Enhancing performance and reliability in LR-FHSS

Journées LPWAN

K. Khawam - Paris Saclay

Macro-Diversity in LR-FHSS: Motivation

- Massive IoT deployments demand:
  - Long-range connectivity
  - Robustness to interference
  - Scalability
- LoRaWAN with CSS faces limitations:
  - Pure ALOHA $\implies$ high collision rate
  - Fixed spreading factors
  - Limited spectral efficiency
- LR-FHSS was introduced to address these issues.

LR-FHSS: Key Features

- Intra-packet frequency hopping
- Header repetition
- Payload fragmentation + erasure coding
- Advantages:
    - Higher robustness to interference
    - Larger payloads allowed in FCC band
    - Better spectral spreading and compliance

LoRa and LR-FHSS Modulation

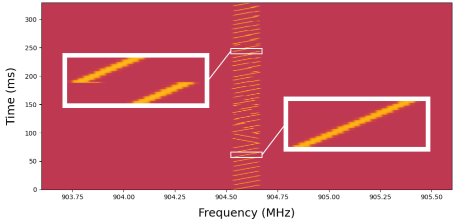


Figure: Waterfall plot of LoRa using DR0 (SF10, 125 kHz bandwidth)

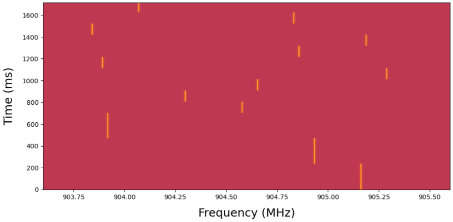


Figure: Waterfall plot of LR-FHSS using DR5 (CR 1/3, 1.523 MHz bandwidth)

- Longer payloads (dwell-time regions)
- Better interference tolerance

- Higher link budget
- Higher network capacity

DR5 and DR6 in LR-FHSS

- Physical Layer Bitrate
  - DR5: 162 bps
  - DR6: 325 bps
- Convolutional Coding Rate
  - DR5: 1/3 (strong redundancy)
  - DR6: 2/3 (higher efficiency, less protection)
- Header Repetitions
  - DR5: 3 header replicas
  - DR6: 2 header replicas
- Reliability vs Efficiency Tradeoff
  - DR5: optimized for robustness and long-range performance.
  - DR6: optimized for capacity and shorter airtime.
- Payload Characteristics
  - DR5: Effective coding threshold $\mu = \mathbf{1/3}$
  - DR6: $\mu = \mathbf{2/3}$ needs more fragments for reconstruction

Problem in Current LR-FHSS Deployments

- Packet reconstructions occur at a single gateway.
- Fragments received by different gateways are discarded.
- Wastes the inherent redundancy of:
  - Frequency hopping
  - Fragmentation
  - Coding
- Limited analytical modeling of LR-FHSS performance.

Contributions

- Propose macro-diversity for LR-FHSS:
  - Gateways cooperate at the fragment level.
- Develop a stochastic geometry model:
  - Interference modeling
  - Header decoding probability
  - Fragment decoding probability
- Derive closed-form formulas for packet success probability.
- Evaluate DR5 and DR6 under macro-diversity vs nearest-gateway.

System Model

- Gateways: PPP $\mathcal{P}_g$ with density λ_g
- Devices: PPP $\mathcal{P}_d$ with density λ_d
- LR-FHSS transmission parameters:
    - R: header replicas
    - L: number of fragments
    - μ: coding threshold (fraction of fragments)
- SINR model with Rayleigh fading and aggregate interference.

SINR Model

The SINR at GW k for message m (header replica or payload fragment) is

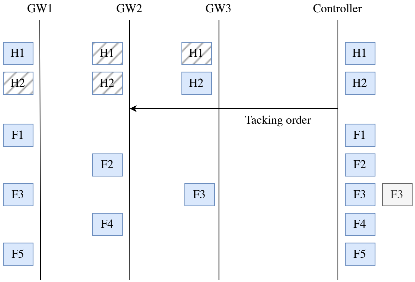
$$\mathrm{SINR}_k(m) = \frac{f \cdot P_t y_k^{-\alpha}}{N_0 + \sum_{j \in \mathcal{I}(m)} P_t h_j z_{j,k}^{-\alpha}}, \tag{1}$$

- where y_k denote the distance between a reference device and GW k,
- f and h_j are independent Rayleigh fading coefficients (exponentially distributed with unit mean),
- α is the path-loss exponent, N_0 is the thermal noise power,
- $\mathcal{I}(m)$ is the set of devices interfering with message m, and $z_{j,k}$ is the distance between interferer j and GW k.

A message is successfully decoded if its SINR exceeds the corresponding threshold (σ_H for header replicas and σ_P for payload fragments).

Proposed Macro-Diversity Architecture

- When a gateway decodes any header:
  1. It forwards the decoded hopping sequence to a controller.
  2. Controller instructs all gateways to track that sequence.
  3. All fragments received anywhere are forwarded.
  4. Controller deduplicates and applies erasure decoding.
- Success if at least μL fragments are collected network-wide.



Analytical Model: Overview

In the proposed macro-diversity architecture, a packet is considered as received successfully if two independent conditions are satisfied:

1. At least one gateway correctly decodes one of the R header replicas,
2. At least μL payload fragments are received correctly across all GWs

These two events are statistically independent, as header decoding enables fragment tracking but does not influence individual fragment receptions once the hopping sequence is known.

- Thus, the overall packet success probability is

$$\mathbb{S} = \mathbb{S}^H \cdot \mathbb{S}^P, \quad (2)$$

where $\mathbb{S}^H$ denotes the probability of successful header decoding, and $\mathbb{S}^P$ denotes the probability of successful payload reconstruction.

Header Decoding Probability

We define the complementary failure probability as

$$\bar{\mathbb{S}}_k^H = \Pr\left(\max_{m\in\{1,\ldots,R\}} \mathrm{SINR}_k(m) \le \sigma_H\right)^1 = \left(\Pr\left(\mathrm{SINR}_k(m) \le \sigma_H\right)\right)^R$$

Assuming independent fading and interference across header replicas, and Rayleigh fading with unit mean, we have

$$\bar{\mathbb{S}}_k^H = \left(\mathbb{E}_{\mathcal{P}_d}\left[1 - \exp\left(-\sigma_H y_k^\alpha I\right)\right]\right)^R = \left(1 - \mathcal{L}_I(\sigma_H y_k^\alpha)\right)^R,$$

where I is the aggregate interference from co-channel devices and $\mathcal{L}_I(\sigma_H y_k^\alpha)$ the Laplace transform of I evaluated at $s = \sigma_H y_k^\alpha$.

[1] $\mathbb{S}_k^H$ is the probability that a given GW k successfully decodes at least one of the R header replicas.

Header Decoding Probability

- The Laplace transform of interference evaluated at $s = \sigma_H y_k^\alpha$ is

$$\mathcal{L}_I(\sigma_H y_k^\alpha) = \exp\left(-K(\alpha)\hat{\lambda}_d \sigma_H^{2/\alpha} y_k^2\right),$$

where $K(\alpha) = \frac{2\pi^2}{\alpha \sin(2\pi/\alpha)}$.

- The effective interferer density:

$$\hat{\lambda}_d = \frac{2\eta_d(Rt^H + Lt^P)}{n_{ocw} n_{obw}} \lambda_d,$$

  - with η_d the average packet generation rate per device, t^H and t^P the durations of a header replica and a payload fragment.
  - Frequency overlap is determined by the number of occupied subchannels n_{obw} across all operating channels n_{ocw}.

Header Decoding Probability

- Header success at GW k:

$$\mathbb{S}_k^H = 1 - \left(1 - e^{-K(\alpha)\hat{\lambda}_d \sigma_H^{2/\alpha} y_k^2}\right)^R$$

- Using the binomial theorem, we deduce

$$\mathbb{S}_k^H = \sum_{r=1}^{R} \binom{R}{r} (-1)^{r+1} \exp\left(-rK(\alpha)\hat{\lambda}_d \sigma_H^{2/\alpha} y_k^2\right).$$

- The total header success probability is[2]

$$\mathbb{S}^H = 1 - \mathbb{E}_{\mathcal{P}_g}\left[\prod_{k\in\mathcal{P}_g} \bar{\mathbb{S}}_k^H\right].$$

[2] Since the device transmission is broadcast, the header is considered successfully received if at least one gateway decodes one header replica.

Header Decoding Probability

Applying the probability generating functional of a PPP, and integrating over all possible distances, we get network-wide success

$$\mathbb{S}^H = 1 - \exp\left(-\int_0^\infty 2\pi\lambda_g \mathbb{S}_k^H(y) y \, dy\right),$$

which simplifies to

$$\mathbb{S}^H = 1 - \exp\left(-K_1(\alpha)K_2(R)\,\sigma_H^{-2/\alpha}\frac{\lambda_g}{\hat{\lambda}_d}\right)$$

where $K_1(\alpha) = \frac{\pi}{K(\alpha)}, \quad K_2(R) = \sum_{r=1}^R \binom{R}{r} \frac{(-1)^r}{r}$

Payload Fragment Success

- Single fragment success:

$$\mathbb{S}_f = 1 - \exp\left(-K_1(\alpha)\sigma_P^{-2/\alpha}\frac{\lambda_g}{\hat{\lambda}_d}\right)$$

- Number of received fragments $X \sim \text{Binomial}(L, \mathbb{S}_f)$
- Payload success probability:

$$\mathbb{S}_P = \Pr(X \geq \lceil \mu L \rceil) = 1 - \sum_{k=0}^{\lceil \mu L \rceil - 1} \binom{L}{k} \left(1 - e^{-\gamma}\right)^k \left(e^{-\gamma}\right)^{L-k}.$$

where $\gamma = K_1(\alpha)\sigma_P^{-2/\alpha}\frac{\lambda_g}{\hat{\lambda}_d}$.

Results: Total Packet Success

Macro-diversity significantly extends the reliable operating region.

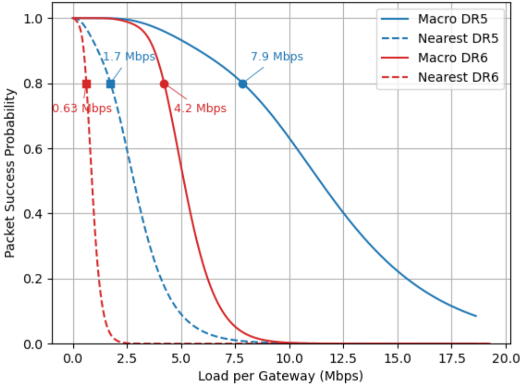


Figure: Total packet success probability as a function of load per gateway.

- DR5:
  - Macro-diversity keeps $S > 80\%$ up to 7.9 Mbps
  - Nearest-gateway saturates at 1.7 Mbps
- DR6:
  - Macro-diversity reliable up to 4.2 Mbps
  - Baseline saturates at 0.63 Mbps

At high success probabilities, header decoding is the limiting factor in DR5, while payload decoding limits performance in DR6.

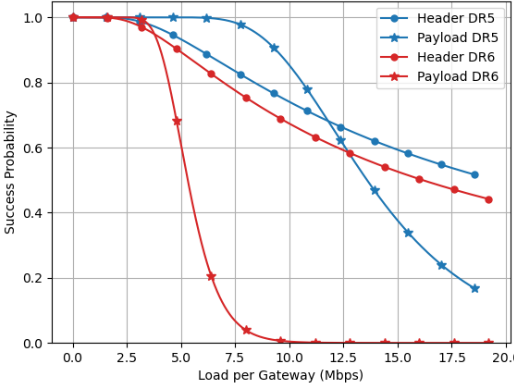


Figure: Header and payload success probabilities under macro-diversity.

Results: Header vs Payload Limitations

- DR5:
  - Header decoding is the bottleneck at moderate load.
  - Payload nearly always recovered once header decoded.
- DR6:
  - Payload becomes limiting earlier

Macro-diversity improves peak goodput by up to 5 times and extends the sustainable load range.

- DR6 peaks higher but saturates earlier;
- DR5 sustains performance at heavier loads.

Goodput: $\mathbb{S}$ $\times$ per-device packet rate $\times$ payload size

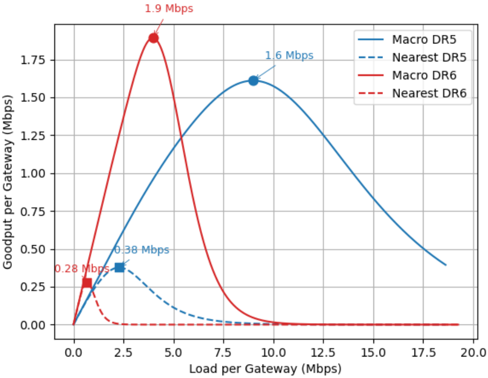


Figure: Goodput per gateway for macro-diversity and nearest-gateway reception.

Results: Goodput per Gateway

- Under macro-diversity:
  - DR6 peaks at 1.9 Mbps
  - DR5 peaks at 1.6 Mbps (more robust)
- Baseline:
  - Stays below 0.4 Mbps

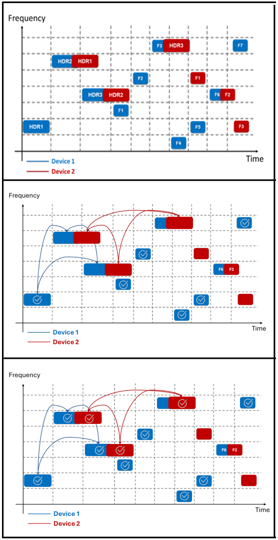
Conclusions

- Proposed fragment-level macro-diversity for LR-FHSS.
- Developed the first stochastic-geometry model for LR-FHSS macro-diversity.
- Closed-form formulas for success probability.
- Macro-diversity yields:
    - Up to $5\times$ improved capacity
    - Higher reliability at high loads

Reliabilty in LR-FHSS: Motivation

- LR-FHSS modulation promises to enhance network resilience in comparison with LoRa modulation
  - Particularly when combined with SIC (Successive Interference Cancellation)
  - We propose an analytical model for the packet success probability in LR-FHSS with SIC
  - Scalability: Extensive simulation results prove that a strategic choice of probabilistic header repetition can significantly improve reliability and hence scalability in dense IoT networks.

Reliabilty in LR-FHSS



Analytical Study of LR-FHSS

We analytically study LR-FHSS transmissions and then extend the model to account for SIC.

The success of an LR-FHSS transmission depends on two conditions:

1. At least one header replica must be received without collision;
2. A sufficient number of payload fragments must be decoded.

Motivation

Header repetitions improve robustness, while SIC can further recover packets that were initially involved in collisions.

Baseline LR-FHSS Model

The average number of packet elements in the vulnerable interval of a header and fragment are (resp.)

$$A_h = \lambda_h 2t_h + \lambda_f(t_h + t_f)$$
$$A_f = \lambda_f 2t_f + \lambda_h(t_h + t_f)$$

where:

- λ_h and λ_f are the arrival rates of headers and fragments;
- t_h and t_f are their transmission times.

Payload fragments are analyzed using the conventional LR-FHSS model. P_1 is the probability of successfully receiving one fragment:

$$P_1 = \left(1 - \frac{1}{C}\right)^{A_f - 1}$$

C: the number of physical channels, R: the number of header replicas.

Payload Decoding and Success Probability

The probability of receiving enough payload fragments is

$$P_\gamma = 1 - \sum_{k=0}^{\gamma-1} \binom{f}{k} P_1^k (1 - P_1)^{f-k}$$

Where:

- f is the total number of transmitted fragments;
- γ is the minimum number of fragments required for decoding;

The overall success probability is then

$$P_s = P_h P_\gamma.$$

The novelty of the model lies in the SIC treatment of repeated headers. For payload fragments, we deliberately retain the original LR-FHSS analysis.

Introducing SIC in LR-FHSS

In conventional LR-FHSS, collisions directly reduce the probability of success.

With SIC, some collided packets may be recovered iteratively:

1. A packet is decoded from a clean header;
2. Its replicas are identified;
3. Its interference contribution is removed;
4. New packets may become decodable.

Modeling choice

We apply the RALI approach to LR-FHSS headers, because headers are repeated and therefore suitable for SIC.

Iterative SIC Analysis for Header Replicas

Let p_i denote the probability that a header replica remains unresolved after the i-th SIC iteration.

A tagged header replica sees a random number of interfering header replicas in its vulnerable interval: $K \sim \mathrm{Poisson}(H)$, where $H = 2\mu N R t_h$ is the offered load seen by one header replica.

During SIC, an interfering packet can be removed if it has been decoded through one of its other $R-1$ header replicas.

At convergence, the residual loss probability of one header replica satisfies:

$$p^\star = 1 - e^{-H} \sum_{k=0}^{S-1} \frac{\left(H\left(1-(p^\star)^{R-1}\right)\right)^k}{k!}$$

$p^\star$: probability that a header cannot be recovered after SIC convergence.

From Replica Recovery to Header Success

Thus, when $S \to \infty$, the fixed-point equation becomes

$$p^\star = 1 - \exp\left(-H(p^\star)^{R-1}\right)$$

A logical header is lost only if all its R replicas remain unresolved. Therefore,

$$P_{\text{loss}} = (p^\star)^R$$

Hence, the probability of successful header reception is

$$P_h = 1 - (p^\star)^R$$

The iterative SIC process is governed by the offered load H.

- When H is low, most packets are recovered;
- when H increases, collisions become harder to resolve.

Analytical Success Delivery Ratio

- Near-perfect delivery is maintained up to approximately 55 000 devices.
- Beyond this operating point, residual collisions cannot be completely resolved by SIC.
- The degradation is progressive rather than abrupt, proving the robustness of LR-FHSS with SIC.

$$N^{\star} \approx 55\,212;\ PDR(N^{\star}) = 1.$$

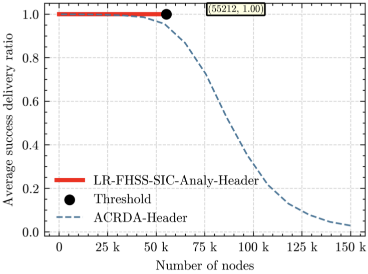


Figure: Analytical PDR predicted by the SIC model as a function of network density for R=3

Irregular Header Repetitions

Using a fixed number of repetitions is not always optimal.

Too many repetitions increase:

- energy consumption;
- channel occupancy;
- collision probability.

ACRDA introduces an irregular repetition strategy.

For repetitions between 1 and 8, the optimized distribution is

$$[0.009,\ 0.472,\ 0.472,\ 0.009,\ 0.009,\ 0.009,\ 0.009,\ 0.009].$$

Main observation

The optimal mass is concentrated on 2 and 3 repetitions.

Simplified Optimal Strategy

Since the optimal distribution mainly selects 2 and 3 repetitions, we restrict the design to

$$R \in \{2, 3\}.$$

The resulting optimal distribution is

$$[0.5,\ 0.5].$$

This means that:

- 50% of packets use two header repetitions;
- 50% of packets use three header repetitions.

Irregular repetition with SIC improves reliability while limiting unnecessary energy consumption and channel load.

Simulation Results

- Network topology: end-devices uniformly distributed, transmitting over 35 physical channels using pseudo-random frequency hopping.
- Traffic model: transmission process follows a Poisson traffic model 1 (inter-arrival time exponential, mean $= 900$).
- Simulation setup: duration of 3600 s, evaluated with and without SIC.

Simulation Results

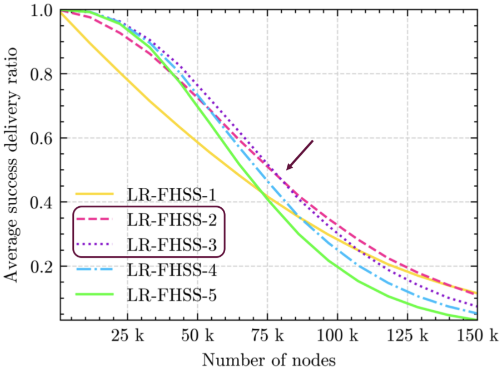


Figure: Impact of the number of header repetitions on the success delivery ratio

Optimal performance is achieved with 2 or 3 header repetitions.

Simulation Results

Simulation and analytical results

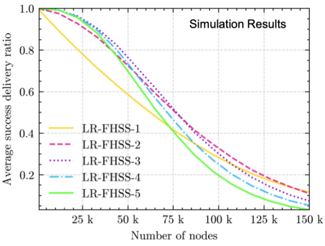


Figure: Impact of the number of header repetitions on the success delivery ratio

The two graphs validate the analytical model, as the corresponding plots follow similar trends.

Simulation Results

LR-FHSS with SIC simulation results:

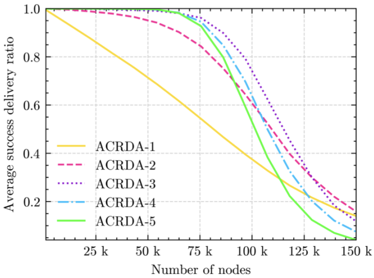


Figure: Impact of the number of header repetitions on the success delivery ratio

- SIC enables near-perfect success probability in moderately dense networks
- 2–3 header repetitions provide the best performance (higher repetitions offer no reliability benefit)

Simulation Results

LR-FHSS with and without SIC simulation results:

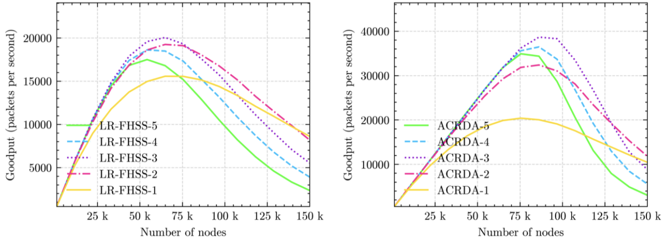


Figure: Impact of the number of header repetitions on the goodput

- SIC significantly increases goodput compared to standard LR-FHSS without interference cancellation
- Best goodput is achieved with 2–3 header repetitions, with 3 repetitions offering the best reliability goodput trade-off

Simulation Results

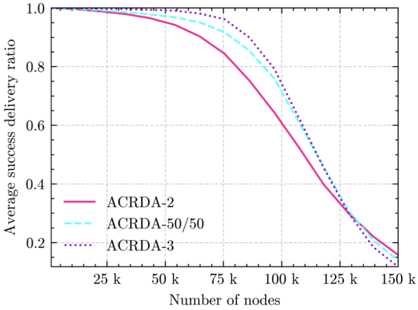


Figure: Optimal probability distribution: Average success delivery ratio

- Probabilistic header repetition (2–3) improves reliability while limiting congestion
- Balanced distribution achieves near-optimal success probability with fewer transmissions

Conclusion

- Analytical and simulation results demonstrate the benefits of SIC for LR-FHSS in dense IoT networks.
- Probabilistic header repetitions balance reliability and congestion.
- Future work will focus on energy efficiency.

Questions

- Samer Lahoud, Kinda Khawam, Fragment-Level Macro-Diversity Reception in LoRaWAN Networks with LR-FHSS. GLOBECOM 2025
- Juliana El Rayess, Kinda Khawam, Samer Lahoud, Melhem El Helou, Modeling and Optimizing Reliability in LR-FHSS Networks with Successive Interference Cancellation. CCNC 2026