Addressing Decentralized LoRaWAN-Based Wildfire Monitoring in Forested Environments

Maurizio Giacobbe[1], Giuseppe Tricomi[2], Antonio Puliafito[2], Marco Scarpa[2]

[1]MIFT Dept. University of Messina (Italy)
[2]Eng. Dept. University of Messina (Italy)

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Focus

This work presents:

- the design and evaluation of a LoRaWAN-based IoT architecture for wildfire monitoring in rural and forested environments
- a solution to support fire prevention
- a study modeling and analyzing the communication dynamics of large-scale LoRaWAN deployments using Generalized Stochastic Petri Nets (GSPNs)

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Monitoring and prevention of wildfires in rural and forested areas

Critical challenges:

- early detection of forest fires
- establishing efficient and resilient communication pathways, particularly when operating in vast areas with real-world constraints
- limited line-of-sight, dense vegetation, and frequent obstacles can inhibit both wired and high-frequency wireless communication

Figure 1: Wildfire spreads rapidly, causing great damage.

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LoRaWAN

In such a scenario, the exploitation of long-range and low-power wide-area network (LPWAN) technologies, particularly LoRaWAN, has emerged as a particularly suitable solution for remote environmental monitoring. Distributed sensor nodes are deployed throughout the forest to detect early indicators of fire, such as sudden changes in temperature, humidity, or smoke levels.

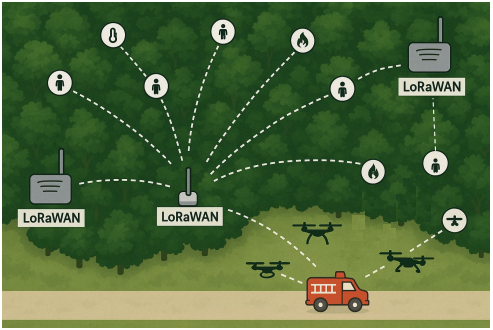

Figure 2: LoRaWAN as suitable solution to early detect wildfire.

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Solution Architectural Design

The solution aims to decentralize the processing of data collected from sensors distributed throughout the forest area.

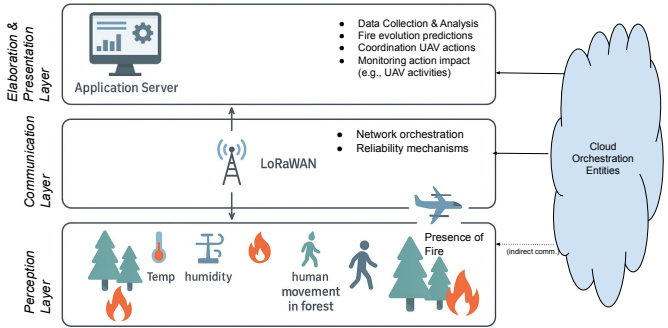

Figure 3: Three-layers Architecture.

Data Flow and Functional Roles in the ChirpStack LoRaWAN Stack

The solution is based on ChirpStack, an open source LoRaWAN network server stack that provides modular components to handle uplink/downlink traffic, device session management, and integration with external services.

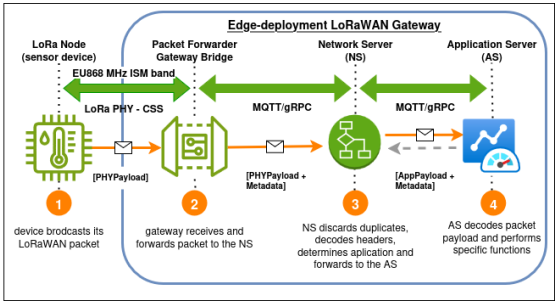

Figure 4: ChirpStack-based data-flow.

Representative ChirpStack compatible sensor/tracker chips

Vendor / Model	Modulation	Freq. Range (MHz)	Key Features
Semtech SX127x	FSK, LoRa, OOK	137–1020	Rx Current (mA): 11; Sensitivity @SF12/125 kHz (dBm): –137; Tx Power (dBm): +20; LoRa BW (kHz): 7.8/125–500
Semtech SX126x	FSK, LoRa, LR-FHSS	150–960; 410–810 (SX1268)	Rx Current (mA): 4.6; Sensitivity @SF12/125 kHz (dBm): –137; Tx Power (dBm): +22; LoRa BW (kHz): 7.8–500
Semtech LR2021	FSK, LoRa, LR-FHSS, FLRC, O-QPSK, OOK	150–960; 1600–2500	Rx Current (mA): 5.5; Sensitivity @SF12/125 kHz (dBm): –142; Tx Power (dBm): +22; LoRa BW (kHz): 7.8–500; 203–812
Semtech LR1121	FSK, LoRa, LR-FHSS	150–960; 1525–1660 (L-band); 1900–2100 (S-band); 2400–2500	Rx Current (mA): 5.4; Sensitivity @SF12/125 kHz (dBm): –141; Tx Power (dBm): +22 (sub-GHz) / +11.5 (2.4GHz); LoRa BW (kHz): 62.5–500; 125–500; 203–812

This information is useful as a future perspective to deploy the proposed architecture in a real scenario.

Representative ChirpStack compatible gateway chips

Vendor / Model	**Freq. Range (MHz)**	**Key Features**
Semtech SX1302, SX1303 *(SX1301 and SX1308 are not recommended for new designs)*	150–960	Operational Current (mA): 100; Sensitivity (dBm): −141; Data Rates: 800–300 Kbps; Temp Range (°C): −40 to +85

This information is useful as a future perspective to deploy the proposed architecture in a real scenario.

Transmission Rate Constraints in LoRaWAN: Duty Cycle Limitations in the EU868 Band

In the **EU868 MHz ISM band**, LoRaWAN devices are subject to strict regulatory constraints defined by *ETSI EN 300 220*. These rules limit transmission power, duty cycle, and channel usage to ensure coexistence across multiple IoT networks.

Parameter	**Limit / Specification**
Frequency Band	863–870 MHz
Max Transmit Power	14 dBm (25 mW); up to 27 dBm in limited sub-bands
Duty Cycle	1% typical; 0.1% or 10% depending on sub-band
Sub-band Allocation	868.0–868.6 MHz (1%); 868.7–869.2 MHz (0.1%); 869.4–869.65 MHz (10%)
Number of Channels	Minimum 3; Maximum 16 (depending on gateway and regional plan)
Default RX2 Channel	869.525 MHz, SF12, 125 kHz, 14 dBm
Typical Bandwidths	125 kHz / 250 kHz / 500 kHz

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Structure of Transmitted Payload

The payload packet consists of exactly fifteen octets, transmitted in network byte order. The structure of the packet is divided into functional blocks, each with a clearly defined size and encoding.

Optimized on-edge LoRaWAN flow

Uplink frames received by the LoRa gateway are forwarded to the Network Server (NS), which performs (i) parsing and Message Integrity Code (MIC) verification, (ii) decryption of the `PHYPayload`, and (iii) lightweight MAC handling (e.g., deduplication, ADR cache lookup). Crucially, the pipeline remains nonblocking by introducing a `in-memory queue` *after* NS fast-path and *before* the Application Server (AS).

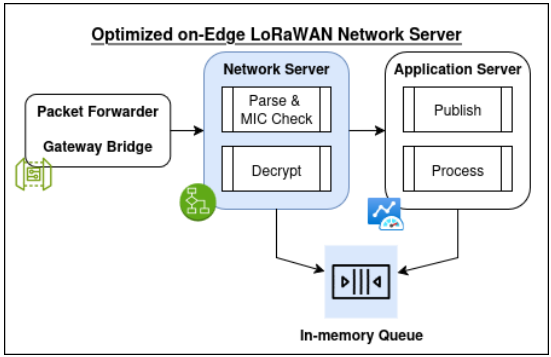
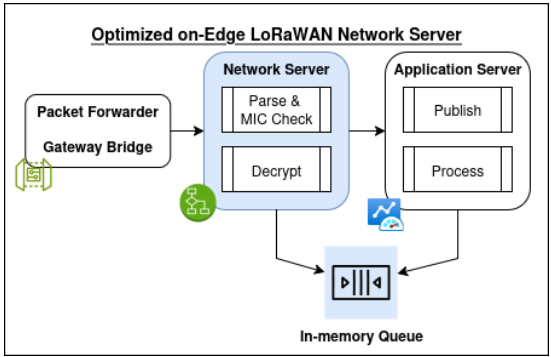


Figure 5: Introducing a in-memory queue in LoRaWAN flow.

Optimized on-edge LoRaWAN flow: Advantages

- The NS does not slow down if the AS or the publish bus experiences small delays.
- Reduces the probability of packet loss when several arrive almost simultaneously from multiple nodes.
- Helps respect the end-to-end processing time, since the pipeline remains fully non-blocking.



GSPN Modeling

Generalized Stochastic Petri Nets (GSPN) provide a modeling methodology to represent and analyze complex systems characterized by stochastic behaviors and uncertainties (i.e., probabilities). The use of GSPNs is particularly advantageous for capturing performance metrics, reliability, and operational dynamics in distributed architectures such as IoT-based edge-cloud systems.

Key benefits:

- **Uncertainty-Aware Modeling.**
- **Hierarchical Structure Matching System Architecture.**
- **Efficient Probabilistic Inference.**
- **Handling Incomplete or Noisy Data.**
- **Compact and Interpretable Model Representation.**

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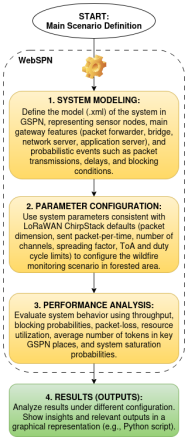
Workflow for GSPN-based modeling



The proposed workflow integrates three main steps: `system modeling`, `parameter configuration`, and `performance analysis` into a unified framework based on WebSPN. The graphical representation of the results (step 4) is currently not implemented in the tool. A dedicated Python script has been created for this step.

GSPN Model implemented for measurements and analysis

Places:

- P_0, P_SF10, P_GW, P_NS.

Transitions:

- T_0 : *transmission attempt* of packets from the Nodes. *Exponential* type with firing rate equals 0,016666667.
- T_OA : Models the *ToA*, *Preemptive repeat different (prd)* type.
- T_1, T_2, T_3 : packet forwarding and bufferization.
- T_comp : *processing of packets* at the NS before forwarding them to the AS. *exponential* type with firing rate equals 10.

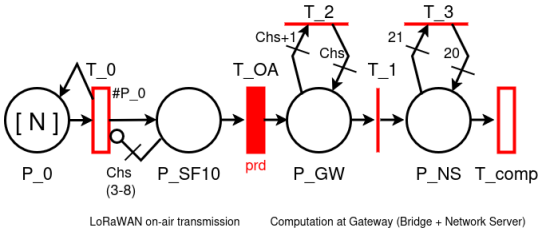


Figure 6: GSPN Model implemented for measurements and analysis. An *inhibitor arc* from P_SF10 to T_0 models the limitation on the number of simultaneously available channels.

LoRaWAN Configuration Parameters

Parameter	Value
Spreading Factor (SF)	10
Bandwidth (BW)	125 kHz
Coding Rate (CR)	4/5
Payload Size	28 bytes (13 overhead + 15 data)
Explicit Header	Yes
Cyclic Redundancy Check (CRC)	Enabled
Preamble Length	8 symbols
Number of Nodes	10, 30, 60, 120, 240
Time on Air (ToA)	412 ms
Packet Transmission Interval	Every 60 s
Network Server Buffer Size	20 packets
Network Server Processing Time	100 ms

Performance Measures with GSPN *(3 Channels and 8 Channels)*

- **Throughput (T_{comp})**: Average number of times per second the transition is fired in the long run, computed as

$$pr\_enabled[T_{comp}] \times firing\_rate[T_{comp}]$$

- **Average number of tokens in each place** ($av\_token[P_x]$), and total sum of $av\_token[P_x]$ over all Places.
- **Avg. Steady-State Delay (s)**
  Average steady-state delay (in seconds) experienced by a packet to reach the application, calculated as:

$$\frac{\sum av\_token[P_x]}{Throughput\ (T_{comp})}$$

- **Packets per hour processed at NS**, computed as

$$Throughput\ (T_{comp}) \times 3600 \text{ seconds}$$

Results

The results demonstrate that, when using SF10 (providing an effective coverage range of 1-3 km) and configuring the network with eight transmission channels instead of the default three, the packet loss remains very low for up to approximately 120 nodes, assuming a fixed packet transmission interval of 60 s. This behavior is reflected by the increasing separation between the curves shown in Fig. 7.

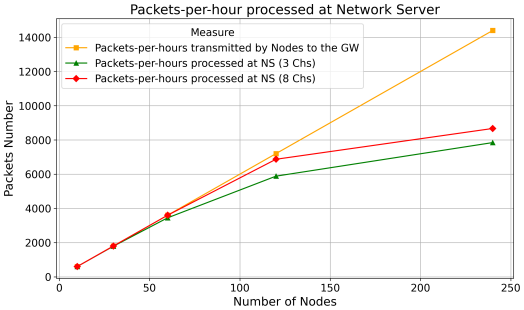


Figure 7: Number of Packets-per-hour processed at Network Server. Packet dim. 28 byte, SF10, Tx-time=60 s, ToA=412 ms. Two configurations: 3 and 8 Channels.

Results

As illustrated in Fig. 8, the average steady-state time for a packet to reach the Application Server increases when using eight channels. This effect occurs because the Network Server must handle a significantly higher number of incoming packets, which, despite introducing a higher latency, leads to substantially lower packet losses compared to the three-channel configuration.

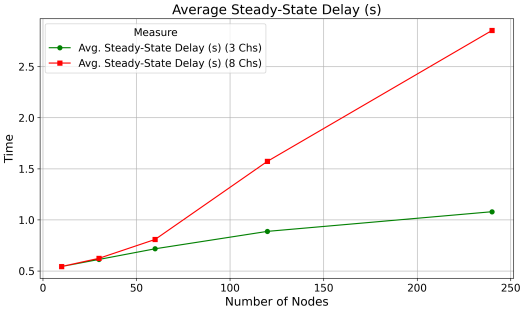


Figure 8: Average steady-state time (s) that a packet takes to reach the application. Packet dim. 28 byte, SF10, Tx-time=60 s, ToA=412 ms. Two configurations: 3 and 8 Channels.

Results

Fig. 9 shows a comparison between the probabilities of successful and lost packets at Network Server. Results are highlighted for the two examined scenarios (3-channels, 8-channels setup).

Successful packets approximates 100% for a number of nodes ≤ 60.

This percentage is greater than 90% for a number of nodes ≤ 120 (8-channels).

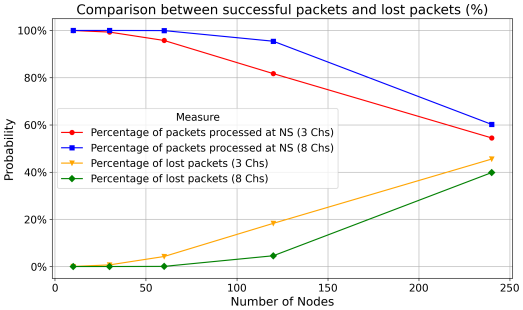


Figure 9: Comparison between successful packets and lost packets (%). Packet dim. 28 byte, SF10, Tx-time=60 s, ToA=412 ms. Two configurations: 3 and 8 Channels.

Results

The following Table reports the resulting percentage of successful and lost packets for the two examined scenarios.

Measures/Nodes	10	30	60	120	240
3 Channels					
Successful	99.96%	99.29%	95.74%	81.70%	54.48%
Lost	0.04%	0.71%	4.26%	18.30%	45.52%
8 Channels					
Successful	99.98%	99.98%	99.92%	95.42%	60.21%
Lost	0.02%	0.02%	0.08%	4.58%	39.79%

Conclusions

Monitoring forest areas for timely prevention of potential wildfires is essential for both environmental safety and population protection.

- This work provides recommendations, supported by preliminary experimental analysis, aimed at implementing an efficient and resilient architecture for this purpose.
- The results obtained, based on probabilistic methods and modeling with Generalized Stochastic Petri Nets (GSPNs), offer a framework for properly scaling an efficient and resilient system, leveraging the capabilities of LoRaWAN technology integrated with the ChirpStack platform.
- Looking ahead, we plan to extend this work by analyzing the behavior of a huge scenario characterized by thousands of nodes.
- This way comparative analysis with other LPWAN solutions will be investigated.
- In addition, we plan to introduce advanced features, such as Adaptive Data Rate, with additional metrics related to energy savings and system reliability.

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Thank You for Your time and attention.

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