A Finer ALOHA-Based Analytical Model for LR-FHSS Performance Evaluation

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Internet of Remote Things

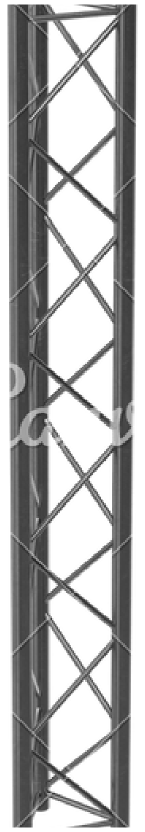
LPWAN Characteristics :

- Long Range
- High Autonomy
- Cost effectiveness

Some IoT use cases :

Field Monitoring | Wild Life Tracking | Disaster Warning | Environmental Monitoring

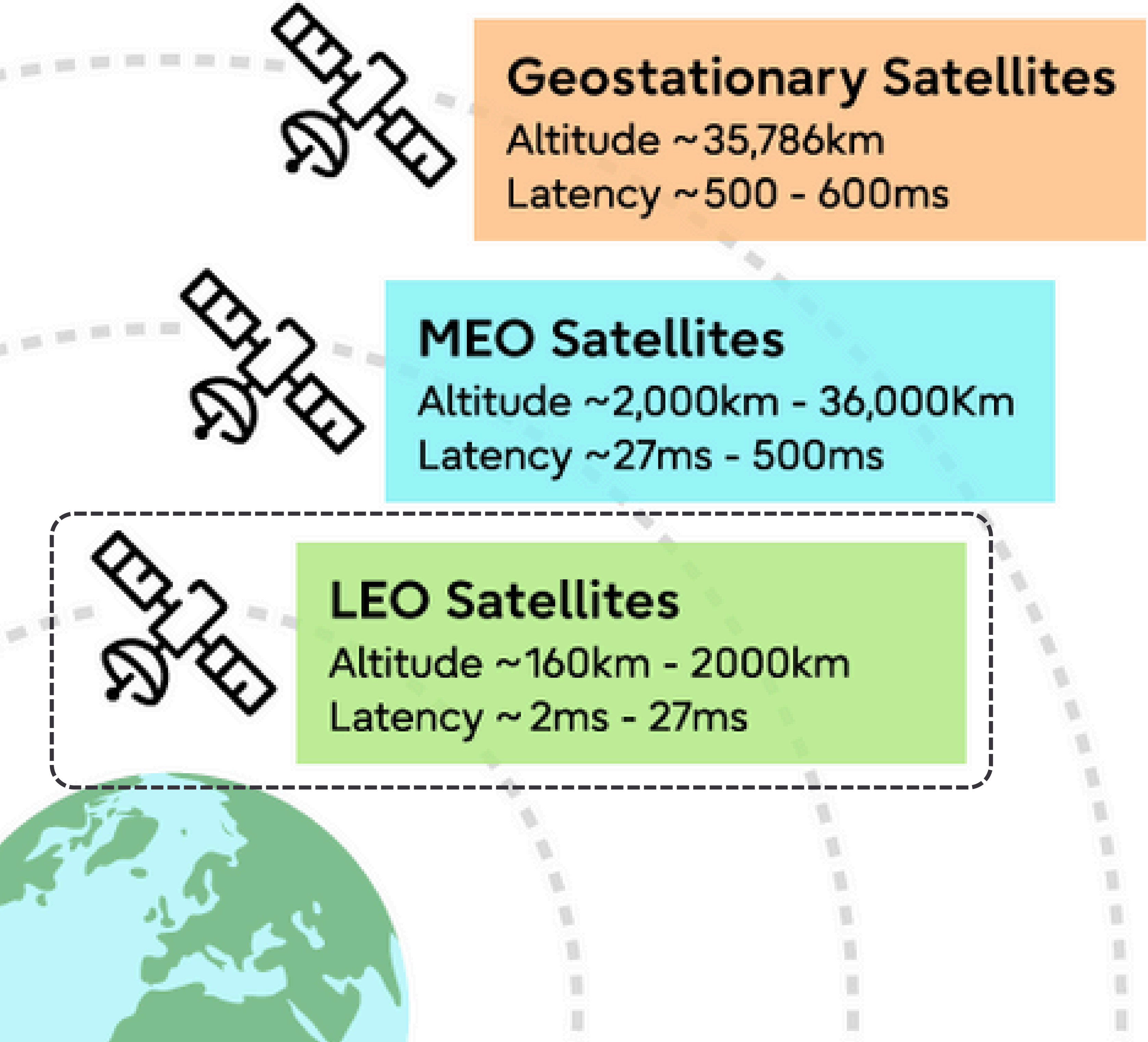
Deployed in hard-to-reach and underserved areas



Deploying Terrestrial infrastructures in remote areas:

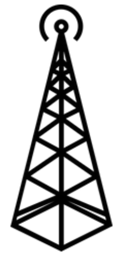
- **Costly**
- **Hard to achieve**
- **Limited by its topology**
- **Difficult to maintain**

LoRaWAN: DtS Scenario



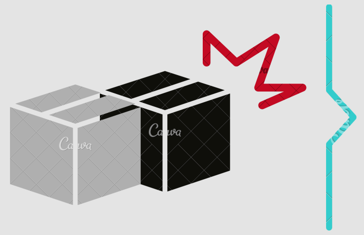
Low Earth Orbit Satellites :

- **Closer to earth**
- **Cheaper deployments**
- **More reachable**
    - **Less signal attenuation**



Ideal Gateway alternative

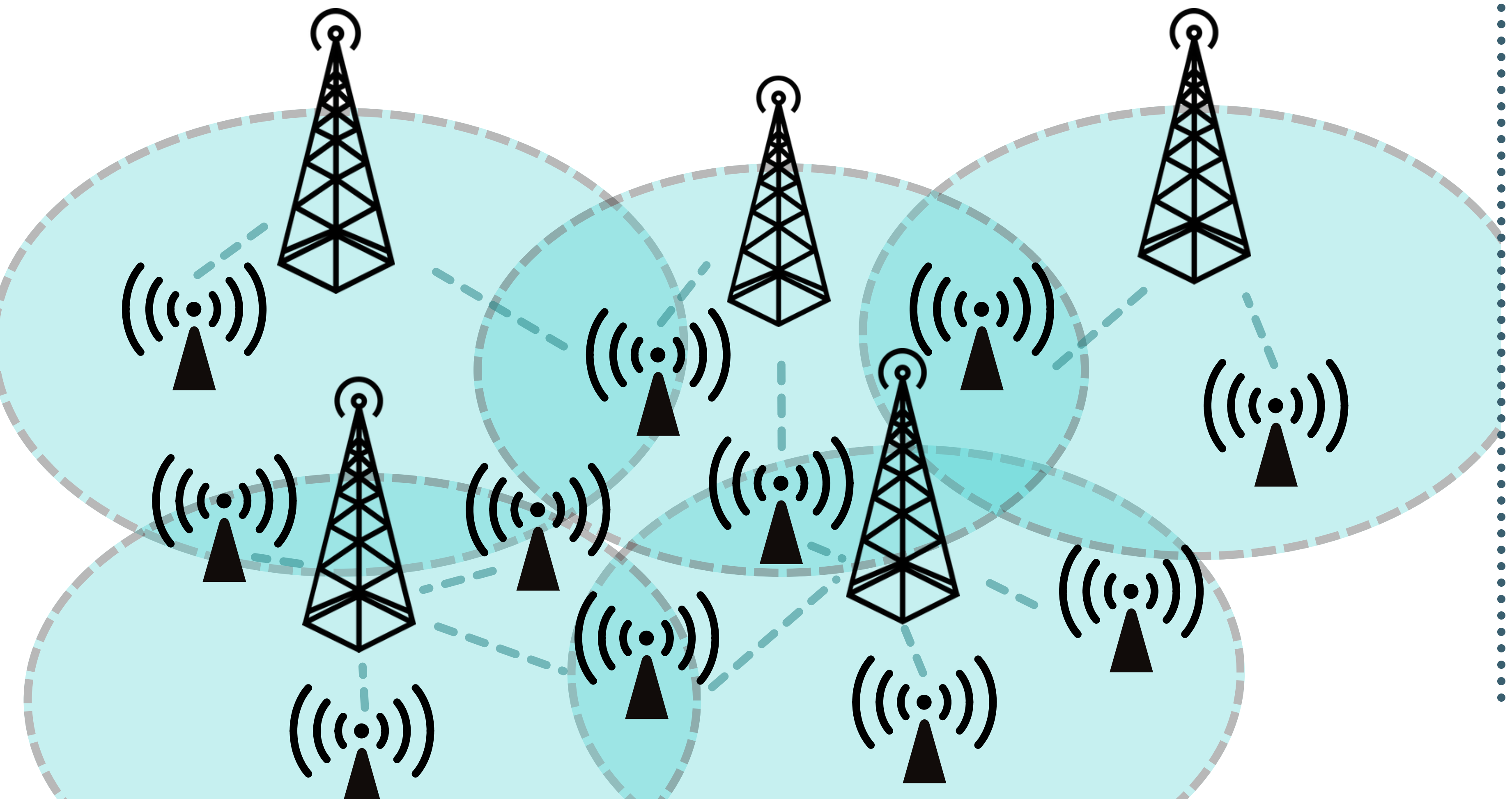
LoRaWAN: DtS Network



Collision = Same :
Time + Channel + SF

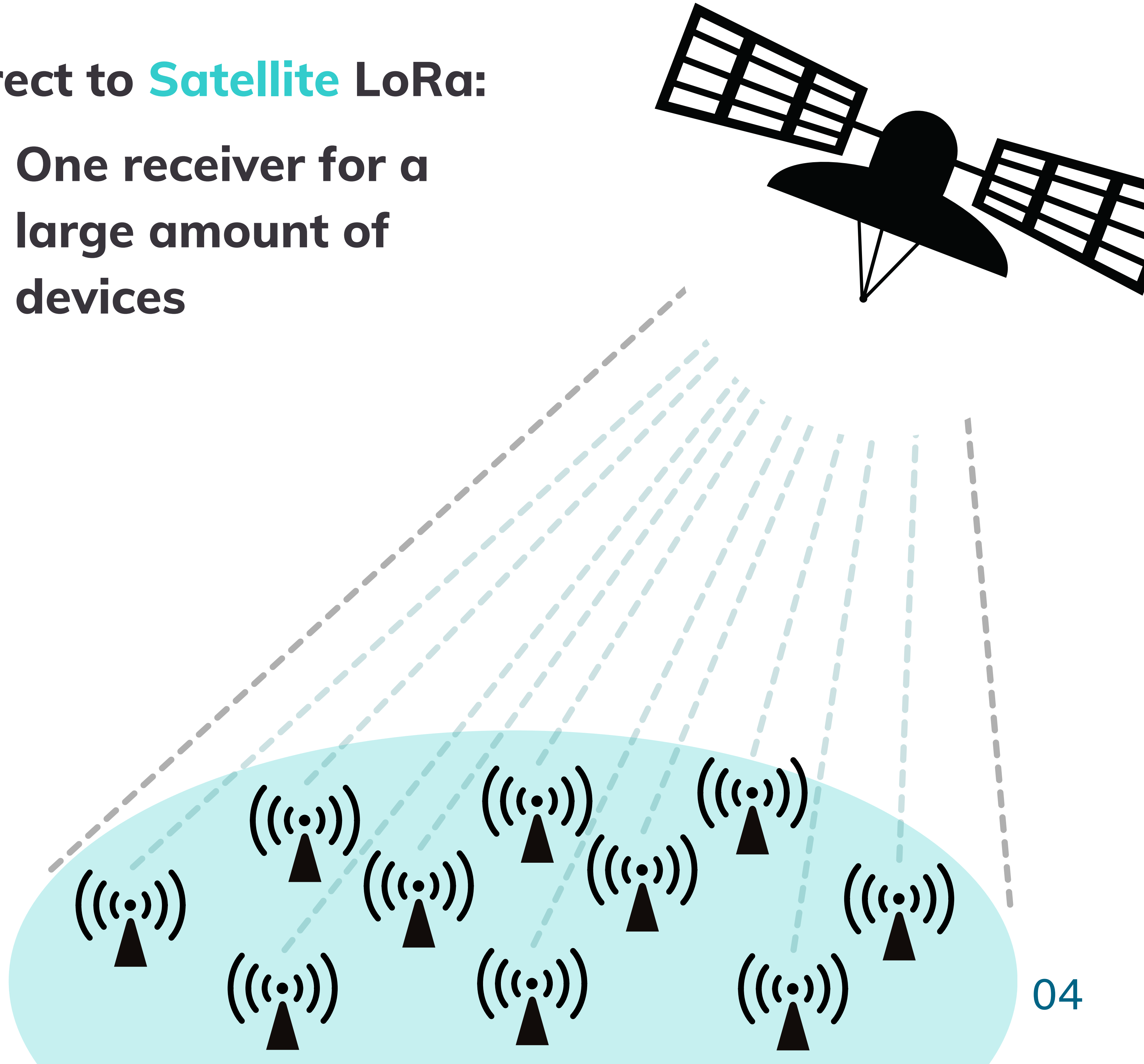
Terrestrial LoRa:

- Multiple Gateways
- Distibuted devices
- Spread traffic



Direct to Satellite LoRa:

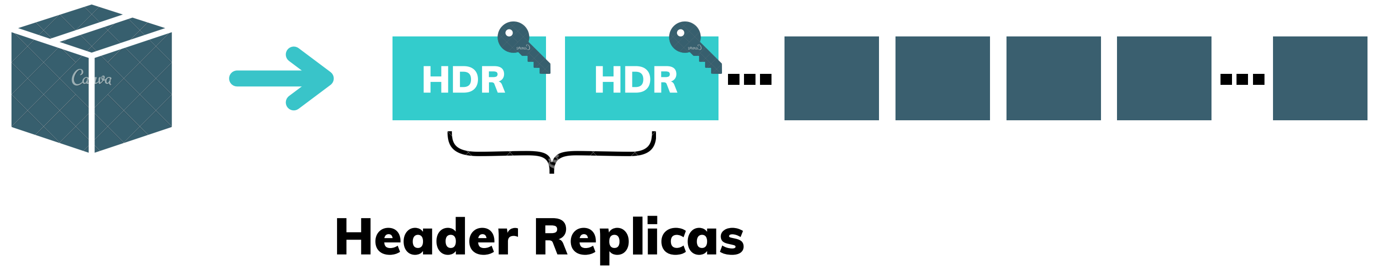
- One receiver for a large amount of devices



LR-FHSS*: New Standard for DtS-LoRaWAN

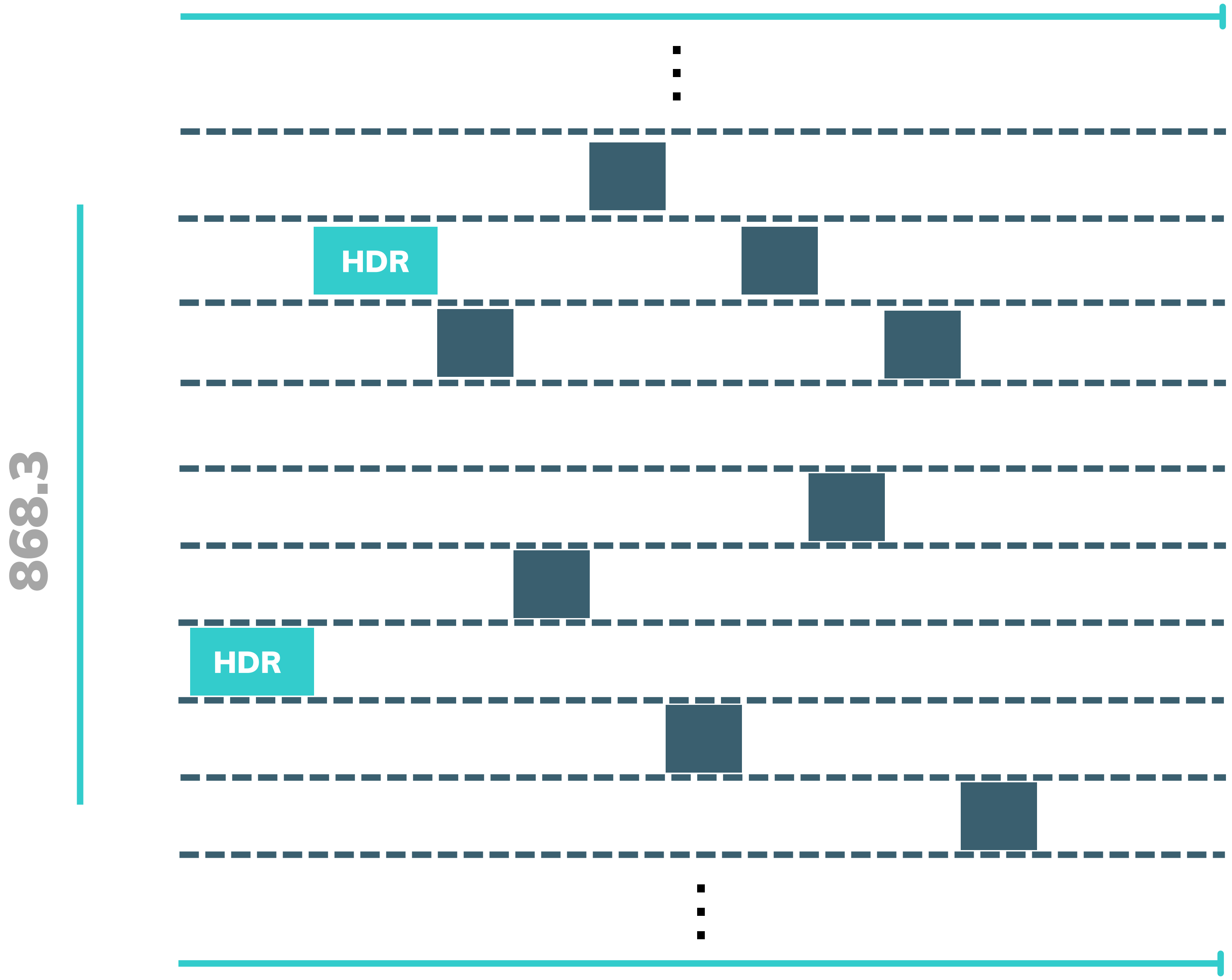
Long Range - Frequency Hopping Spread Spectrum

1 Packet fractionning



2 (even more) Spreading Spectrum

3 Frequency Hopping



Pseudo Random Hopping Sequence

"RP002-1.0.4 Regional Parameters." Accessed: Oct. 07, 2024. [Online]. Available: [1] G. Boquet, P. Tuset-Peiró, F. Adelantado, T. Watteyne, and X. Vilajosana, "LR-FHSS: Overview and Performance Analysis," IEEE Communications Magazine, vol. 59, no. 3, pp. 30–36, Mar. 2021, doi: 10.1109/MCOM.001.2000627.

LR-FHSS: Packet Fractionning

GMSK modulation

Header Replicas

Payload Fragments

Carries the packet's metadata — the key to decoding the payload

The packet's data — encoded with redundancy for resilience

Data Rates:

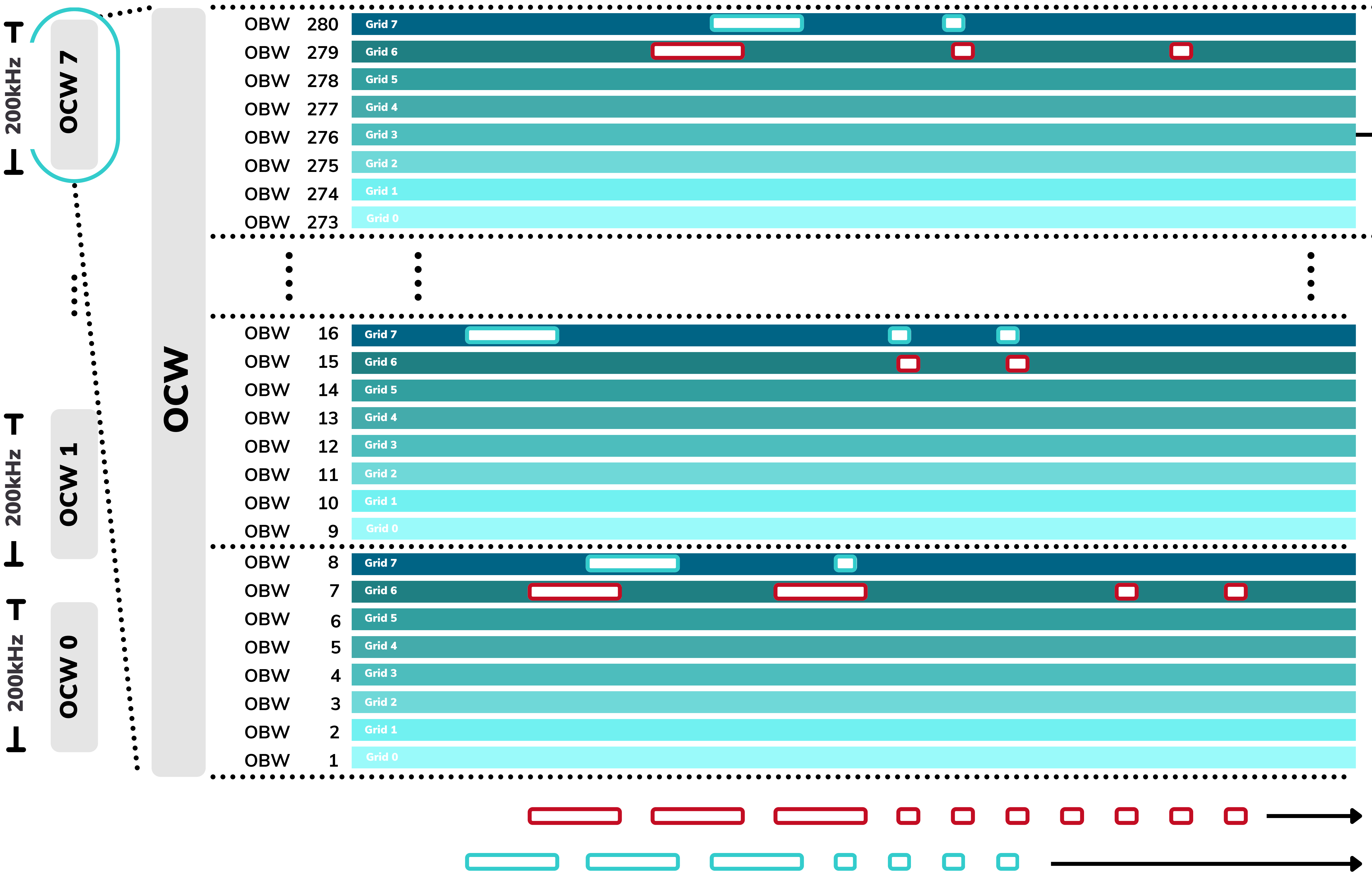
Coding Rates:

Data Rates	Header Replicas	Coding Rates
US DR5 & EU DR8 / DR10	**3 Replicas**	**CR 1/3:** • More robust • 1/3 of the fragments allows full data retrieval
US DR6 & EU DR9 / DR11	**2 Replicas**	**CR 2/3:** • Less redundancy • 2/3 of the fragments allows full data retrieval

LR-FHSS: Frequency Hopping

Header replica - 233ms

Payload fragment - 102.4ms



Physical Channel Size
-OBW-
488Hz

Grid Spacing
3.9kHz

Grid = 35 OBW

When a packet needs to be sent

A device will chose:

- **The OCW**
- **An offset frequency (grid)**
- **A hopping sequence**

(pseudo) Randomly

Hops over Grid 6

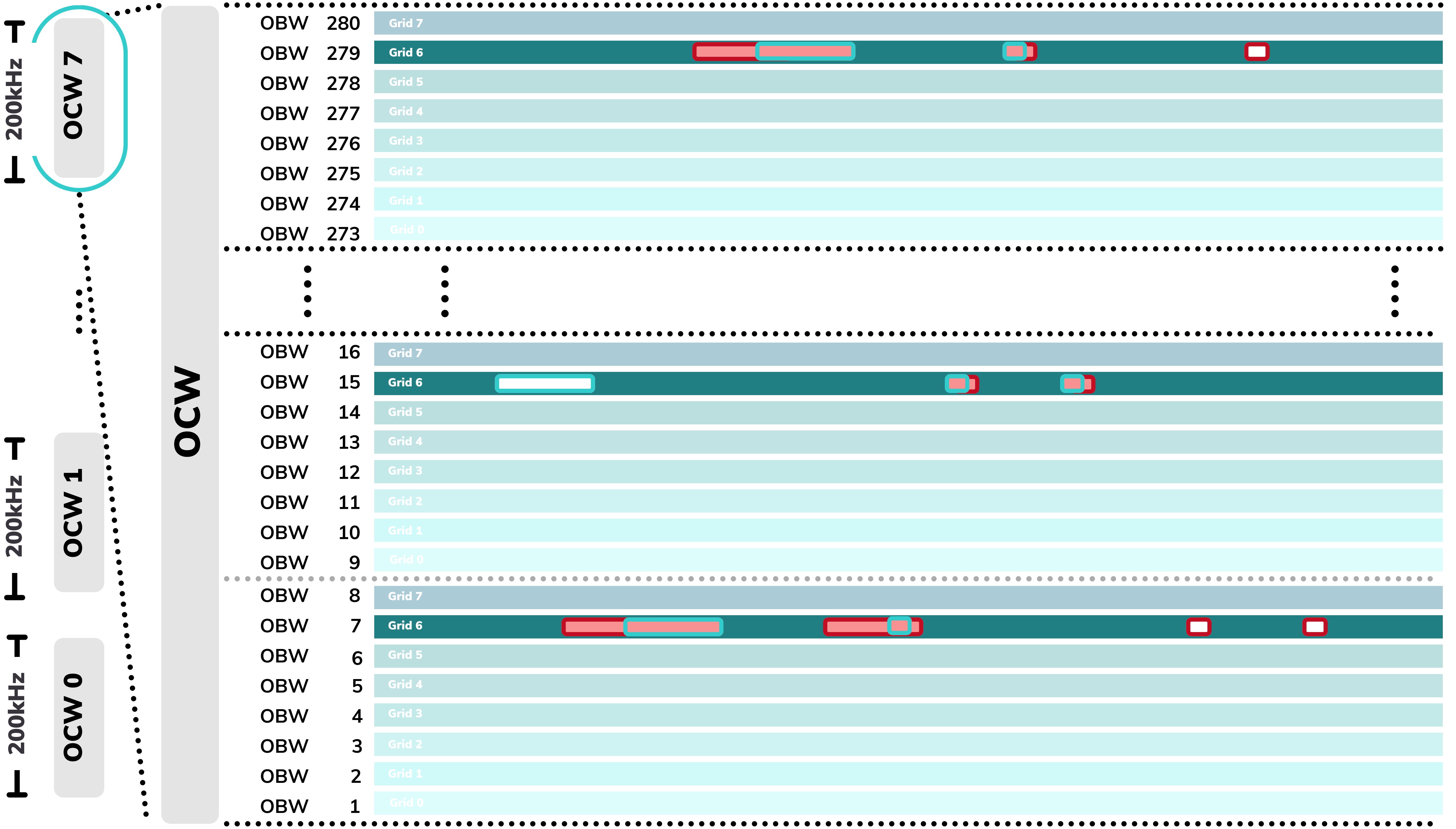
Hops over Grid 7

Orthogonal

LR-FHSS: Collisions

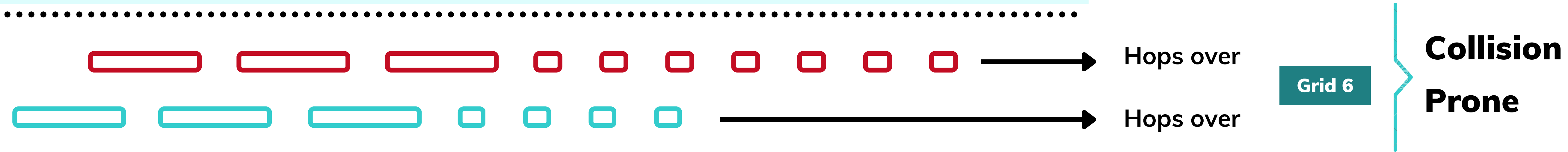
Header replica - 233ms

Payload fragment - 102.4ms



A **packet** is successfully **decoded** iff:

- **At least one header replicas is received**
- **CR% of the payload is received**

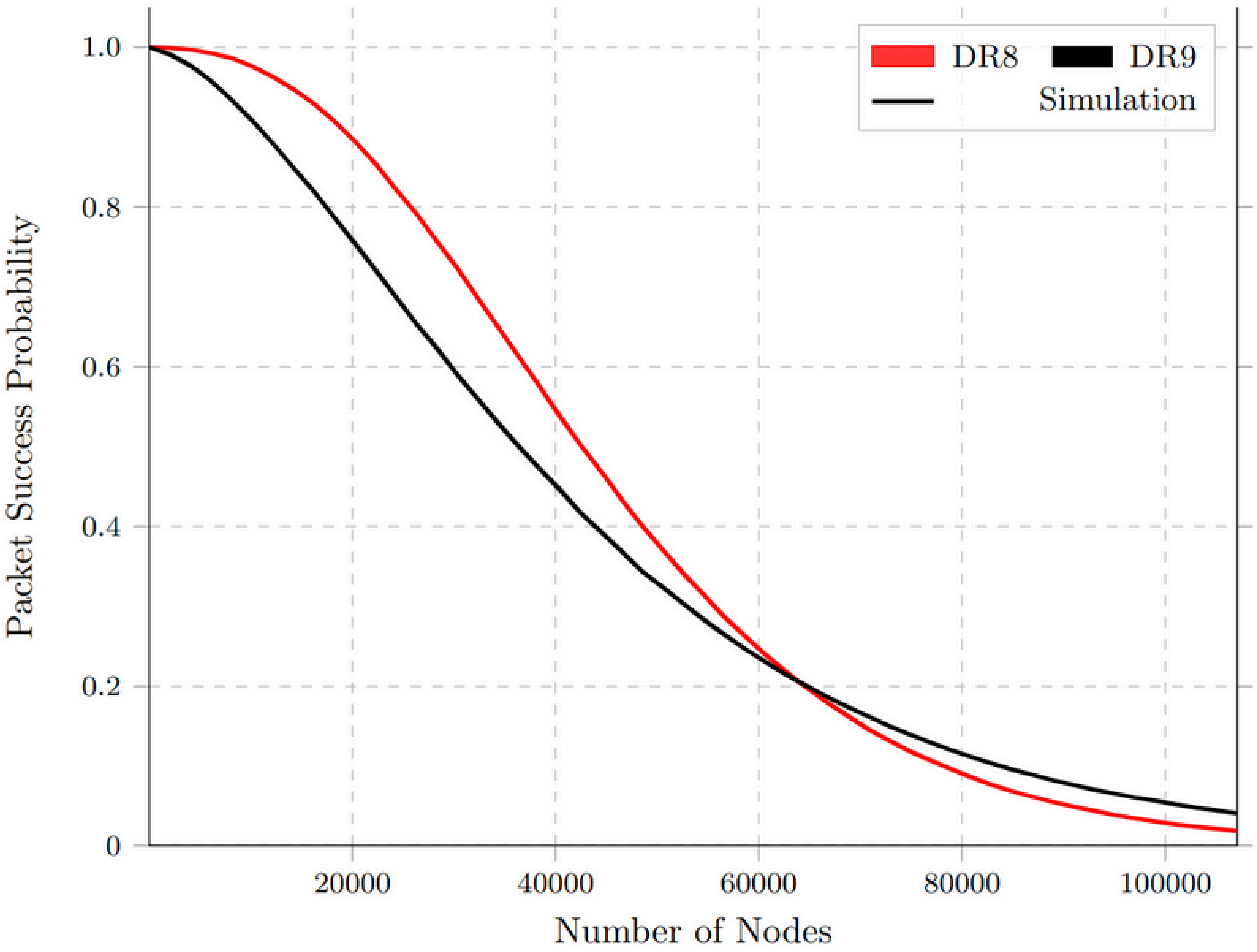


Objective

Develop an **analytical model** whose predictions match the **simulation** results

Simplified Network Model :

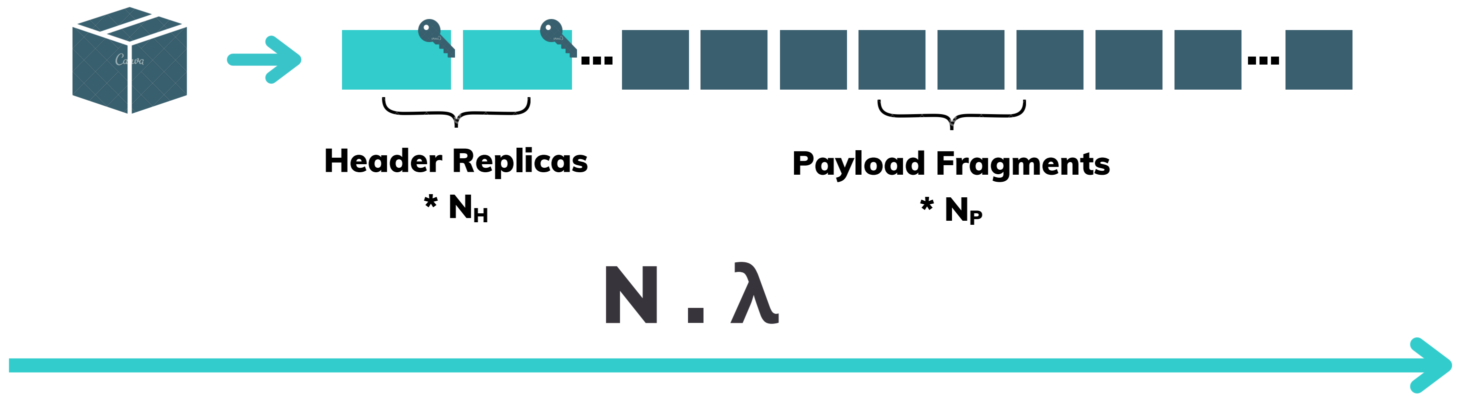
- Single static gateway
  - All devices within range
- Homogeneous transmissions
- Poisson packet arrival process
- Physical-layer effects ignored
  - Focus on the MAC layer

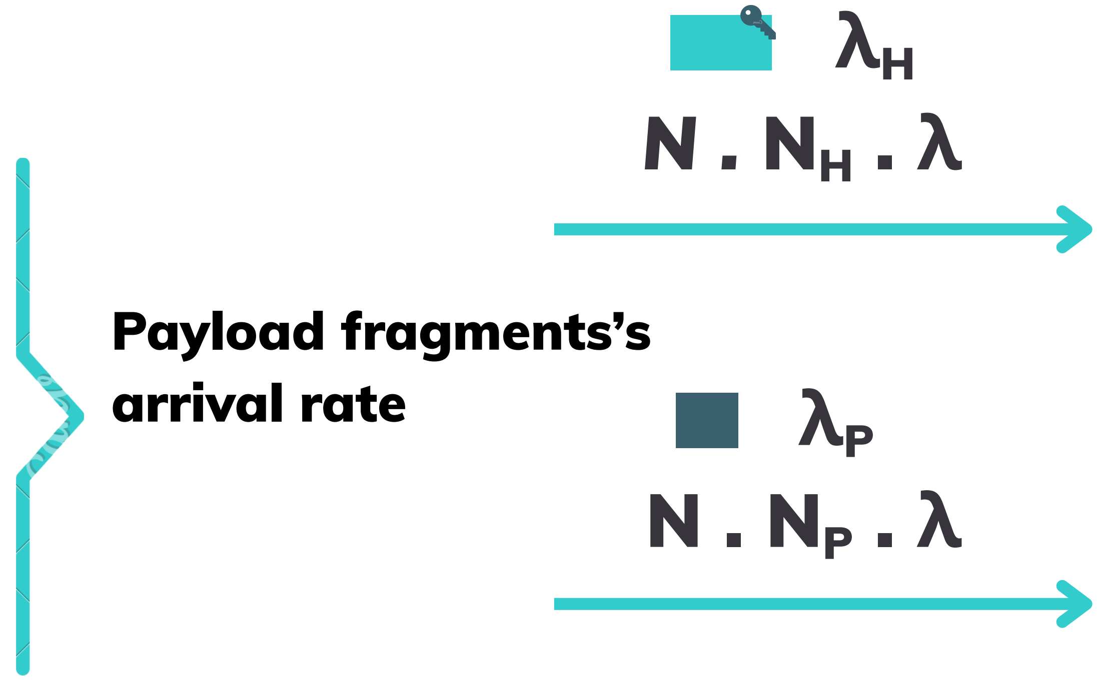


Model's Structure

- N : number of devices
- λ : packet's arrival rate

1. Poisson Flow Division





2. Find the fragment collision probability model for each type

3. Combine to find the packet success probability

Probability of receiving at least one header replica:

$$P_H = 1 - (1 - p_{\text{ok,H}})^{N_H}$$

Probability of receiving at least CR% Payload fragments:

$$p_{\text{ok,P}}(X = k) = \binom{N_p}{k} (p_{ok}^P)^k (1 - p_{ok}^P)^{N_p - k}$$

$$P_P = 1 - \sum_{k=1}^{CR.N_P} p_{\text{ok,P}}(X = k)$$

Probability of successfully decoding a packet:

$$P_{success} = P_H \times P_P$$

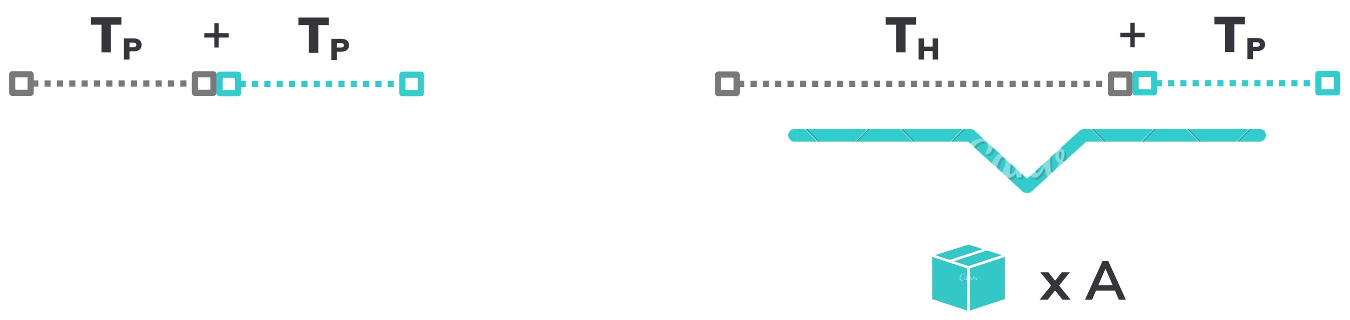
SoTA* Model : Balls in Bins

- A : number of arrivals in a time period
- C : number of channels

Vulnerability periods:

For header replicas:

For payload fragments:



No Fragment Collision probability:

$$\left(\frac{C-1}{C}\right)^{A-1} \longrightarrow \left(\frac{C-1}{C}\right)^{\mathrm{E}(A)-1}$$

Balls in Bins Inspired

Approximation by average:

Mathematically wrong

In Low Density Scenarios :

$$E(A) - 1 < 0 \longrightarrow \left(\frac{C-1}{C}\right)^{E(A)-1} > 1$$

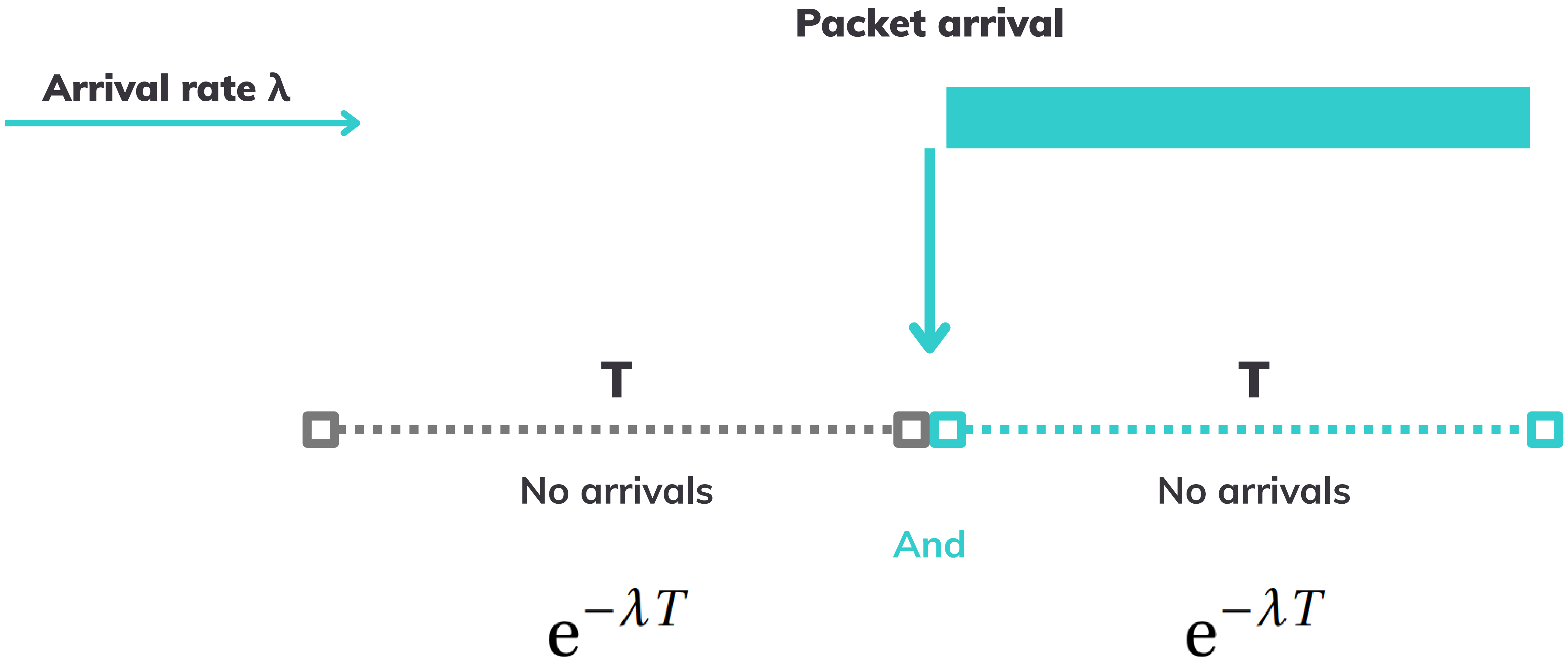
Used in all formulas

the model only provides reliable estimates in high-density networks

M. A. Ullah, K. Mikhaylov, and H. Alves, "Analysis and Simulation of LoRaWAN LR-FHSS for Direct-to-Satellite Scenario," IEEE Wireless Communications Letters, vol. 11, no. 3, pp. 548–552, Mar. 2022, doi: 10.1109/LWC.2021.3135984.

Basic ALOHA* Reminder

- **λ : packet's arrival rate**



No collision Probability: $$p_{\mathrm{ok}} = e^{-\lambda T} e^{-\lambda T} = e^{-2\lambda T}$$

N. Abramson, "THE ALOHA SYSTEM: another alternative for computer communications," in Proceedings of the November 17-19, 1970, fall joint computer conference on - AFIPS '70 (Fall), Houston, Texas: ACM Press, 1970, p. 281. doi: 10.1145/1478462.1478502.

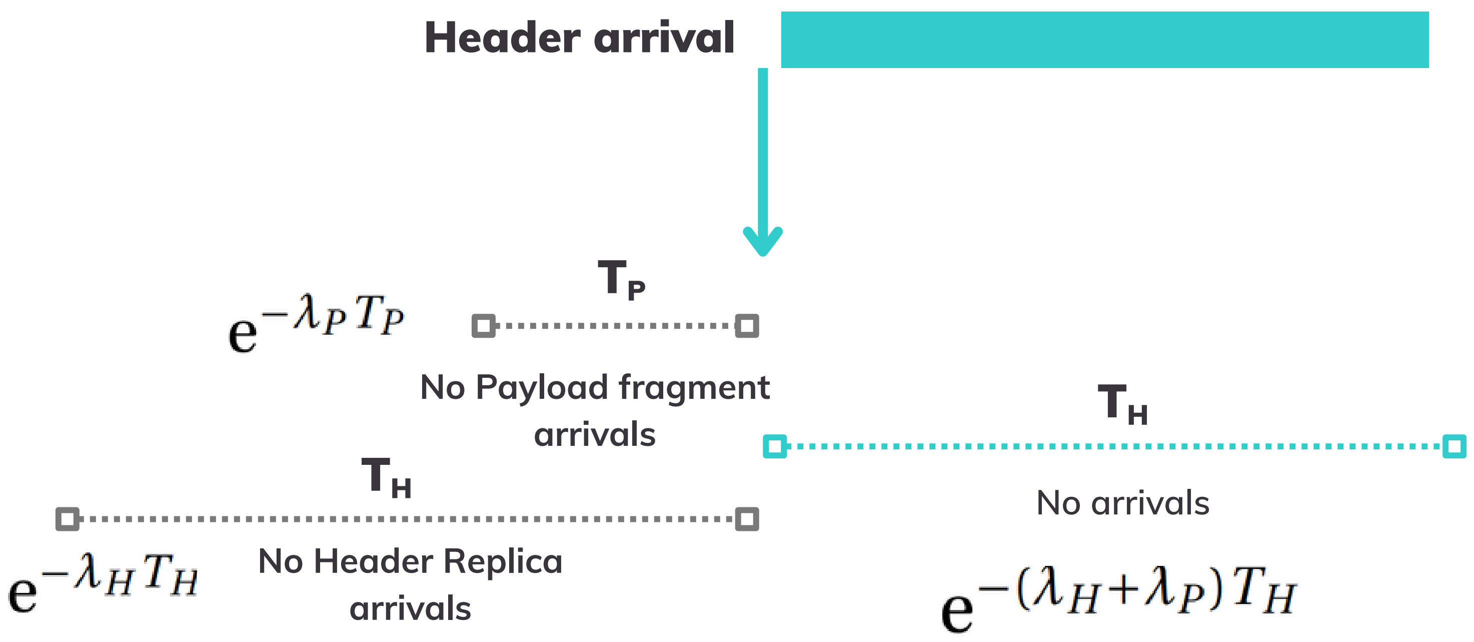
LR-FHSS: ALOHA Based Model

- **N : number of devices**
- **C : number of channels**

1. Multi Channel

2. Multi Class

Reasoning with Header:



Using the Aloha Logic :

No payload fragment collision Probability:

$$p_{\mathrm{ok,P}} = \mathrm{e}^{-[2\lambda_P T_P + \lambda_H (T_H + T_P)]}$$

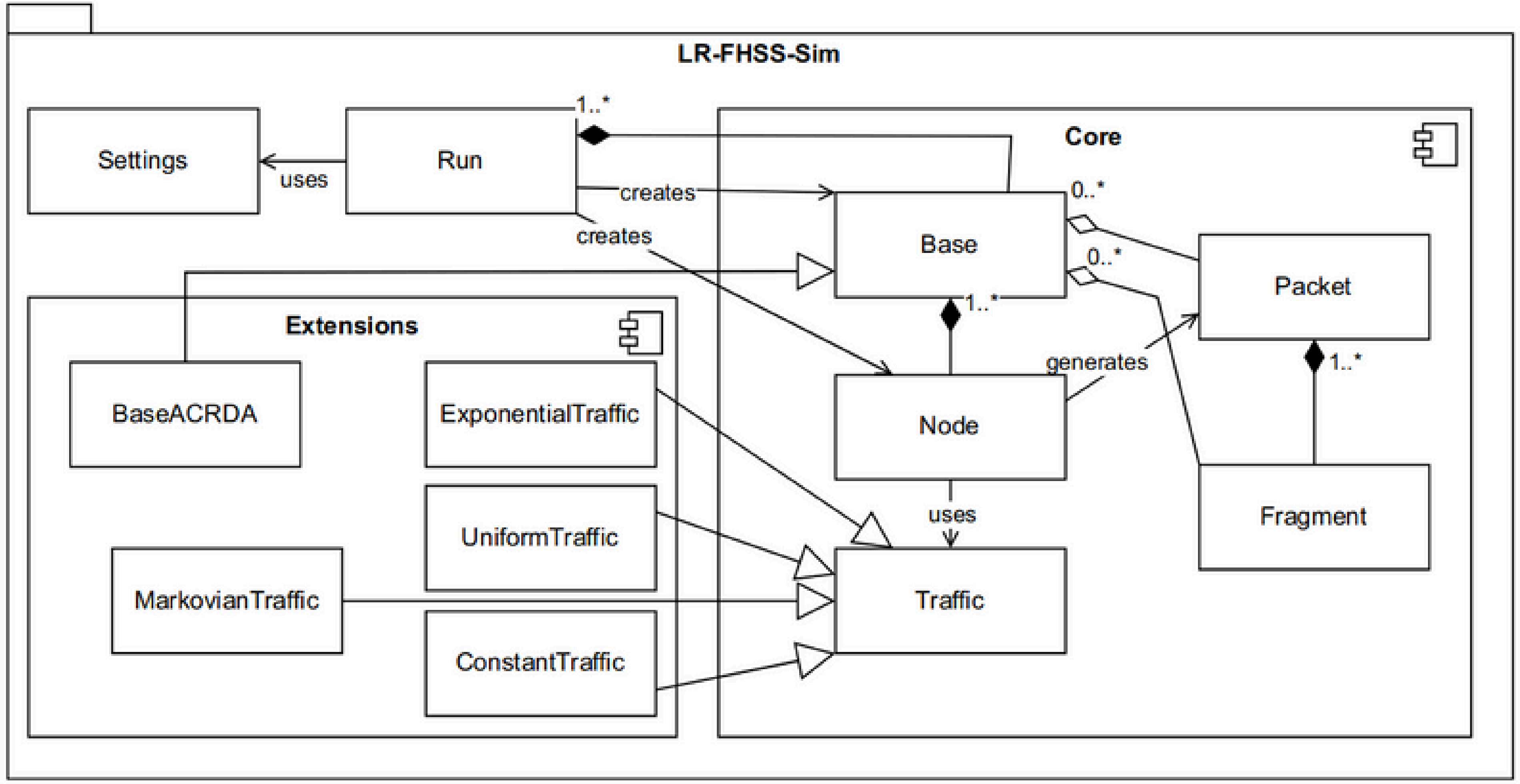
No header collision Probability:

$$p_{\mathrm{ok,H}} = \mathrm{e}^{-[2\lambda_H T_H + \lambda_P (T_H + T_P)]}$$

Simulation Environment

LR-FHSS Sim* : Discrete event simulator

Model and Simulation results side by side comparison



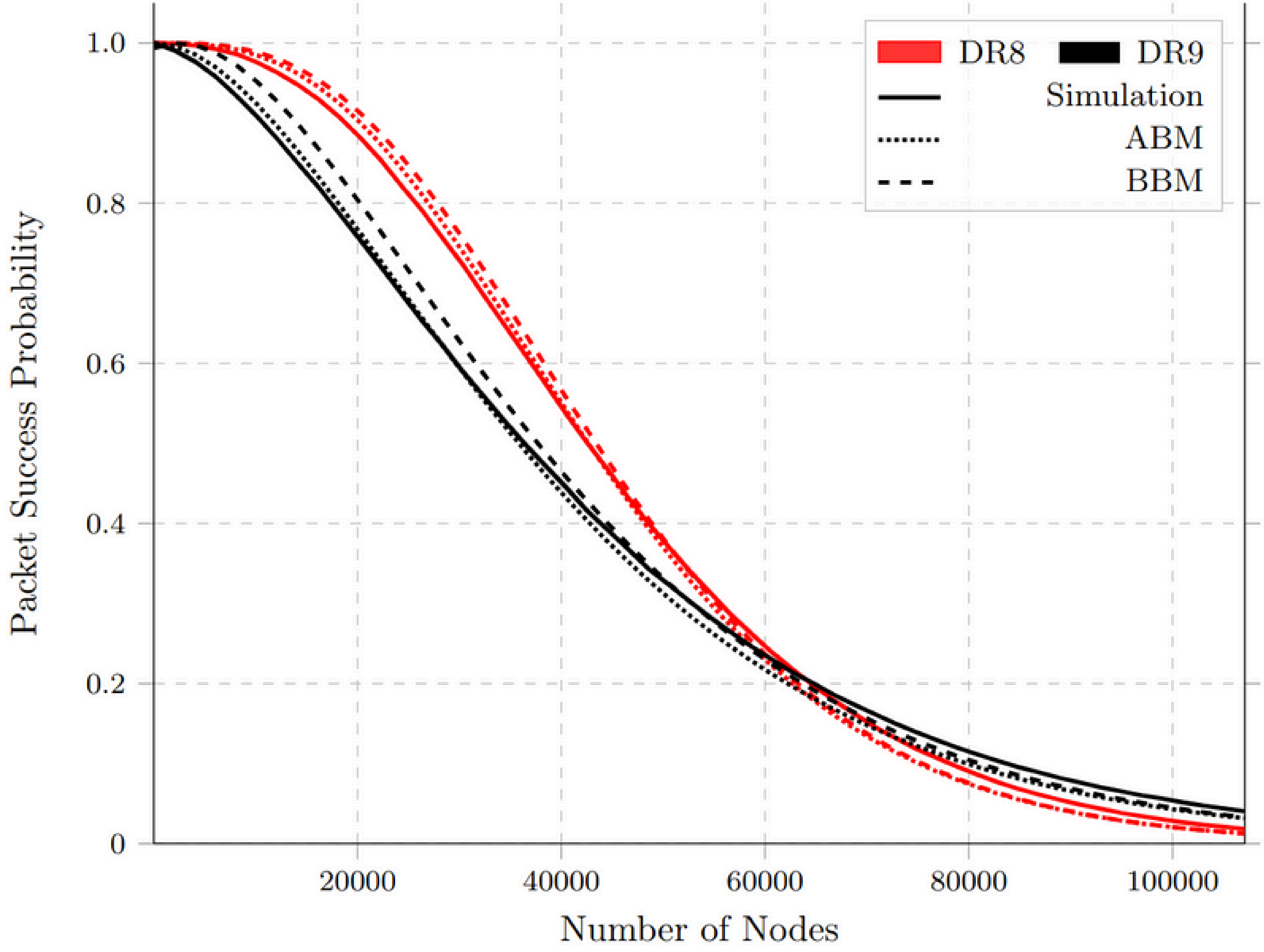
Simulation scenarios :

- Poisson packet arrivals
- Payload length of 10 bytes
- Data rates 8 and 9
- Physical Layer abstraction

J. M. de S. S. Ana, A. Hoeller Jr., H. Alves, and R. D. Souza, “LR-FHSS-Sim: A Discrete-Event Simulator for LR-FHSS Networks,” Apr. 15, 2024, arXiv: arXiv:2404.09539. doi: 10.48550/arXiv.2404.09539.

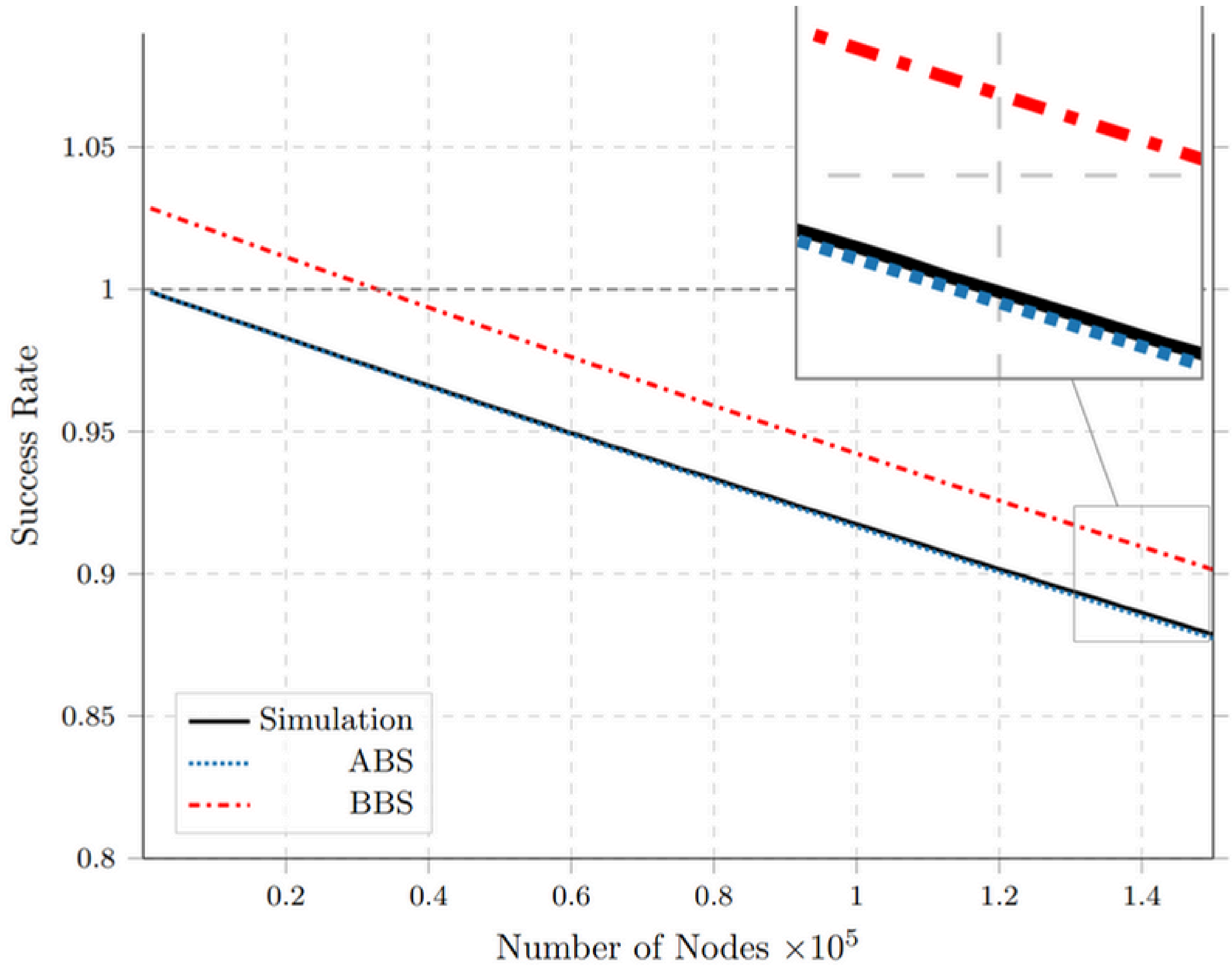
LR-FHSS: Simulation vs. Analytical Results

λ = 0.002 pkt/s

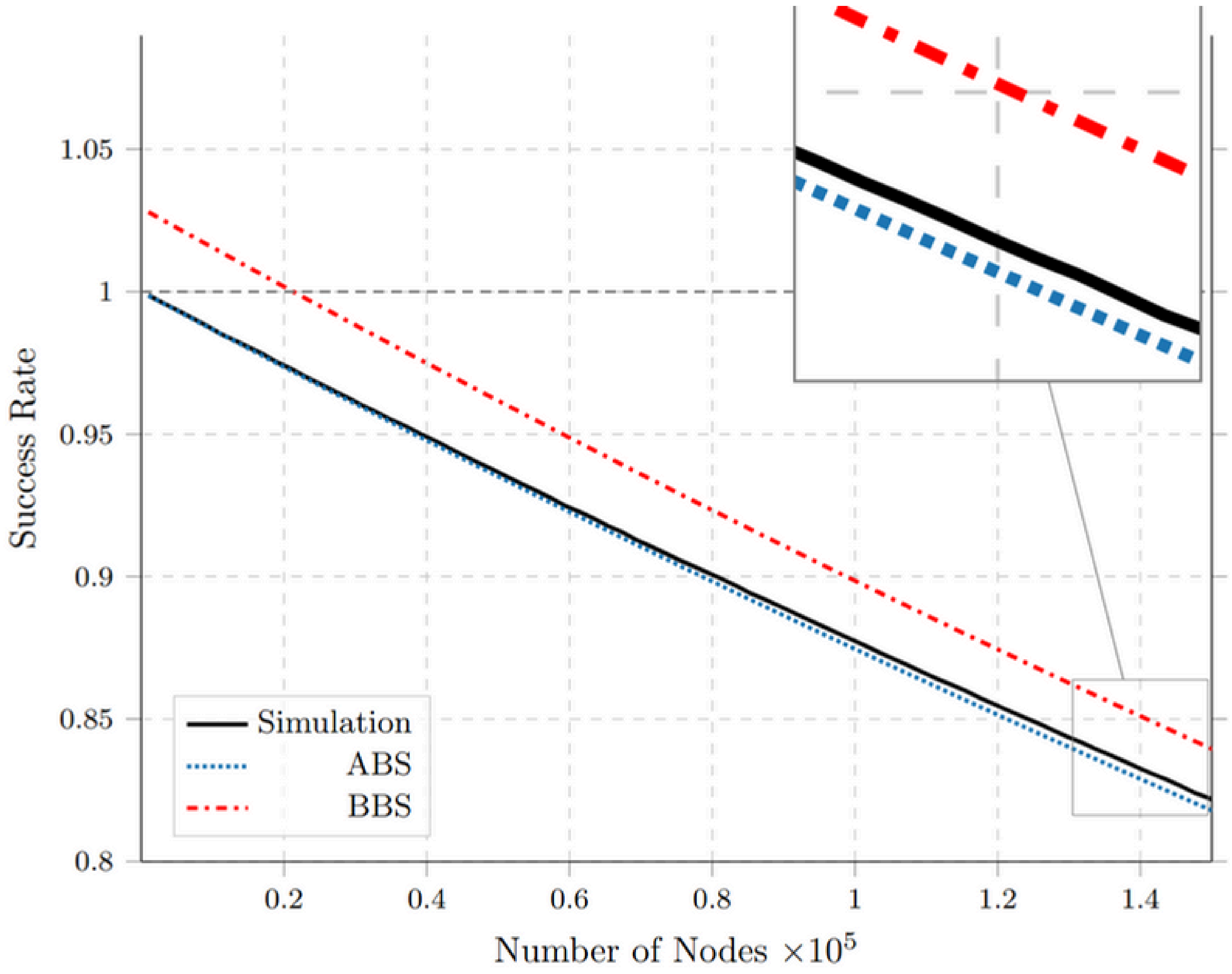


LR-FHSS: Low Arrival Rate

$\lambda = 10^{-4}$ pkt/s
DR 8



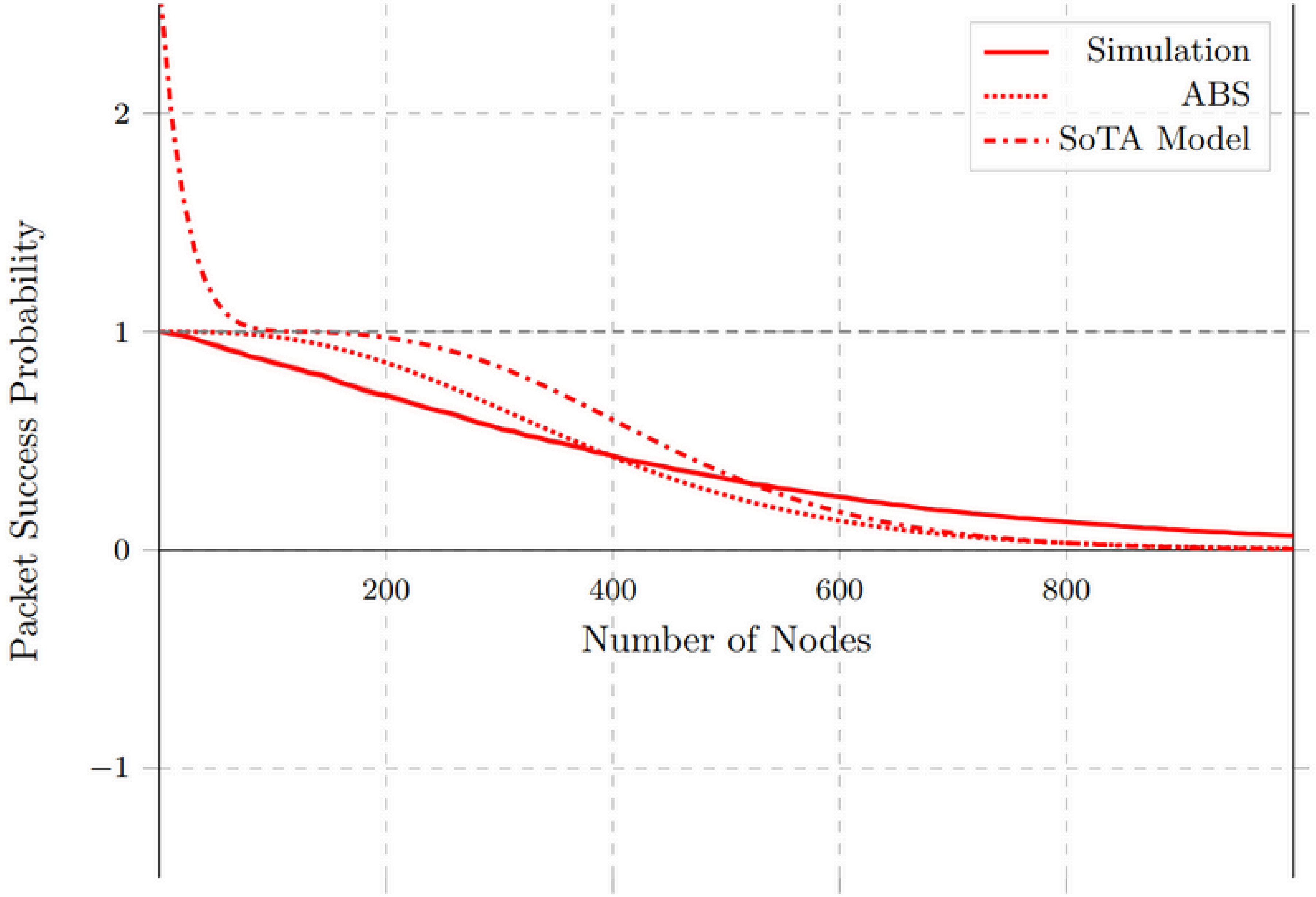
Headers



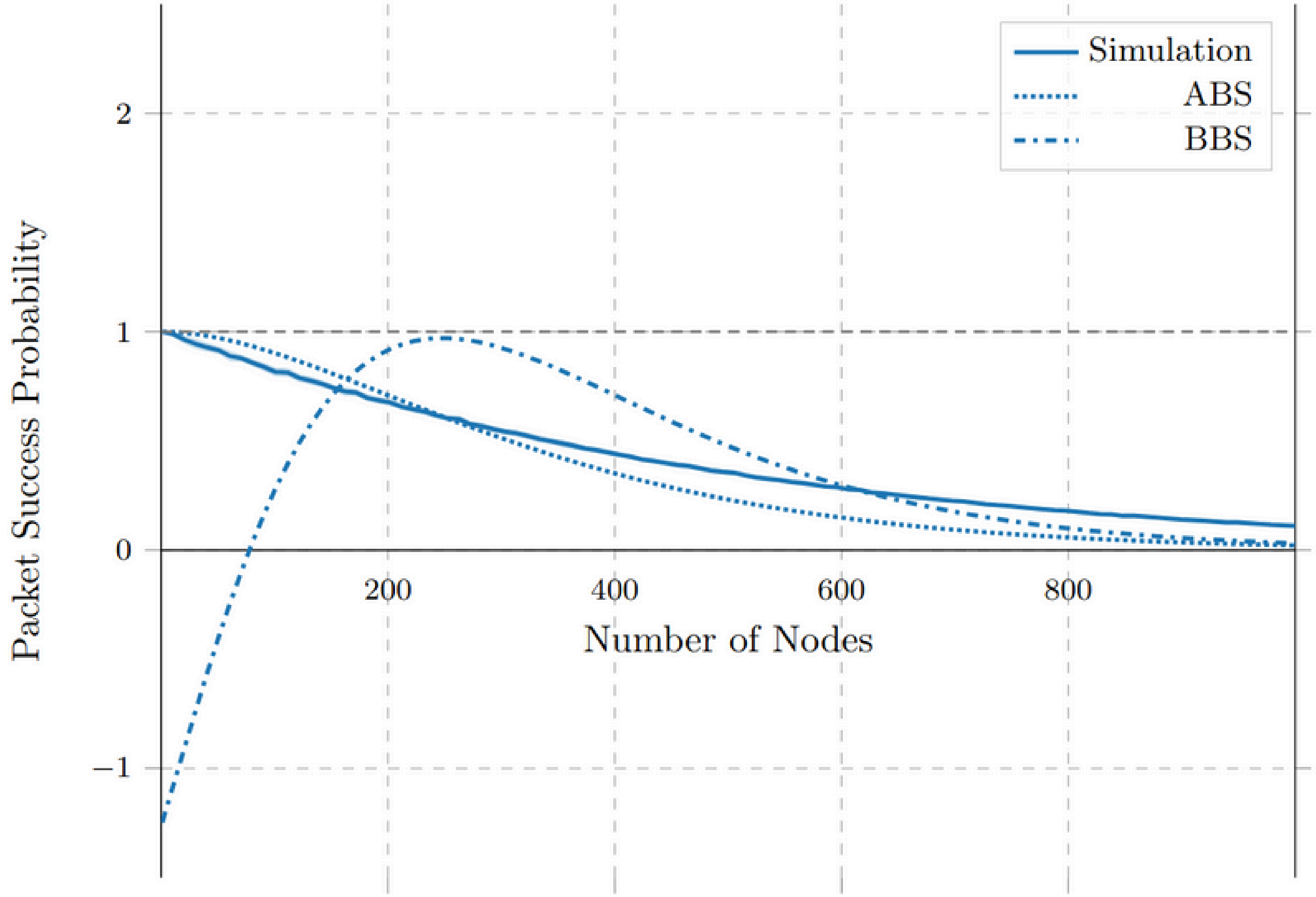
Payload Fragments

LR-FHSS: With only 3 Channels

λ = 0.002 pkt/s
C = 3



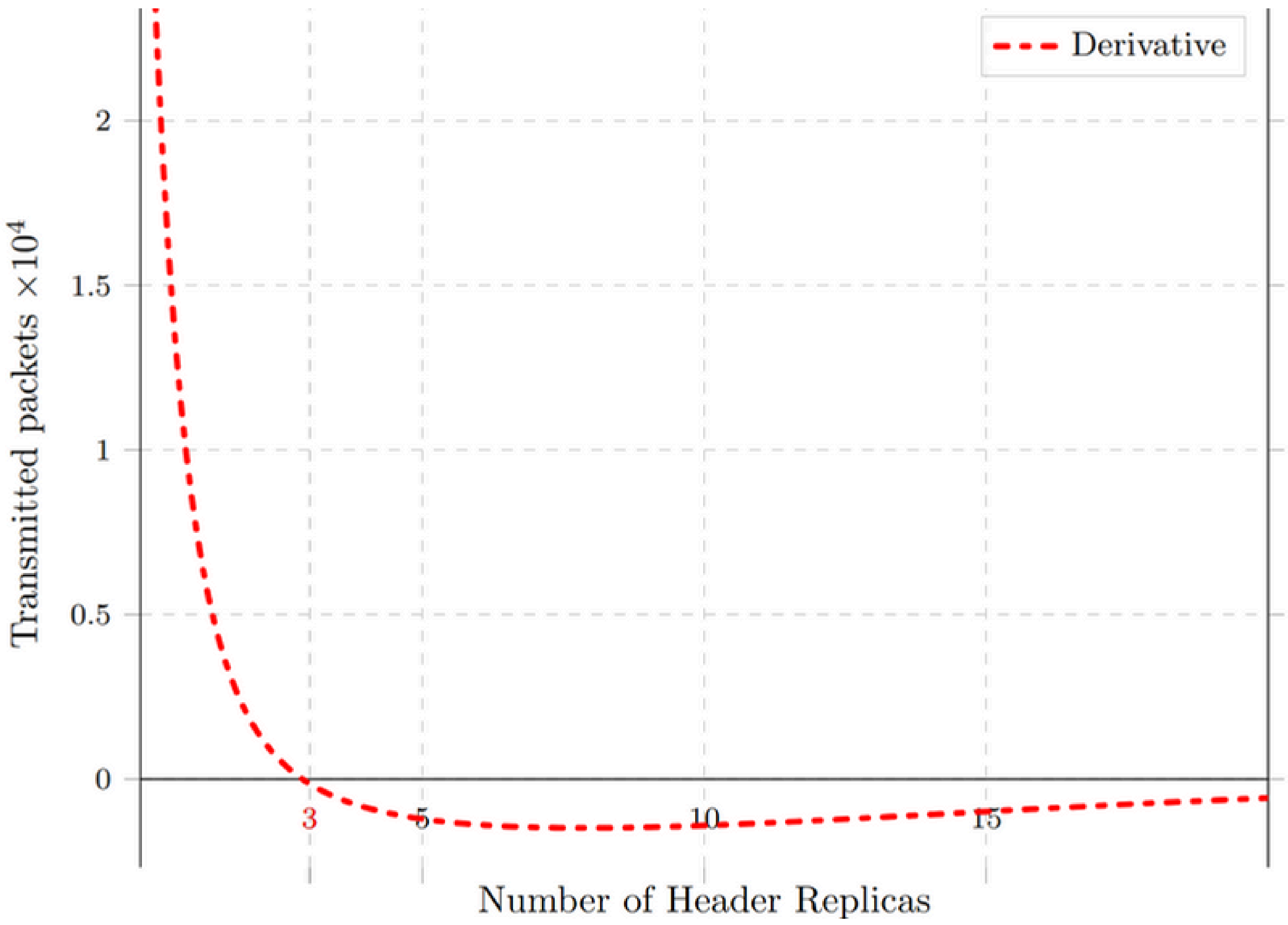
DR8

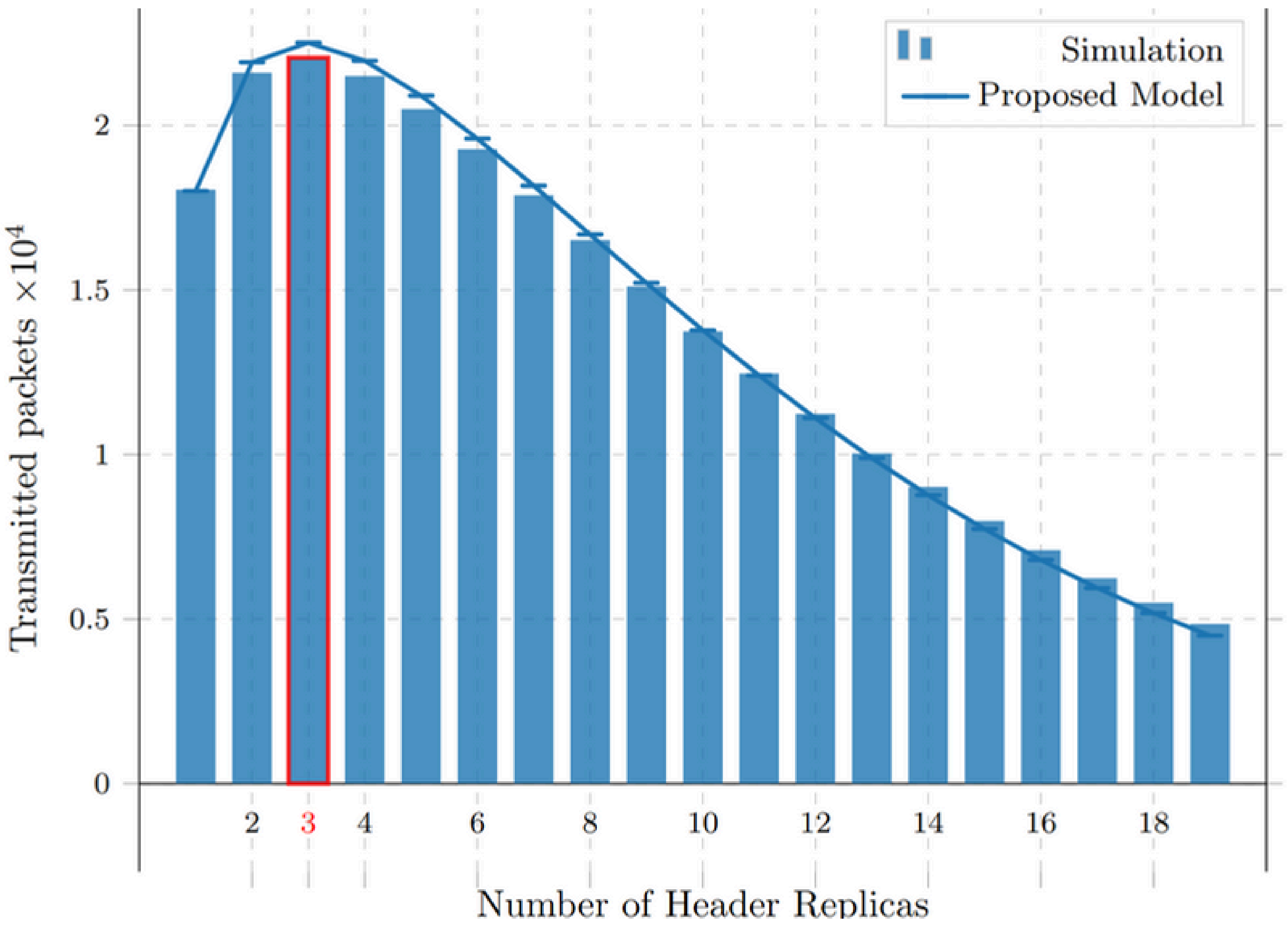


DR9

LR-FHSS: Exploiting the Model's Derivative

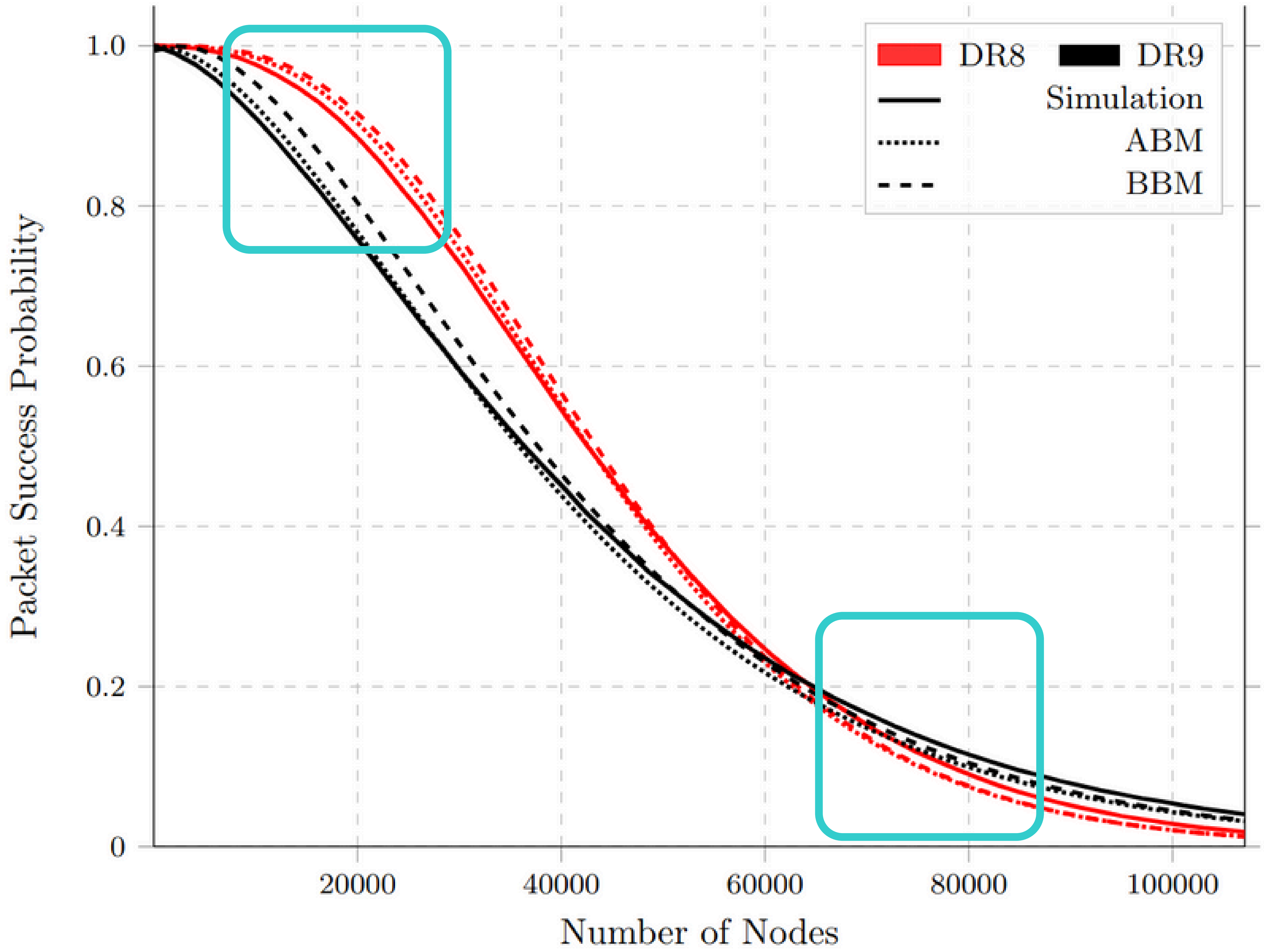
λ = 0.002 pkt/s
DR 8





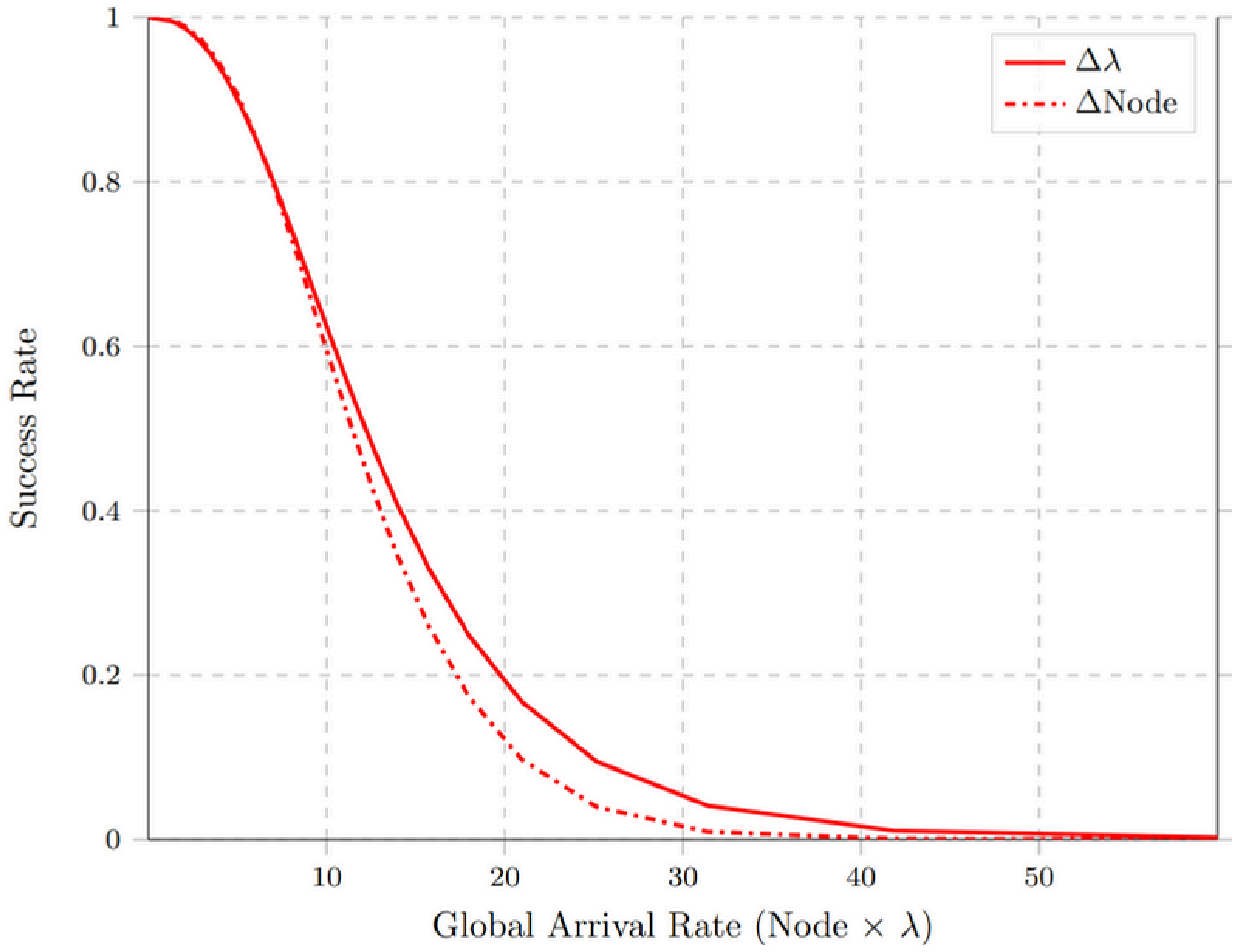
LR-FHSS: Model's limitations

λ = 0.002 pkt/s

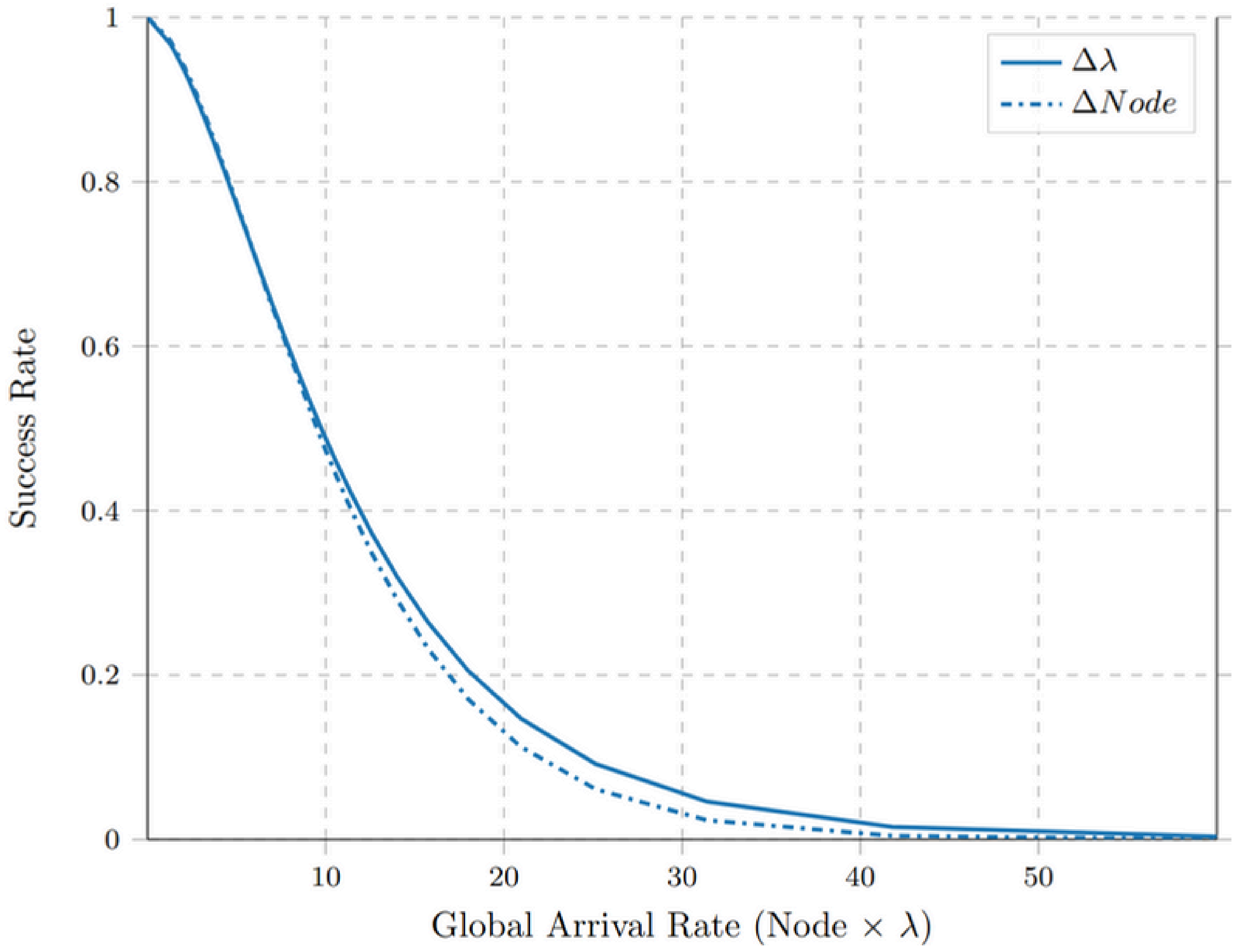


LR-FHSS: Model's limitations

Fixed λ = 0.05 pkt/s
Fixed Node = 125



DR8



DR9

Towards an even finer model...

ALOHA-based fragment collision probabilities enhance the robustness and the reliability of the model

Refine modeling assumptions to overcome limitations of the existing hypothesis

Incorporate physical effects (e.g., fading, capture, noise) for more realistic performance predictions

Thanks !

Any questions ?