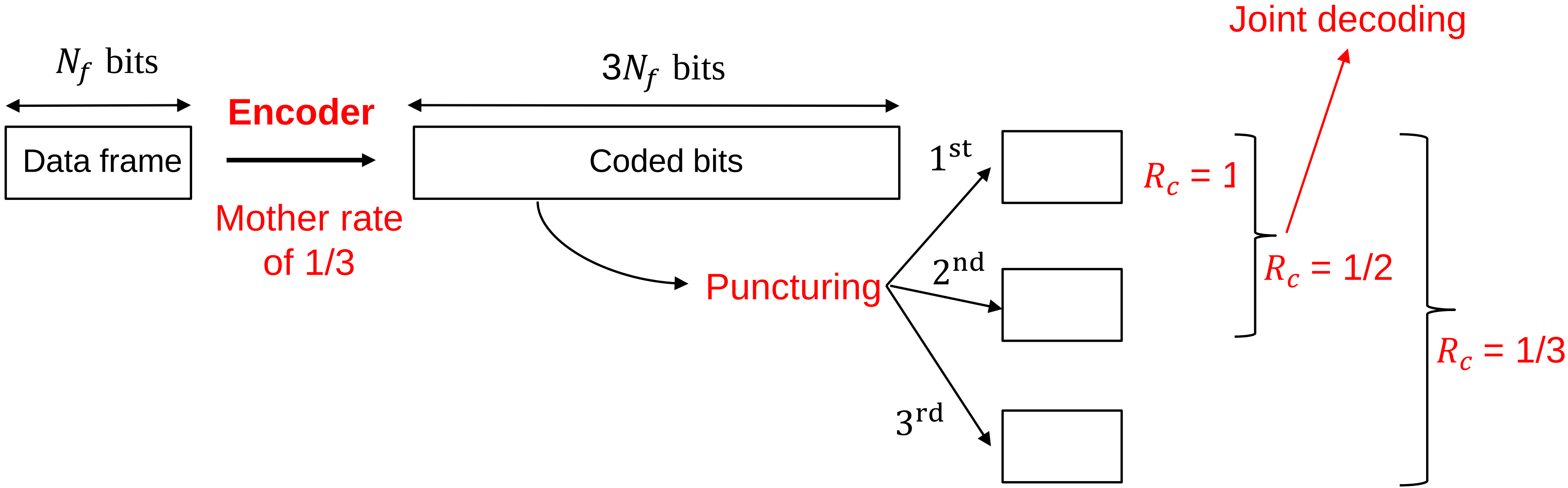
- We want to see how IR-HARQ can be applied for FSO-based satellite communication systems
  - Uncertainty of atmospheric channels
  - High-latency of satellite systems
  - High speed connection: different from RF communications
- Our goals:
  - We study the **design of IR-HARQ protocol** for **FSO burst transmission** in satellite communication system
  - Find the **optimal setting** (provided turbulence conditions and connection speed) **for system performance** (throughput)

IR-HARQ Protocol

IR-HARQ protocol

- *Rate-compatible puncturing convolutional code (RCPC)*: a data frame encoded by a mother code (low code rate, e.g., 1/3), is punctured into the coded bits with higher code rates for transmissions
- *Sliding window ARQ*: using selective-repeat mechanism to retransmit the coded bits and combine all the previous received ones to correct the frame

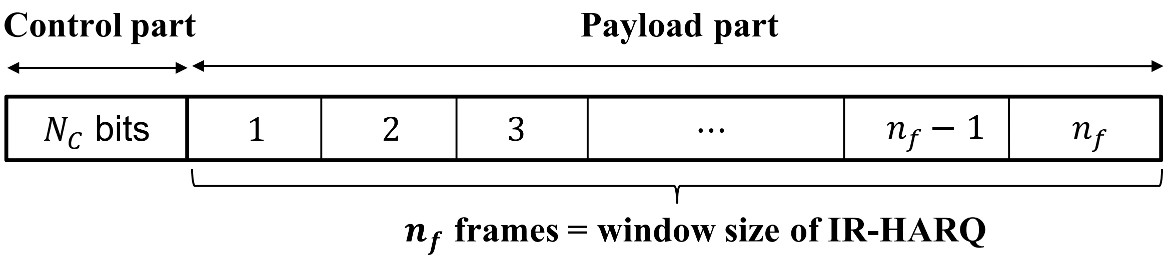
Example: persistent level of HARQ = 3



Burst Transmission Design

- Long channel coherence time → design the burst transmission at the PHY layer
  - Coherence time of FSO channels is typically 1 to 10ms or longer [3].

    [3]. I. Djordjevic, “Adaptive modulation and coding for free-space optical channels,” IEEE JOCN 2010
  - For example: 1Gbps FSO transmission takes $1\mu s$ to transmit one frame with size of 1080 bits, and it may cover at least 1000 frames in a coherence time
- Burst transmission
  - *Control part*: for the detection of burst at receiver
  - *Payload part*: contains multiple frames deigned by a window size of IR-HARQ



Control part

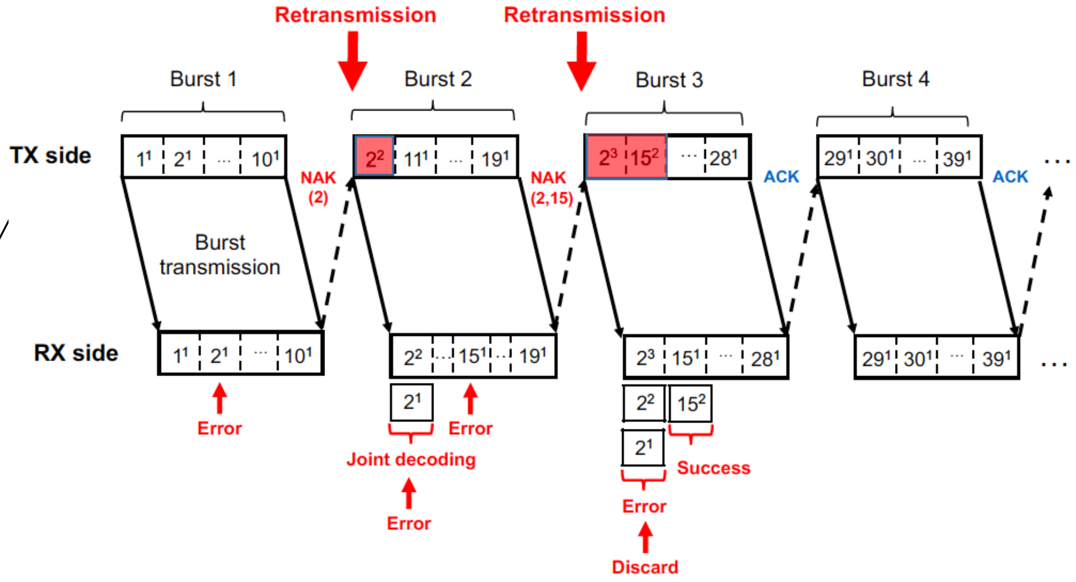
Payload part

N_C bits	1	2	3	$\cdots$	$n_f - 1$	n_f

n_f frames = window size of IR-HARQ

Example of Burst Transmission

- Example:
  - Burst size = 10 frames
  - Persistent level of IR-HARQ, N = 3



- To analyze system throughput, we need to build the burst loss model

- Consider the time-varying behavior of turbulence fading and channel modeling for burst transmission
  - Gamma-gamma (GG) turbulence fading channel is assumed [3]

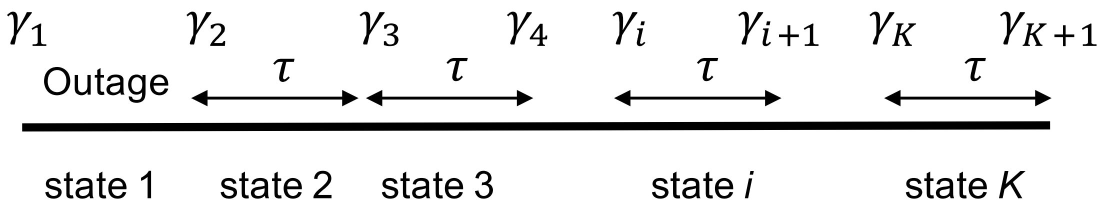
[4]. D. R. Kolev, et al., (NICT), “Received-Power Fluctuation Analysis for LEO Satellite-to-Ground Laser Links,” IEEE JOCN 2017

Channel-State Modeling

- Modelling the burst transmission over turbulence fading channel

→ The transmission of burst and its feedback signal is assumed to be within a fixed-time slot of channel states whose average duration is chosen to be shorter than the fading coherence time

γ: signal-to-noise ratio (SNR) threshold



Channel duration

Probability of the channel state i-th

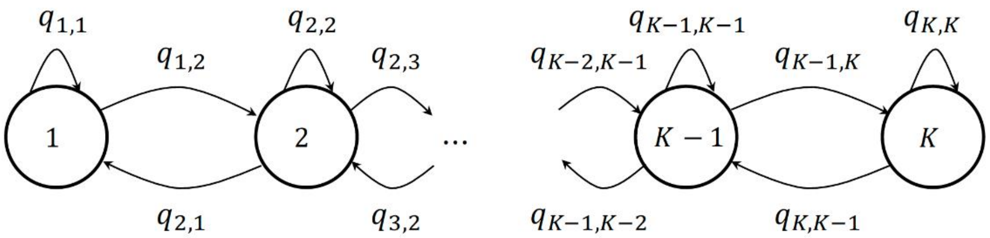
$$\bar{\tau}_i = \frac{\mathrm{Pr}_i}{N(\gamma_i) + N(\gamma_{i+1})} = T_{\mathrm{burst}} + 2t_{\mathrm{prop}} \leq t_0$$

Level crossing rate at a given γ_i

Channel coherence time

Channel-State Transition

- Finite-state Markov Chain to model the behavior of channel



$q_{i,j}$: transition probability from *i*-th state to *j*-th state

Given $q_{i,j}$, we can find the steady-state probability, $\Pr_i$, at *i*-th state

$$q_{i,j} = \begin{cases} 0 & \text{if } \ |i-j| \geq 2, \\ \frac{N(\gamma_{i+1})T_{\text{burst}}}{\Pr_i} & \text{if } \ j = i+1 \ \text{ and } \ i = 1, \ldots, K-1, \\ \frac{N(\gamma_i)T_{\text{burst}}}{\Pr_i} & \text{if } \ j = i-1 \ \text{ and } \ i = 2, \ldots, K, \\ 1 - p_{i,i+1} - p_{i,i-1} & \text{if } \ i = j \ \text{ and } \ 0 < i < K, \\ 1 - p_{0,1} & \text{if } \ i = j = 0, \\ 1 - p_{K,K-1} & \text{if } \ i = j = K. \end{cases}$$

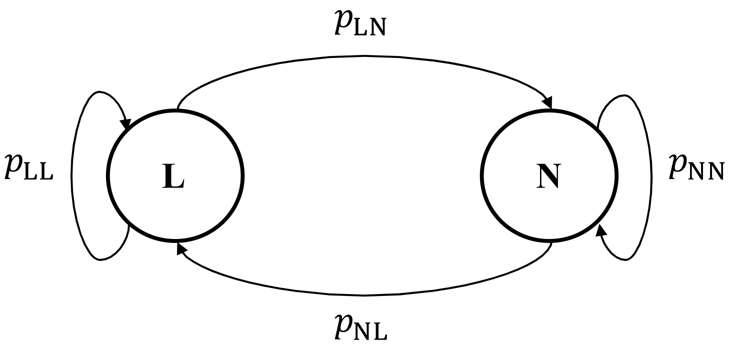
➡ **We use the channel model to develop the burst loss model for analyzing the system throughput**

Burst Loss Model

- We develop the data burst loss model to derive the system throughput
  - Loss state (L-state): burst loss happens (i.e., either the header is corrupted or one of frames is lost) with a probability,

$$\mathrm{BLP}_i = 1-(1-\overline{\mathrm{BER}}_{\mathrm{H},i})^{N_\mathrm{C}} \times (1-\overline{\mathrm{FLR}}_i)^{n_f}$$

    - $\overline{\mathrm{BER}}_{\mathrm{H},i}$: average bit error rate of the control part at channel-state *i*-th
    - $\overline{\mathrm{FLR}}_i$: average frame loss rate at channel-state *i*-th
  - Non-loss state (N-state): none of frames in burst are lost

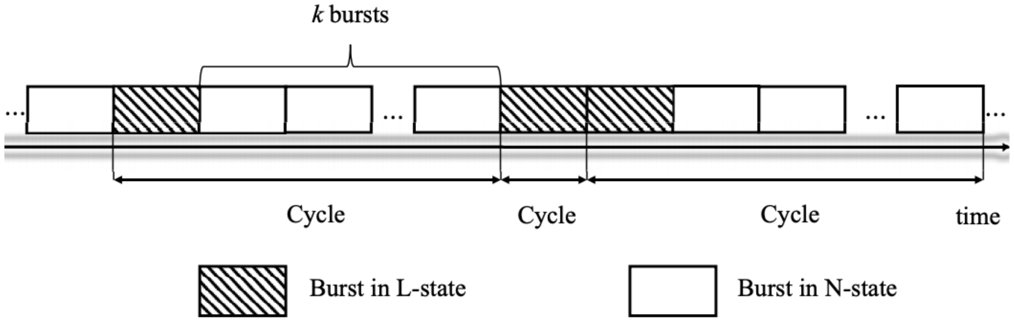


- Transition probabilities
  - $$p_{\mathrm{LN}} = \frac{\sum_{i=1}^{K}\sum_{j=1}^{K}\mathrm{Pr}_i\mathrm{BLP}_i q_{i,j}(1-\mathrm{BLP}_j)}{\sum_{i=1}^{K}\mathrm{Pr}_i\mathrm{BLP}_i}$$
  - $$p_{\mathrm{NL}} = \frac{\sum_{i=1}^{K}\sum_{j=1}^{K}\mathrm{Pr}_i(1-\mathrm{BLP}_i) q_{i,j}\mathrm{BLP}_j}{\sum_{i=1}^{K}\mathrm{Pr}_i(1-\mathrm{BLP}_i)}$$

- Pr_i: the steady-state probability at channel-state *i*-th
- q_{ij}: the transition probability from *i*-th to *j*-th channel-state

System Throughput Analysis (1)

- We consider an infinite sequence of transmitting bursts which is divided into cycles
  - Each cycle starts by a burst in L-state and ended by the burst just before another L-state one



- Throughput is defined as the ratio between the average no. of successful received frames in a cycle and average cycle duration

System Throughput Analysis (2)

- System Throughput: $\bar{\eta} = \dfrac{E_f \times N_f}{(1+E_b) \times T_{\mathrm{slot}}}$

  - E_b: average no. of bursts in N-state of a cycle

$$E_b = p_{\mathrm{L,N}} \times \sum_{k=1}^{\infty} k \times p_{\mathrm{N,L}}(k) + 0 \times p_{\mathrm{L,L}}$$

  - E_f: average no. of successful frames in a cycle

$$E_f = \frac{E_b \times n_f}{\overline{M}} + \sum_{i=1}^{n_f-1} i \binom{n_f - 1}{i} p_s^i (1 - p_s)^{n_f-1-i} \left(1 - \overline{\mathrm{BER}}_{\mathrm{H}}\right)^{N_{\mathrm{C}}}$$

    - p_s: probability that a frame is correctable (received successfully)
    - $\bar{M}$: average number of transmissions for a frame

Numerical Results

- We consider a FSO transmission from low-earth orbit (LEO) satellite to ground station
- The system parameters

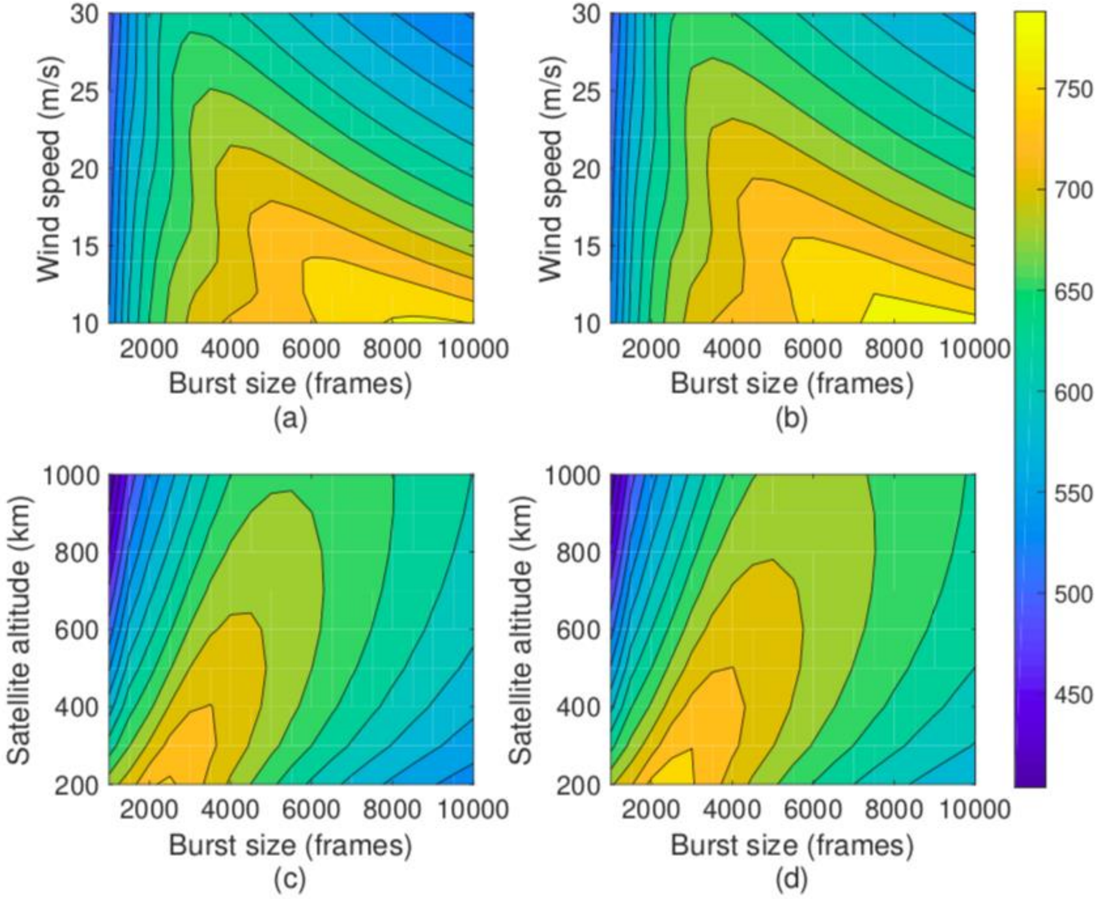
Name	**Value**
Frame size	$N_f = 1500$ bytes
Burst-control part size	$N_C = 40$ bits
Persistent level of HARQ	$M = 3$
Data rate	$R_b = 1$ Gbps
Satellite Altitude	$H = 610$ km
Zenith angle	$\xi = 60^o$
Wind speed	$v_{\text{wind}} = 21$ m/s
RCPC family code	(1, 4/5, 1/2) (1, 1/2, 1/3)
Optical wavelength	$\lambda = 1.55\ \mu$m

Burst Size Selections

- $T_{\text{slot}} = T_{\text{burst}} + 2t_{\text{prop}} \leq t_o$
- Coherence time

$$t_0 = \frac{\sqrt{\lambda H \sec(\xi)}}{v_{\text{wind}}}$$

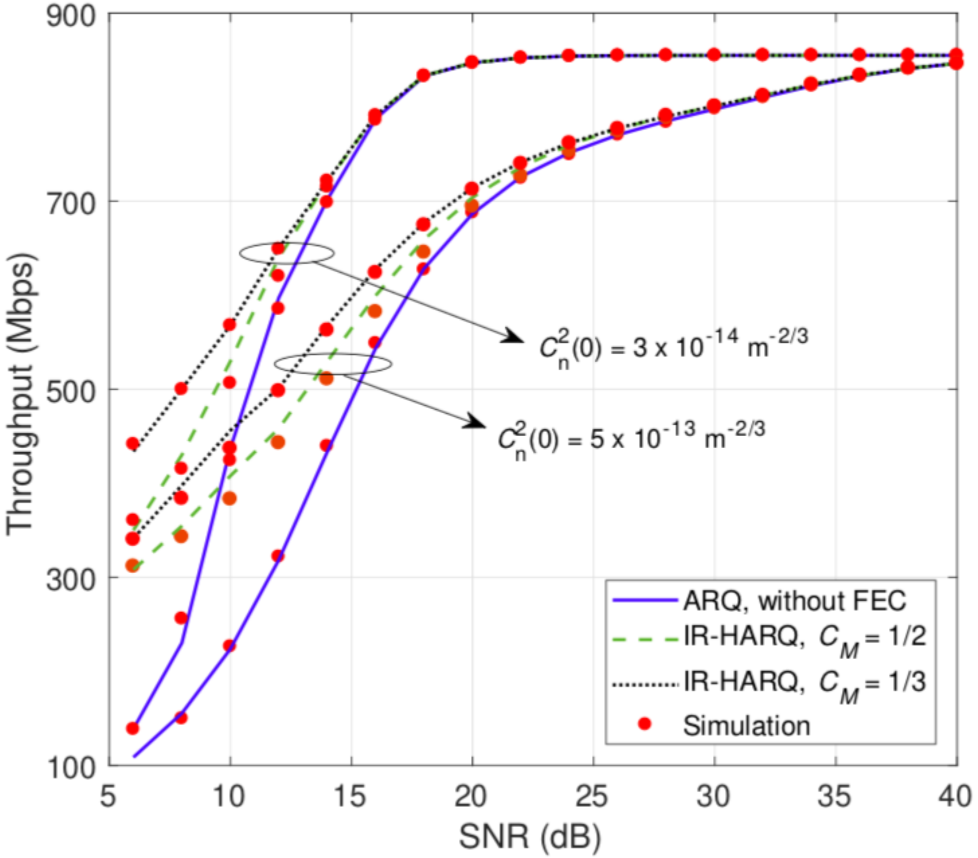
- By varying wind speed or satellite altitude, the optimal burst size can be observed to maximize system throughput



- Given H = 610 km: (a) C_M = 1/2 and (b) C_M = 1/3
- Given v_{wind} = 21 m/s: (a) C_M = 1/2 and (b) C_M = 1/3

Throughput vs. received SNR

- IR-HARQ outperforms pure sliding window ARQ in high error rate environment



Burst size = 4000 frames, H = 610 km, v_{wind} = 21 m/s

Conclusions

- The paper studied the design and analyzed the throughput performance of IR-HARQ protocol for FSO burst transmission in satellite communication systems.
- Numerical results
  - showed the impact of atmospheric turbulence on throughput performance.
  - confirmed the effectiveness of using IR-HARQ.
  - supported the optimal selection of burst size to maximize the system throughput.
- Future work
  - Consider a comprehensive design by exploring the queuing model and adaptive modulation and coding (AMC) schemes.

Thank you for your listening!

(Attendance supported by Telecommunications Advancement Foundation)

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