

RESEARCH PRESENTATION

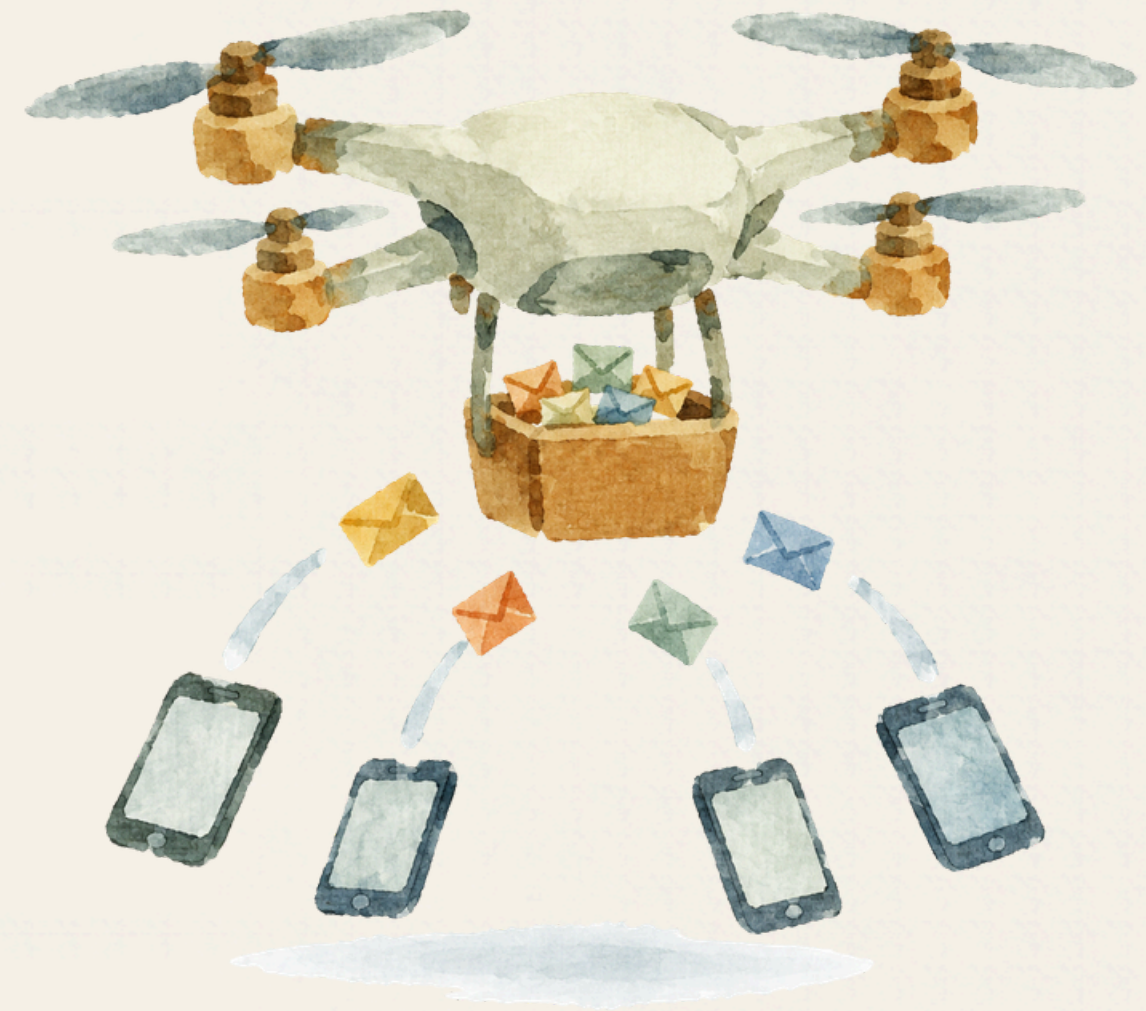
Tandem Queueing Analysis and Airtime Validation for UAV-Assisted Heterogeneous Wi-Fi-LoRa Disaster Networks

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Project overview

Earthquakes, floods and hurricanes can disable ground telecommunications and disconnect affected populations from rescue teams.

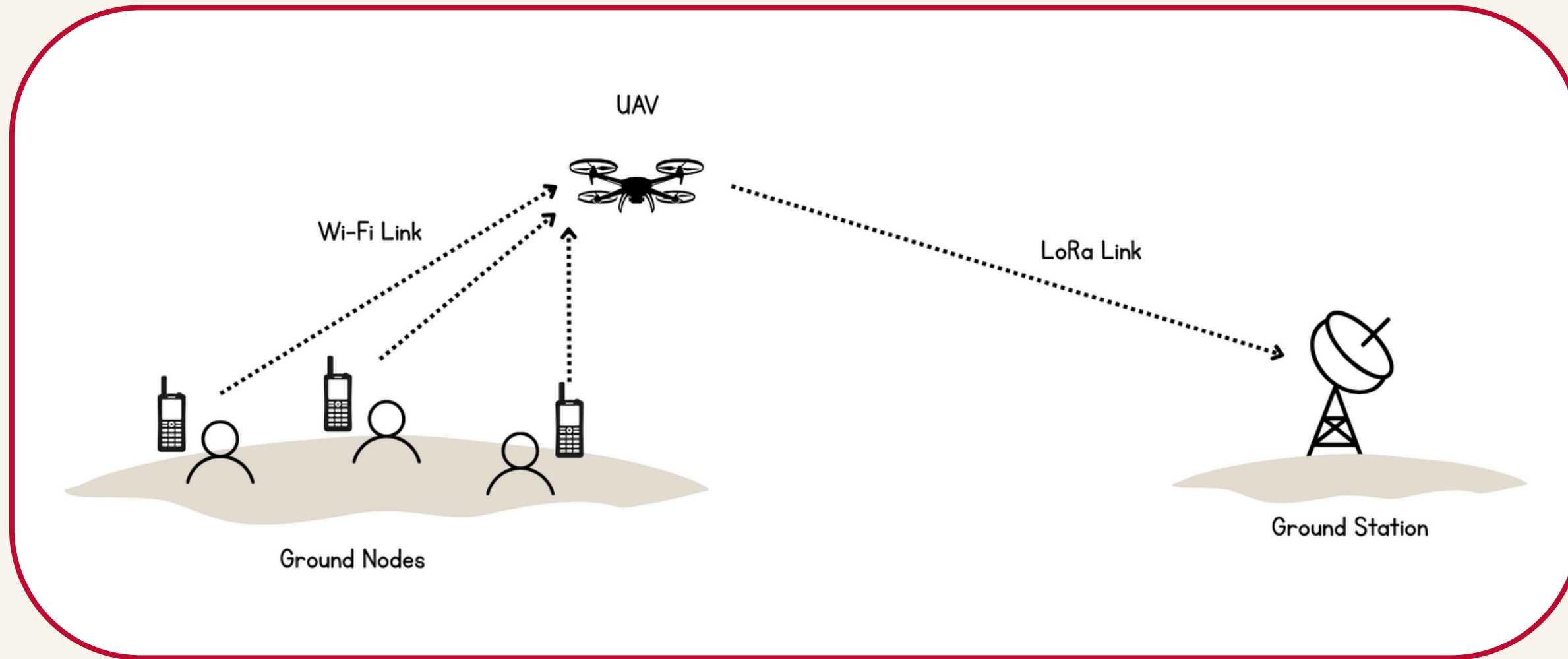
UAVs offer rapid deployment, flexible positioning and elevated line-of-sight links.

This study combines Wi-Fi access with LoRa backhaul and models the two-hop path using airtime-derived tandem queues.

Goal: Understand packet loss, queue delay and operating limits for emergency reporting



System Architecture



Local Wi-Fi access

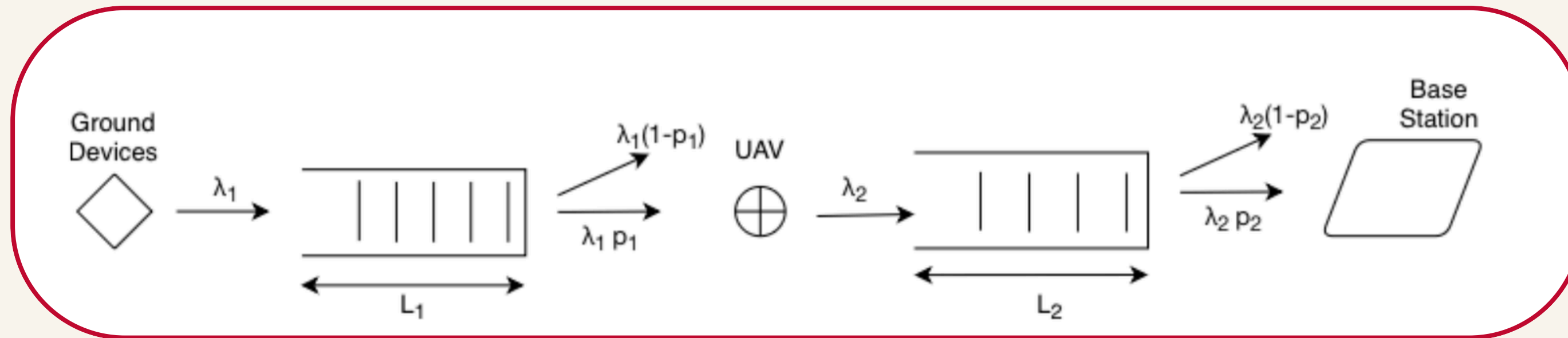
- Wi-Fi standard: IEEE 802.11n
- Frequency: 2.4 GHz
- Channel bandwidth: 20 MHz
- Modulation and coding scheme: MCS0
- Nominal PHY rate: 6.5 Mb/s
- Payload: 11 bytes, encapsulated with UDP, IPv4, and IEEE 802.11 MAC headers

Long-range LoRa forwarding

- Backhaul technology: LoRa
- Frequency: 868 MHz
- Bandwidth (BW): 125 kHz
- Coding rate (CR): 4/5
- Time-on-air (ToA): Determined by the spreading factor (SF)

Capacity mismatch: rapid Wi-Fi ingestion can overwhelm LoRa, building queues and delay.

Queueing Model: M/D/1



M: Poisson arrivals

N independent sources generate reports at mean rate r , giving aggregate input $\lambda_1 = Nr$.

D: deterministic service

Fixed frame size and radio settings give a fixed transmission time for each modeled stage.

1: One server per stage

Each FIFO queue forwards packets sequentially through its modeled transmitter.

Queueing Model: M/D/1

Symbols	Details
λ_1	Arrival rate Wi-Fi queue
λ_2	Arrival rate LoRa queue
L_1, L_2	Wi-Fi and LoRa buffer capacities
T_W, T_L	Fixed Wi-Fi and LoRa packet service times
$\mu_1 = 1/T_W$	Wi-Fi service rate
$\mu_2 = 1/T_L$	LoRa service rate
$1 - p_1$	Probability that an arriving packet is discarded because the Wi-Fi buffer is full
$1 - p_2$	Probability that an arriving packet is discarded because the LoRa buffer is full
d_1	Wi-Fi departure rate
d_2	LoRa departure rate: packets completing transmission to the base station

Packet design: What fits into 11 bytes?

Field	Bytes	Purpose
Packet type	1	Identify report format
Device identifier	2	Identify the reporting node
Encoded latitude	3	Locate the affected person
Encoded longitude	3	Complete the position
Emergency status	1	Signal urgency or condition
Battery level	1	Indicate remaining device energy
Total application payload	11	Compact emergency telemetry

Why keep it compact?

Only essential reporting fields are sent.

A smaller fixed payload reduces transmission overhead and makes airtime predictable.

After encapsulation: 81-byte Wi-Fi frame and 28-byte LoRa physical payload.



Experimental setup: 3 complementary parts

1. Analytical model

Calculate airtime and service rates from radio settings.

Use finite buffer M/D/I/K blocking as a reference for packet delivery.

2. Python simulation

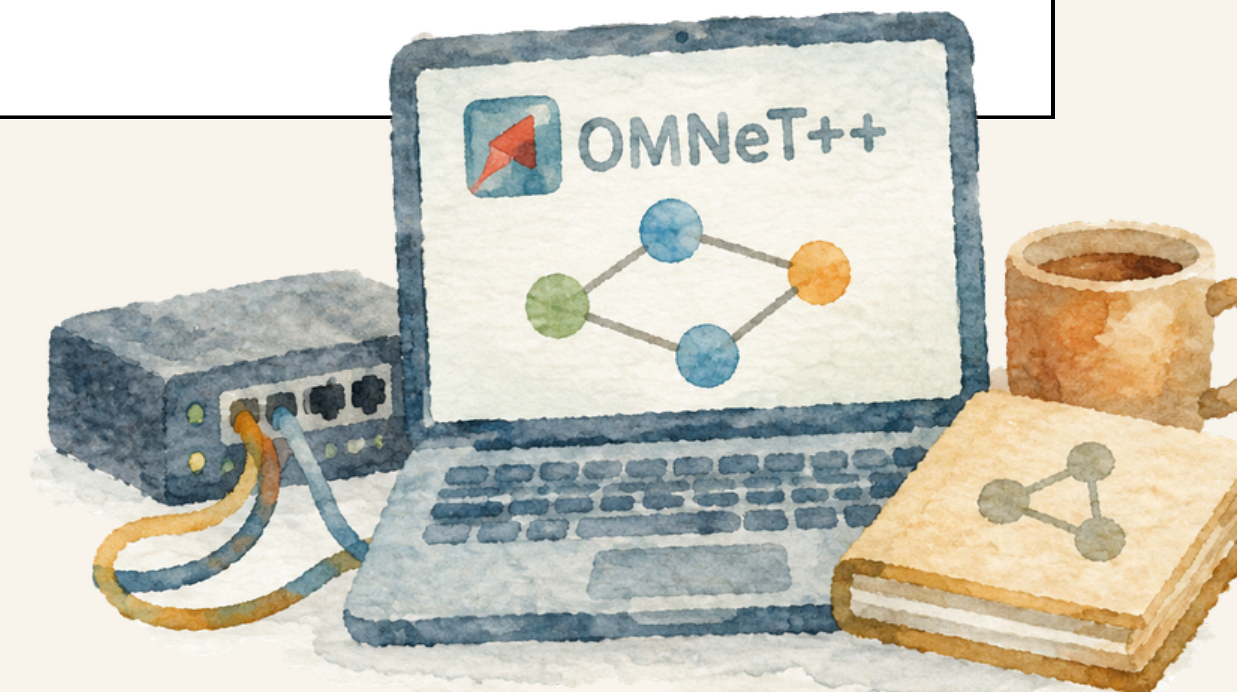
Feed the calculated service times into two FIFO queues.

Vary arrival rate, spreading factor and buffer capacity.

3. OMNeT++

Model real protocol modules and packet forwarding.

Check airtimes, two-hop traversal and multinode Wi-Fi collection.



Analytical Model: From Airtime to Service Rate

Link	Service Time (ms)	Service Rate (packets/s)
WiFi	0.142	7,042
SF7	66.816	14.97
SF8	123.392	8.10
SF9	226.304	4.42



Long-range LoRa forwarding

$$T_{\text{sym}} = \frac{2^{SF}}{BW},$$

$$T_{\text{pre}} = (N_{\text{pre}} + 4.25) T_{\text{sym}}.$$

$$\Gamma = \frac{8PL - 4SF + 28 + 16C - 20H}{4(SF - 2D)},$$

$$N_{\text{pay}} = 8 + \max \{0, \lceil \Gamma \rceil (CR + 4)\},$$

Encapsulated frame size (PL): 28 bytes

Preamble length (Npre): 8 symbols

Bandwidth (BW): 125 kHz

Spreading factor (SF): 7

Symbol duration: 1.024 ms

Payload symbols (Npay): 53

Total airtime (TL): 66.816 ms

LoRa takes much longer to transmit each report, limiting the relay's forwarding capacity.

Analytical Model: Delay and Packet Loss

Under stable conditions ($\rho_i < 1$), the mean queue waiting time for an infinite-capacity M/D/1 queue is given by the Pollaczek–Khinchine formula:

$$W_{q,i} = \frac{\lambda_i T_i^2}{2(1 - \rho_i)}.$$

Hence, end-to-end transfer latency for successfully forwarded reports is approximated by:

$$D_{\text{E2E}} \approx W_1 + W_2 + T_{\text{proc}},$$

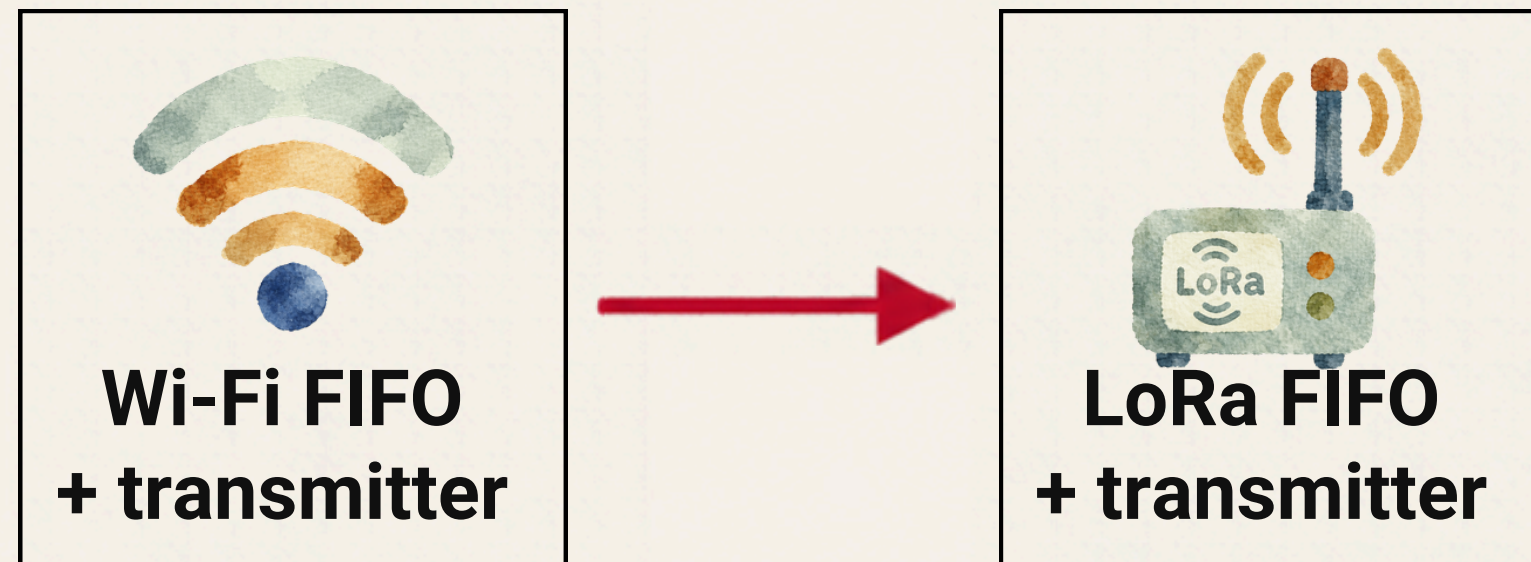
where T accounts for onboard MCU processing and interface switching.

Larger buffers can reduce drops, but they cannot increase transmission capacity and may increase delay.

Python Simulation

How the network was modelled?

Track individual reports as they arrive, wait and transmit through two queues.



Successful departures feed the next stage.

Random arrivals

Poisson traffic represents independent reporting.

$\lambda_i = N r_i$, with mean arrival gap $1/\lambda_i$.

Fixed transmission times

Analytical airtimes become service times:

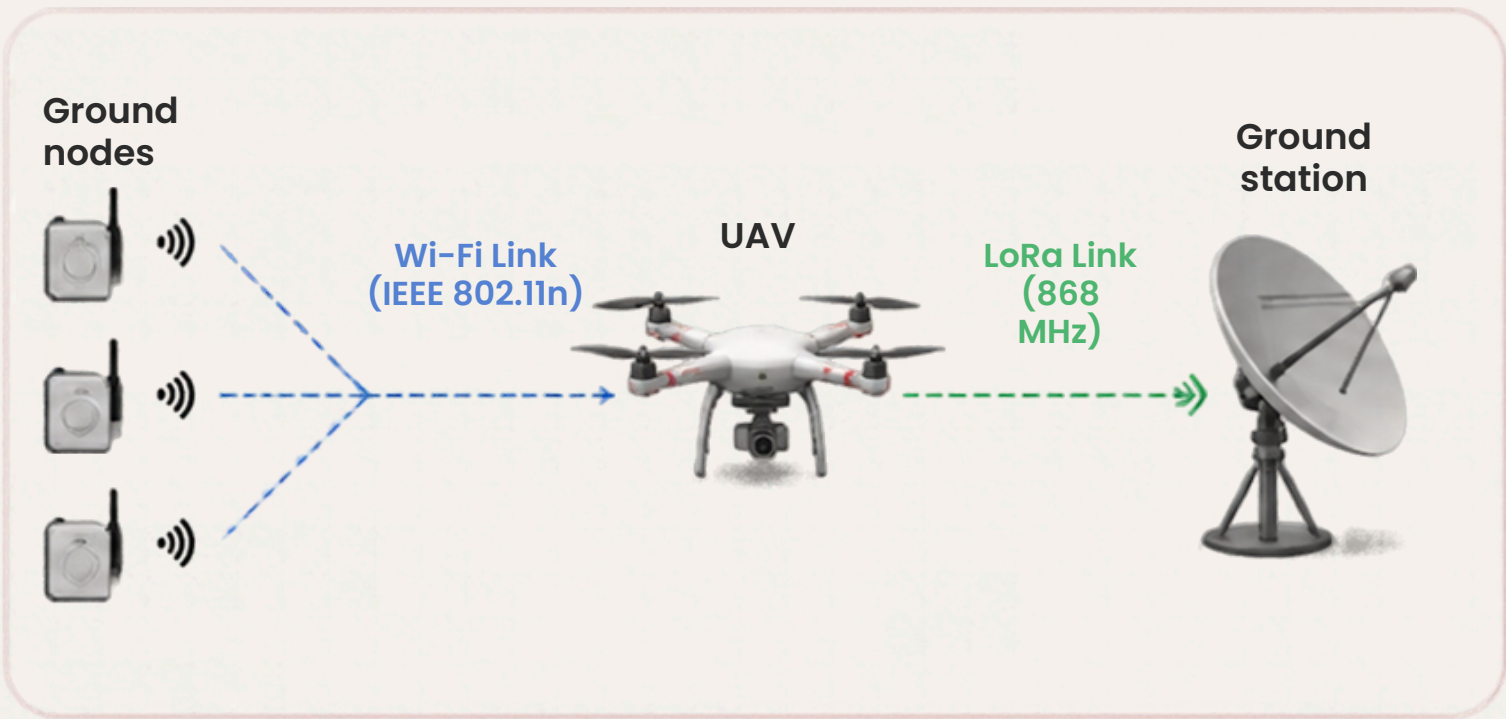
Wi-Fi 0.142 ms and LoRa SF7 66.816 ms.

FIFO and finite buffers

Serve packets in arrival order.

If the buffer is full, record a drop.

Packet-level network model



Two experimental scenarios

Scenario	Setup and purpose
Single node	UAV at 50 m. Trace a report across both hops to verify airtime and packet delivery.
20 ground nodes	Random positions in 60 × 60 m. One report each during 6–8 s. 100 s run to test Wi-Fi collection.

Simulation environment

OMNET++ 6 with INET 4.4 for Wi-Fi/IP and FLoRa 1.1.0 for LoRa communication.

Ground-to-UAV access

UdpBasicApp generates 11-byte reports. IEEE 802.11n sends them to the UAV's UdpSink.

UAV-to ground forwarding

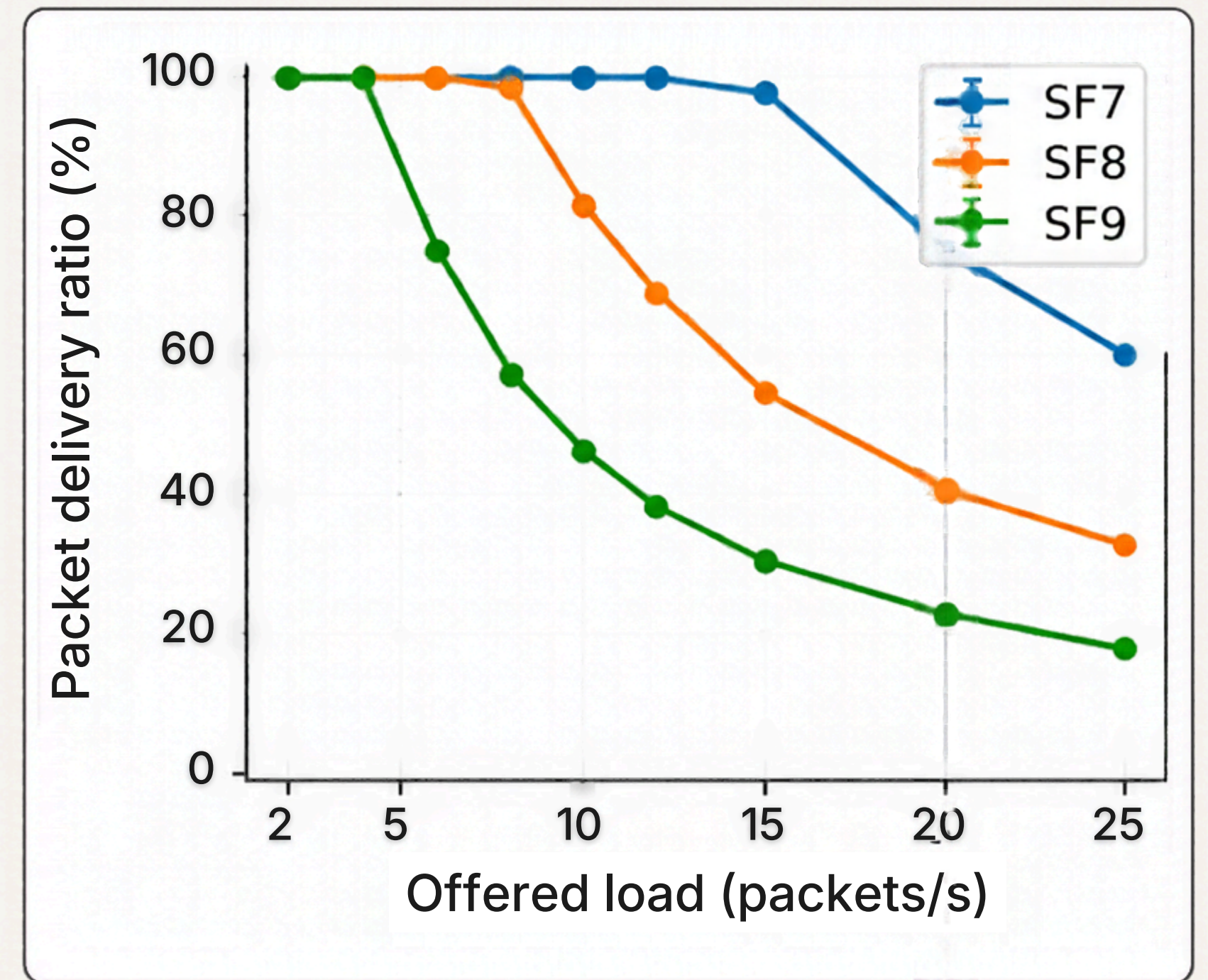
An event-driven bridge triggers SimpleLoRaApp to forward reports over LoRa at 868 MHz.

Results

Packet delivery ratio

At 20 reports per second

SF	Delivered
SF7	75.24%
SF8	40.74%
SF9	22.21%



Higher SF increases airtime. The relay forwards fewer reports as its queue becomes full.

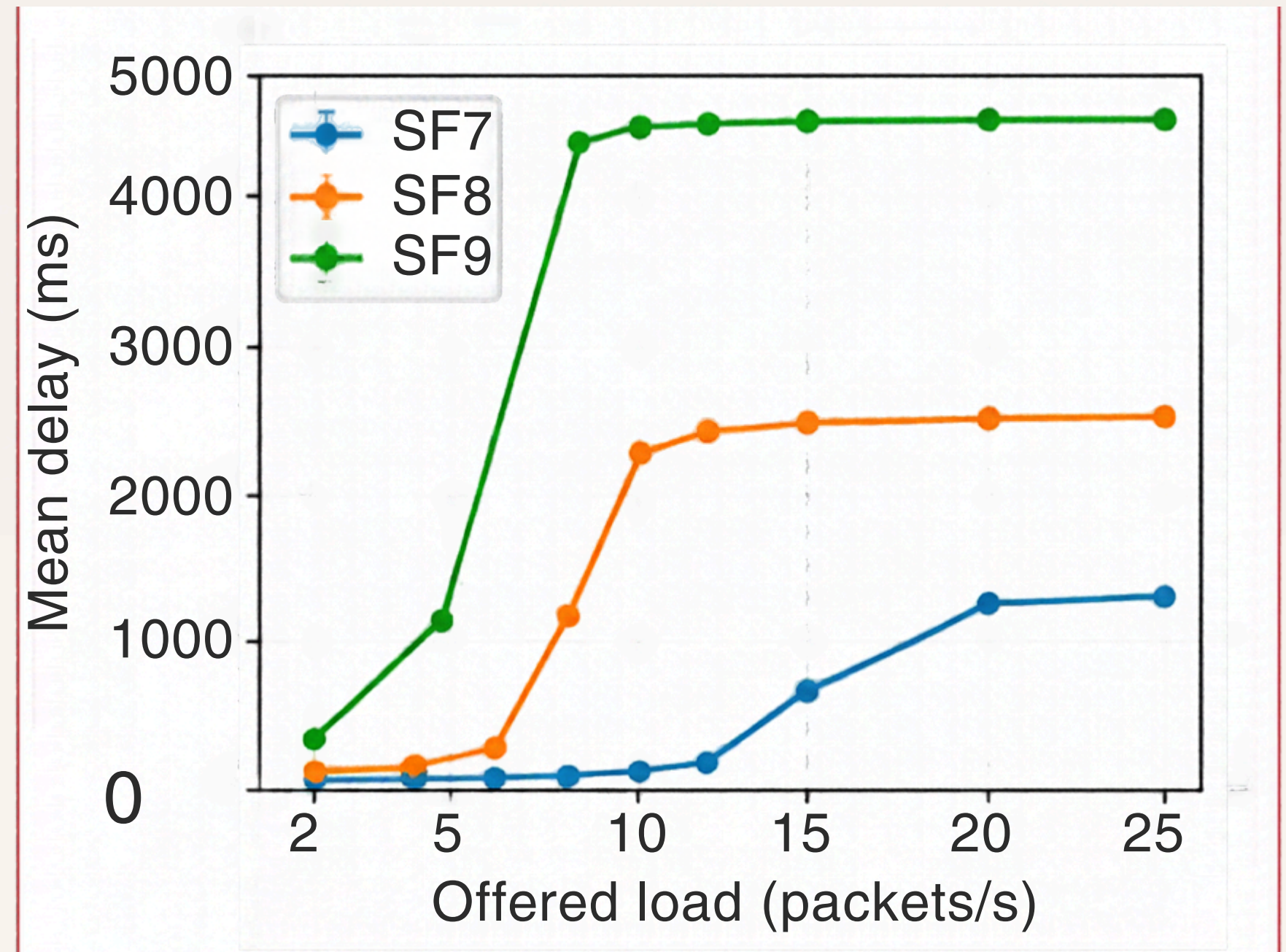
Results

End-to-end delay

At 20 reports per second



SF	Delay
SF7	1.293 s
SF8	2.535 s
SF9	4.702 s



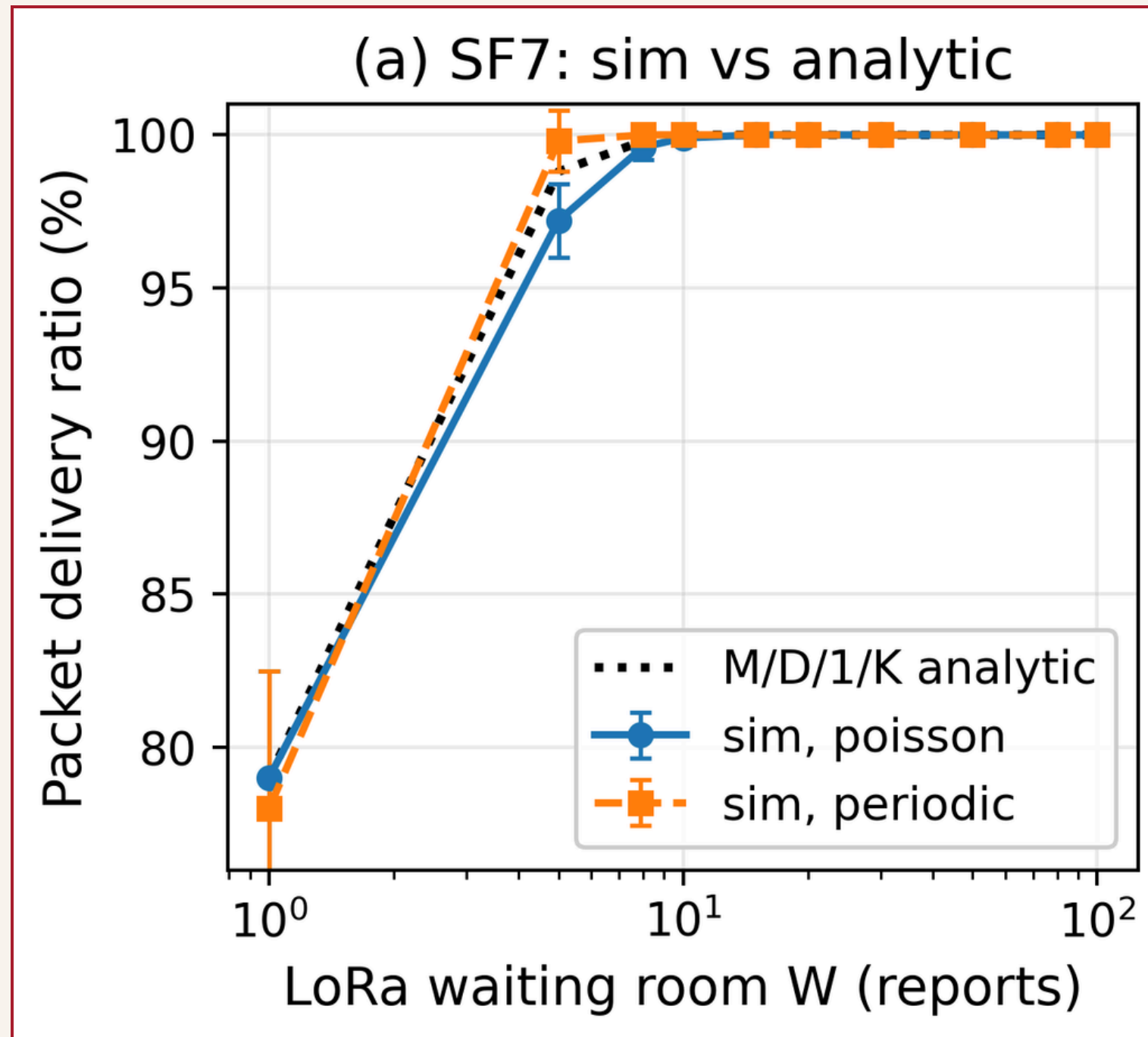
Longer transmissions keep the server busy. Reports spend more time waiting in the queue.

Airtime validation

Analytical prediction	OMNET++ measurement
66.816 ms	66.823 ms
Calculated from the LoRa airtime equations.	Recorded in the single-node transmission trace.

Measured LoRa airtime is about 506× Wi-Fi airtime (0.132 ms).

Analytical and Simulated PDR agree



For SF7, the analytical curves and simulation results closely agree.

This supports the queue model's prediction of blocking and packet delivery.

Larger buffers help most near the service-capacity boundary.

References

- [1] E. Casmin and E. Ever, “An analytical approach for modelling unmanned aerial vehicles and base station interaction for disaster recovery scenarios,” *Wireless Networks*, vol. 30, pp. 3299–3319, 2024.
- [2] J.-H. Huh, D. Tanjung, D.-H. Kim, S. Byeon, and J.-D. Kim, “Improvement of multichannel LoRa networks based on distributed joint queuing,” *IEEE Internet of Things Journal*, vol. 9, no. 6, pp. 4343–4355, 2022.
- [3] K. G. Panda, S. Das, D. Sen, and W. Arif, “Design and deployment of uav-assed post-disaster emergency network,” *IEEE Access*, vol. 7, 2019.
- [4] H. Ullah, M. Abu-Tair, S. McClean, P. Nixon, G. Parr, and C. Luo, “Connecting disjoint nodes through a uav-based wireless network for bridging communication using ieee 802.11 protocols.” *EURASIP Journal on Wireless Communications and Networking*, vol. 2020, p. 142, 2020.
- [5] Y. Yao, D. Dong, C. Cai, S. Huang, X. Yuan, and X. Gong, “Multi-UAV-assisted internet of remote things communication within satellite-aerial-terrestrial integrated network,” *EURASIP Journal on Advances in Signal Processing*, vol. 2024, p. 10, 2024.
- [6] U. B. Cakmakci, “Design and optimization of IoT data processing via non-terrestrial networks: Development and performance evaluation of an emergency gateway node for two-hop communication,” Master's thesis, University of Padova, 2025.
- [7] Semtech Corporation, SX1276/77/78/79 Wireless and Sensing *Products Datasheet*, rev. 7 ed., 2020. [Online]. Available: <https://cdnsparkfun.com/assets/7/7/3/2/SX1276 Datasheet.pdf>
- [8] F. Adelantado, X. Vilajosana, P. Tuset-Peiro, B. Martinez, J. Meliá-Segui, and T. Watteyne, “Understanding the limits of LoRaWAN,” *IEEE Communications Magazine*, vol. 55, no. 9, pp. 34–40, 2017.
- [9] R. B. Sørensen, J. J. Nielsen, and P. Popovski, “Queuing with deterministic service times and no waiting lines in machine type communications,” *arXiv preprint arXiv:2009.03973*, 2020, [Online]. Available: <https://arxiv.org/abs/2009.03973>
- [10] E. Ever, P. Shah, L. Mostarda, F. Omondi, and O. Gemikonakli, “On the performance, availability and energy consumption modelling of clustered IoT systems,” *Computing*, vol. 101, pp. 1935–1970, 2019.