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**Towards Improving the Scalability of LR-FHSS: Transmission Policies and
Performance Analysis**

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Performance Analysis**

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*"He not busy being born is busy dying."
Bob Dylan*

RESUMO

As Redes de Área Ampla de Baixo Consumo (LPWANs) revolucionaram a conectividade da Internet das Coisas (IoT) ao possibilitar comunicações de longa distância com dispositivos de baixo custo e consumo mínimo de energia. O LoRaWAN, atualmente a principal tecnologia de redes LPWAN, é um protocolo de rede que opera sobre tecnologias físicas como o Long Range (LoRa) e, mais recentemente, o long range–frequency hopping spread spectrum (LR-FHSS). O LoRa é uma modulação baseada em chirp spread spectrum (CSS) amplamente utilizada por oferecer longas distâncias e baixo consumo de energia. Já o LR-FHSS, introduzido de forma mais recente no padrão LoRaWAN, foi projetado para aumentar a escalabilidade da rede em cenários de alta densidade em relação à modulação LoRa convencional. No entanto, a tecnologia ainda requer avanços para atingir maior maturidade, especialmente no que diz respeito à confiabilidade em redes massivas. Este estudo analisa três técnicas de transmissão de mensagens — concatenação, retransmissão embutida e replicação — em redes LR-FHSS sob diferentes cargas de tráfego, utilizando abordagens teóricas e baseadas em simulação. A concatenação agrupa várias mensagens em um único pacote, reduzindo o número de transmissões, a sobrecarga de pacotes e o congestionamento da rede. Por outro lado, aumenta a latência, sendo mais adequada para aplicações tolerantes a atraso. A retransmissão embutida anexa cópias de mensagens anteriores aos pacotes subsequentes, equilibrando confiabilidade e atraso, com bom desempenho em redes de baixa a média densidade. A replicação, que transmite cópias independentes de um mesmo pacote, melhora a confiabilidade, mas pode aumentar o congestionamento da rede, tornando-se menos eficaz em ambientes com alta densidade de dispositivos. Os resultados indicam que a concatenação apresenta uma vantagem clara em relação às demais técnicas analisadas nos cenários estudados, alcançando até 44% de melhoria na probabilidade de sucesso da entrega de mensagens em comparação com a transmissão LR-FHSS convencional em redes com 50.000 dispositivos.

Palavras-chave: Internet das Coisas. LPWAN. LR-FHSS. Replicação

ABSTRACT

Low Power Wide Area Networks (LPWANs) have revolutionized Internet of Things (IoT) connectivity by enabling long-range communication with low cost end devices and minimal power consumption. LoRaWAN, currently the leading LPWAN technology, is a network protocol that operates on physical layer technologies such as Long Range (LoRa) and, more recently, long range–frequency hopping spread spectrum (LR-FHSS). LoRa is a modulation based on chirp spread spectrum (CSS), widely used for providing long-range communication with low energy consumption. LR-FHSS, introduced more recently into the LoRaWAN standard, was designed to improve network scalability in high-density scenarios compared to the conventional LoRa modulation. There remains a need for research to mature the technology further, particularly in massive networks, where ensuring reliability remains a challenge. This study examines three message transmission techniques, concatenation, embedded retransmission, and replication, in LR-FHSS networks under different traffic loads, using both theoretical and simulation-based approaches. Concatenation merges multiple messages into a single payload, reducing the number of transmissions, packet overhead, and alleviating network congestion. However, it increases latency, making it more suitable for delay-tolerant applications. Embedded retransmission attaches copies of previous messages to subsequent packets, balancing reliability and delay, and performing well in low to moderate-density networks. Replication, which involves transmitting independent copies of the same packet, enhances reliability but can contribute to network congestion, limiting its effectiveness in high-density environments. The results indicate that concatenation offers a clear advantage over the other investigated techniques in the analyzed scenarios, while achieving up to 44% higher message success probability compared to regular LR-FHSS at 50,000 end devices.

Keywords: Internet-of-Things. LPWAN. LR-FHSS. Replication.

RESUMO EXPANDIDO

Introdução: Low power wide area networks (LPWANs) são fundamentais para a conectividade de dispositivos IoT em áreas remotas, com ênfase em baixo custo e longa duração de bateria. A tecnologia LoRaWAN é amplamente adotada no contexto de LPWANs, sendo padronizada internacionalmente. Contudo, o esquema de modulação tradicional LoRa enfrenta desafios de escalabilidade, especialmente em redes densas. Para resolver esse problema, foi introduzido o long range-frequency hopping spread spectrum (LR-FHSS), provendo maior robustez e capacidade de rede. Ainda assim, garantir a confiabilidade de transmissão em redes massivas segue sendo um desafio importante. Este trabalho investiga o uso de três técnicas de transmissão de mensagens em LR-FHSS: concatenação, retransmissão embutida e replicação. Utilizando modelagem teórica e simulações, o estudo compara as abordagens sob diferentes condições de tráfego e densidade de dispositivos.

Objetivos: O principal objetivo deste estudo é avaliar o impacto de diferentes técnicas de transmissão de mensagens na confiabilidade durante escala, latência e consumo energético em redes LR-FHSS. Os objetivos específicos incluem: (i) modelar teoricamente a taxa de sucesso, atraso e consumo energético de cada técnica; (ii) validar os modelos via simulação com o simulador LR-FHSS-Sim (SOUZA SANT'ANA *et al.*, 2024a); (iii) entender o impacto das técnicas sob diferentes densidades de rede e cargas de tráfego, inclusive considerando tráfego de fundo; (iv) analisar a efetividade de cada técnica em diferentes cenários.

Metodologia: A abordagem teórica considera um modelo de rede com múltiplos dispositivos finais transmitindo para um gateway. São derivadas expressões para probabilidade de sucesso de mensagens, atraso médio e máximo, e consumo energético médio por mensagem entregue. As três técnicas são modeladas considerando seus parâmetros principais; o fator de concatenação c , o fator de retransmissão embutida p e o fator de replicação n . As equações são validadas por meio de simulações utilizando o LR-FHSS-Sim, incluindo a implementação de novos recursos para representar cada técnica. Diversos cenários são simulados, variando o número de dispositivos, a presença de tráfego de fundo e o tamanho da carga útil.

Resultados e discussão: As simulações mostram que a concatenação reduz significativamente o tráfego de rede e o consumo energético por mensagem, atingindo até 44% mais sucesso de entrega que o LR-FHSS padrão em redes com 50.000 dispositivos. Contudo, ela impõe maiores atrasos, sendo mais adequada a aplicações tolerantes à latência. A retransmissão embutida melhora a confiabilidade em cenários com baixa densidade populacional e altas taxas de apagamento. Já a replicação não

oferece ganhos significativos nos cenários analisados quando comparada com as outras técnicas de transmissão. A análise de tráfego de fundo revela que a concatenação melhora inclusive o desempenho de dispositivos legados, enquanto a replicação tende a prejudicá-los. Além disso, combinações como $c = 5$ e $p = 2$ podem alcançar resultados superiores ao uso isolado das técnicas em contextos específicos. A modelagem analítica mostrou-se bem ajustada às simulações, validando sua utilidade prática.

Considerações finais: Este trabalho fornece uma análise abrangente de técnicas de transmissão para LR-FHSS, destacando que a concatenação é a técnica mais promissora para redes densas e aplicações tolerantes à latência, com ganhos expressivos de eficiência energética e escalabilidade. A retransmissão embutida equilibra confiabilidade e latência, enquanto a replicação não apresentou vantagens significativas. Os resultados podem guiar a escolha de políticas de transmissão para dispositivos IoT em cenários terrestres ou via satélite. Como trabalho futuro, sugere-se a investigação de técnicas adaptativas baseadas em contexto de rede e a validação prática com experimentos reais.

Palavras-chave: Internet das Coisas. LPWAN. LR-FHSS. Replicação

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LIST OF ACRONYMS

Aol	Age of Information
CR	Coding Rate
CSS	Chirp Spread Spectrum
DR	Data Rate
DtS	Direct-to-Satellite
EPM	Energy per Message
EPP	Energy per Packet
FEC	Forward Error Correction
FSK	Frequency Shift Keying
GMSK	Gaussian Minimum-Shift Keying
IoT	Internet of Things
ITU	International Telecommunication Union
LEO	Low Earth Orbit
LoRa	Long Range
LPWAN	Low Power Wide Area Network
LR-FHSS	Long Range-Frequency Hopping Spread Spectrum
MAC	Media Access Control
OCW	Operating Channel Width
RT-E	Embedded Retransmission Technique
RT-I	Independent Retransmission
ToA	Time on Air

LIST OF SYMBOLS

CR	Coding rate
L	Payload length in bytes
ToA	Time on Air for a packet
U	Number of LR-FHSS end devices operating in the network
λ	Inverse of the average interval between messages
ε	Erasur probability
δ	Fraction of end devices employing regular LR-FHSS
c	Concatenation factor
p	Embedded retransmission factor
n	Replication factor
S	Total number of frequency hops
N	Number of header replicas
F	Total number of payload fragments
γ	Payload fragments required for decoding
F_δ	Total number of payload fragments in regular LR-FHSS
γ_δ	Payload fragments required for decoding in regular LR-FHSS
μ_H	Average inter-arrival time for headers
μ_F	Average inter-arrival time for payload fragments
A_H	Average number of packet elements in a header's interval
A_F	Average number of packet elements in a fragment's interval
t_H	Time-on-Air for a single header
t_F	Time-on-Air for a single payload fragment
P_H	Probability of receiving at least one transmitted header
C	Number of available non-overlapping frequency channels
P_F	Probability of decoding more than γ payload fragments
p_F	Success probability of a single fragment
P_P	Overall payload success probability
P_S	Overall message success probability
d_c	Message reception delay using concatenation
d_p	Message reception delay using embedded retransmission
d_n	Message reception delay using replication
φ	Binary indicator variable for replication use
T_{RX1}	Duration of first receive window
T_{RX2}	Duration of second receive window
T_{TX}	Duration of the transmission period (ToA)
T_{Sleep}	Duration of the sleep period
I_{avg}	Average current consumption

I_{RX1}	Current consumption during first receive window
I_{RX2}	Current consumption during second receive window
I_{TX}	Transmission mode current consumption
V	Supply voltage
EPM	Energy per successfully delivered message

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1 INTRODUCTION

Low Power Wide Area Networks (LPWAN) have become increasingly important in recent years due to their ability to provide long-range, low-power, and low-cost connectivity for Internet of Things (IoT) applications. LPWAN technologies can be deployed in unconnected remote areas to enable IoT applications (ASAD ULLAH *et al.*, 2021; FRAIRE, Juan A. *et al.*, 2022a). Among LPWAN technologies, LoRaWAN (LORA ALLIANCE, INC., 2020) stands out as a leading low-power and long-range solution (OMDIA, 2024). Due to the use of unlicensed spectrum, LoRaWAN is a low-cost connection solution and has gained significant recognition as a global LPWAN standard, with its formal acknowledgment by the International Telecommunication Union (ITU) (LORA ALLIANCE, 2024; INTERNATIONAL TELECOMMUNICATION UNION, 2021). This standardization ensures interoperability, regulatory compliance, and broader adoption across various industries. Moreover, the LoRa Alliance¹ continually refines the LoRaWAN specifications. Fig. 1 presents an overview of how this technology enables connected services in urban environments. These applications range from smart parking and waste management to environmental monitoring, public lighting, and utility metering.

The LoRaWAN network protocol operates on top of the physical layer technologies of long range (LoRa), long range frequency-hopping spread spectrum (LR-FHSS), and frequency shift keying (FSK) modulations. LR-FHSS supports only uplink communications, whereas downlink transmissions can use either LoRa or FSK. LoRa is based on chirp spread spectrum (CSS) modulation (SELLER *et al.*, 2016; SEMTECH CORP., 2015), which enables long-range communication with low power consumption, making it well-suited for low data rate IoT applications. However, despite its advantages,

¹ <https://loro-alliance.org/about-lora-alliance/>

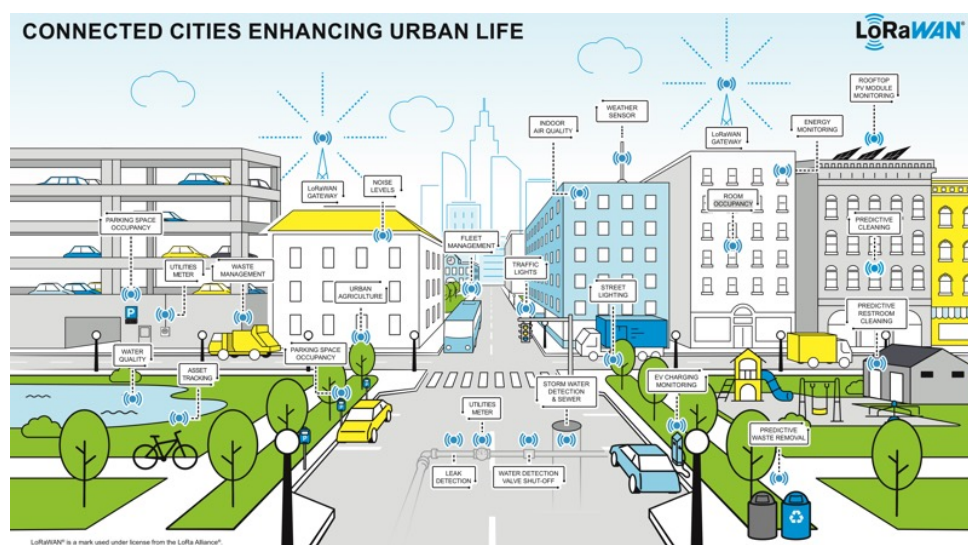


Figure 1 – Illustration of connected city applications enabled by LoRaWAN. Adapted from (MESHED AUSTRALIA, 2024).

LoRa employs a medium access control (MAC) protocol similar to pure ALOHA, facing scalability issues in massive IoT deployment scenarios (GEORGIOU *et al.*, 2017).

Although LoRa's quasi-orthogonal spreading factors enable the simultaneous coexistence of multiple devices, it is difficult to optimally allocate the appropriate spreading factors in dynamic network environments. For instance, selecting the optimal spreading factor is particularly challenging in direct-to-satellite (DtS) communications, especially in low Earth orbit (LEO), such as the LacunaSat system (CAPEZ *et al.*, 2022), where satellites continuously move around the Earth. These challenges motivated the development and introduction of the LR-FHSS physical layer into the LoRaWAN specifications (SEMTECH CORP., 2022). LR-FHSS adopts Gaussian minimum-shift keying (GMSK) and is designed to enhance performance in massive networks, such as those used in DtS IoT solutions, enabling end devices to communicate directly with LEO satellites without relying on terrestrial gateways.

Recent DtS theoretical studies and field test experiments have confirmed the feasibility of the concept and identified both open challenges and opportunities (CENTENARO *et al.*, 2021; FRAIRE, Juan A. *et al.*, 2022b; ULLAH *et al.*, 2023). Furthermore, the integration of LEO satellites with LR-FHSS has garnered significant academic and industrial attention due to its relevance in long-range and large-scale IoT solutions (FRAIRE, Juan A. *et al.*, 2022a; ASAD ULLAH *et al.*, 2021; ULLAH *et al.*, 2022a; BOQUET *et al.*, 2021). Despite the demonstrated feasibility of LR-FHSS for DtS communications, interference remains a critical issue, particularly as the density of the network increases.

Redundant transmission techniques have proven to be effective in improving the reliability and scalability of LPWANs (MONTEJO-SÁNCHEZ *et al.*, 2019). For example, message replication improves network scalability by transmitting multiple copies of the same message. This approach takes advantage of time diversity to increase the probability that at least one copy is received successfully by the gateway. Replication has been widely studied in the literature and has even been incorporated into LPWAN standards (LAVRIC *et al.*, 2019; CHEN *et al.*, 2017). In the context of LoRa technology, energy-efficient and latency-aware message replication strategies have also been proposed (RATHI *et al.*, 2024a), in which replicas are either transmitted independently or piggybacked onto new messages. A similar replication concept is also employed in NB-IoT, where the 3GPP Release 13 standard includes repetitive transmissions to enhance reliability and coverage (RATASUK *et al.*, 2016).

Similarly, LR-FHSS also partially adopts the redundant transmission concept by transmitting multiple header copies and a codified and fragmented payload, which aims at improving reliability and consequently also the network scalability. Specifically, the standard LR-FHSS protocol inherently employs header replication, in which multiple header copies are transmitted independently to increase the likelihood of successful

reception (SEMTECH CORP., 2022). However, such redundant transmission comes at the cost of increased network congestion, which increases the number of collisions and limits overall performance gains. Therefore, there remains a need to optimize message transmission techniques to further improve LR-FHSS scalability.

This work presents a detailed investigation of three such message transmission techniques within LR-FHSS networks: concatenation, embedded retransmission, and replication. These techniques are analyzed in terms of message success probability, delay, network congestion, and energy per delivered message.

1.1 OBJECTIVES

The main contributions of this work are:

1. A comprehensive analysis of three message transmission techniques for LR-FHSS communications, namely concatenation, embedded retransmission, and replication.
2. Theoretical and simulation-based evaluations of the aforementioned techniques under different conditions, including network density and background traffic levels.
3. Practical insights into trade-offs involving reliability, delay, network load, and energy consumption, offering guidelines for optimizing LR-FHSS networks.

The remainder of this work is organized as follows:

- Chapter 2: Provides a detailed overview of the LR-FHSS physical layer, its design principles, and its relevance in both terrestrial and satellite IoT networks. It also reviews recent academic and industrial progress in LR-FHSS research.
- Chapter 3: Describes the network architecture, transmission models, and assumptions used throughout the analytical and simulation evaluations. It introduces the key parameters and metrics used in performance assessment.
- Chapter 4: Formally defines the three techniques (concatenation, embedded retransmission, and replication), detailing their packet structures and theoretical implications.
- Chapter 5: Presents the mathematical models used to evaluate reliability, delay, and energy efficiency. Includes derivations of success probability, average delay, maximum delay, and energy per message.
- Chapter 6: Compares the techniques using numerical simulations and analytical results under varying network densities and background traffic loads. Discusses the trade-offs and practical implications of each technique.
- Chapter 7: Summarizes the key findings, highlights the most suitable techniques for different scenarios, and outlines possible future research directions.

1.2 PUBLICATION

The main results of this thesis were published in the IEEE Open Journal of the Communications Society:

L. B. Rocha, R. D. Souza, J. M. S. Sant'Ana, M. A. Ullah, S. Montejo-Sánchez, J. L. Rebelatto, "Towards Improving the Scalability of LR-FHSS: Transmission Policies and Performance Analysis," in *IEEE Open Journal of the Communications Society*.

2 LR-FHSS: BACKGROUND AND RECENT DEVELOPMENTS

Unlike traditional LoRa modulation, which leverages CSS, LR-FHSS uses GMSK modulation and employs a fast frequency hopping technique. The total bandwidth of the LR-FHSS system is defined by the Operating Channel Width (OCW). The OCW is governed by regional regulatory requirements and affects the number of discrete transmission channels that can be defined within the spectrum. For example, in the EU 863 – 870 MHz band, the OCW can be 137 kHz or 336 kHz, divided into $C = 280$ or $C = 688$ individual transmission channels with OBW of 488 Hz each. These narrowband channels form the basis for LR-FHSS's hopping mechanism. Each packet element (whether a header or payload fragment) is assigned to a different channel according to a pseudo-random sequence, providing spectral separation from both other elements of the same packet and transmissions from other end devices. This channel hopping increases spatial reuse and decreases the probability of collisions, particularly in high-density deployments.

LR-FHSS employs convolutional coding for forward error correction (FEC). Importantly, the coding schemes differ between the packet header and the payload. While the header is always protected by a fixed convolutional code with coding rate (CR) of $\frac{1}{2}$ and memory depth 4, payload data fragments are encoded with a different convolutional scheme of memory depth 6 (BUKHARI *et al.*, 2024a), with four coding rate options defined: $CR \in \left[\frac{5}{6}, \frac{2}{3}, \frac{1}{2}, \frac{1}{3}\right]$. Currently, the LoRaWAN specification supports only two of these, $\frac{1}{3}$ and $\frac{2}{3}$, while the remaining options are reserved for future use. The LoRaWAN Data Rate (DR) parameter defines both the coding rate and the effective information bit rate. In regions governed by ETSI regulations, data rates DR8 and DR10 use $CR = \frac{1}{3}$, while DR9 and DR11 use $CR = \frac{2}{3}$. In areas under FCC regulations, DR5 and DR6 correspond to $CR = \frac{1}{3}$ and $CR = \frac{2}{3}$, respectively. It is worth noting that a lower coding rate improves the gateway's ability to decode received packets in the presence of noise and interference.

With an OBW of 488 Hz, LR-FHSS offers a raw bit rate of $R = 488.28125$ bits per second (bps), including FEC overhead. However, the actual information bit rate depends on the selected CR. For example, 162.76 bps and 325.52 bps for $CR = \frac{1}{3}$ and $CR = \frac{2}{3}$, respectively. Additionally, the LoRaWAN protocol introduces a minimum overhead of 13 bytes to the application payload, which must be factored into performance models, as it affects time on air (ToA) and network throughput. Figure 2 illustrates the key components of an LR-FHSS packet, while Table 1 summarizes the main parameters for DR8 and DR9 (THE THINGS NETWORK, 2025). These configurations directly influence system performance and determine trade-offs between robustness, delay, and energy efficiency.

The maximum application payload size L in LR-FHSS depends on the employed

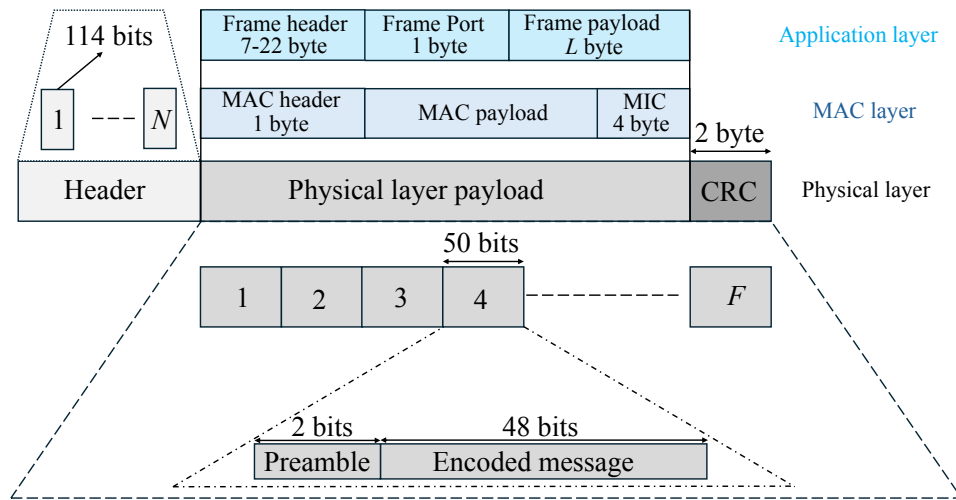


Figure 2 – Key components of the LR-FHSS packet structure.

Table 1 – Parameters of LR-FHSS data rates (DRs) under ETSI and FCC regulations.

Region	DR	Coding Rate (CR)	Max. app. payload length (L) [bytes]	Header replicas (N)	Bit rate [bps]
ETSI	DR8	1/3	50	3	162
ETSI	DR9	2/3	115	2	325
ETSI	DR10	1/3	50	3	162
ETSI	DR11	2/3	115	2	325
FCC	DR5	1/3	50	3	162
FCC	DR6	2/3	125	2	325

DR, coding rate, and header replicas, limiting the maximum ToA. These parameters define the total ToA of a packet, which in turn must comply with regional duty cycle and airtime fairness regulations. Exceeding permitted ToA could lead to packet rejection or regulatory non-compliance. Therefore, precise modeling of packet structure, frequency channel occupancy, and ToA is essential for both protocol design and large-scale network planning.

Downlink communication in LoRaWAN is typically constrained to two predefined receive windows (RX1 and RX2) that open following each uplink (LORA ALLIANCE, INC., 2020). The first receive window (RX1) uses a DR that depends on the uplink. If LR-FHSS is utilized in the uplink transmission, RX1 employs DR1 for uplink frames transmitted with DR8 or DR10 and DR2 for uplinks with DR9 or DR11. The second receive window (RX2) always uses a fixed configuration, set to DR0 (SANCHEZ-VITAL *et al.*, 2024). It should be emphasized that, regardless of whether the uplink uses LR-FHSS, all downlink transmissions rely on LoRa CSS modulation.

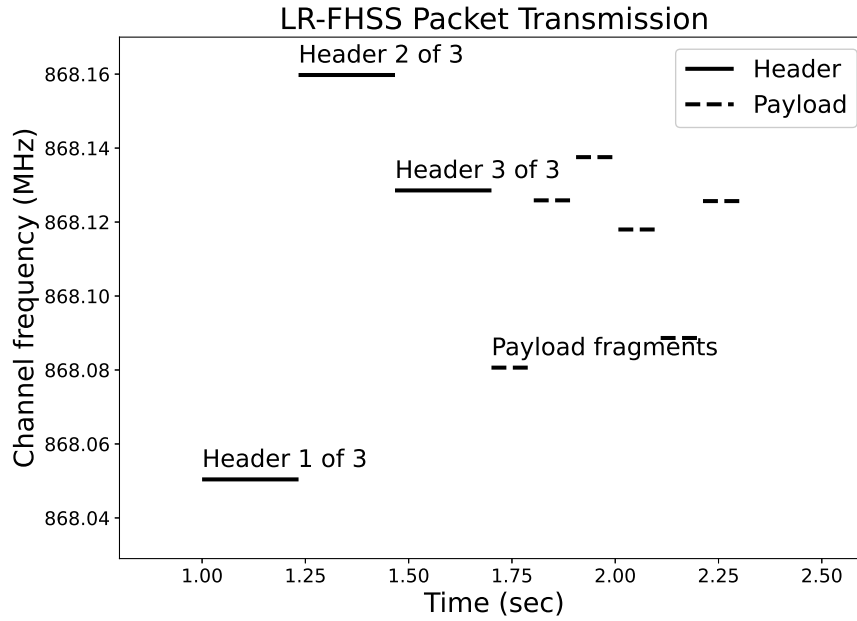


Figure 3 – Visual representation of the transmission of an LR-FHSS packet (DR8) containing header replicas and payload fragments. Adapted from (BOQUET *et al.*, 2021).

2.1 PACKET STRUCTURE

As illustrated in Figure 2, LR-FHSS packets consist of a header, a physical layer payload, and a cyclic redundancy check (CRC). The packet is fragmented into multiple discrete transmission elements, which include both payload fragments and headers. Each of these elements is transmitted independently using the frequency hopping scheme, spreading the transmission across time and frequency to reduce the likelihood of collision and interference.

Figure 3 illustrates the transmission of an LR-FHSS packet, which, in this case, is composed of three headers and six payload fragments. As presented in Figure 2, each encoded payload fragment has 50 bits (48 payload bits and 2 preamble bits), resulting in a fixed duration of 0.1024 s, while the total number of fragments depends on both the payload length and the coding rate (LORA ALLIANCE, 2022). Each encoded header comprises 114 bits, resulting in a header duration of 0.233472 s (ULLAH *et al.*, 2024). Note that LR-FHSS employs header replication, each header being replicated by default two or three times depending on the configured DR, to ensure reliable reception even in challenging channel conditions. It contains essential information such as the hopping sequence, the payload length, and the CR used in the payload fragments. Finally, all packet elements (term for headers and payload fragments) are spread across multiple frequencies, increasing network capacity and reducing collision probability (SEMTECH CORP., 2022).

2.2 LR-FHSS RECENT DEVELOPMENTS

Previous studies have investigated the LR-FHSS link budget and scalability in terrestrial and non-terrestrial networks, with a particular focus on DtS communication for IoT in remote areas. In (BOQUET *et al.*, 2021), an overview of LR-FHSS is presented, along with a comparison of its goodput against that of LoRa. The results show that LR-FHSS provides significantly higher network capacity than LoRa modulation. In (ULLAH *et al.*, 2022b; MALEKI *et al.*, 2024b, 2023), analytical and simulation models are proposed to evaluate LR-FHSS scalability for DtS communication, with the analysis incorporating channel fading and the capture effect, factors not considered in (BOQUET *et al.*, 2021). More recently, (TESTI *et al.*, 2025) introduces a packet collision probability model for DtS communication, further comparing LR-FHSS and LoRa. Consistent with (BOQUET *et al.*, 2021), the results confirm that LR-FHSS can support massive IoT connectivity.

In (BEN TEMIM *et al.*, 2023), interference blanking techniques are proposed to enhance the capacity of LR-FHSS receivers. Research in (JUNG *et al.*, 2023, 2024) explores LR-FHSS transceiver design, highlighting that the GMSK modulation outperforms QPSK in DtS scenarios with interference and Doppler effects. In (FARHAT *et al.*, 2025), the probabilistic allocation of payload coding rates and header replications is shown to improve network performance over legacy LR-FHSS. Additionally, (FRAIRE, Juan Andres *et al.*, 2023) presents a linear programming model to recover headerless LR-FHSS packets. Message replication has also shown promising results for enhancing reliability in LR-FHSS-based DtS communications (RATHI *et al.*, 2024b).

It is important to emphasize that long battery life is a critical requirement for DtS IoT end devices deployed in remote areas, where they are expected to be battery-powered. Experiment-based models for LR-FHSS ToA and current consumption are introduced in (ULLAH *et al.*, 2024). The results indicate that, with a 2400 mAh battery, an LR-FHSS end device can operate for up to 4.2 years when transmitting one packet every 30 minutes.

Table 2 summarizes selected relevant LR-FHSS publications and the topics they address. Most existing studies focus on developing analytical models and simulation frameworks to evaluate performance, while some works explore transceiver design to improve scalability in massive networks. Although many of these performance-enhancing techniques could, in principle, benefit large-scale deployments, their direct applicability may be limited in practice because LR-FHSS end devices are typically battery-powered and operate under strict resource constraints. As a result, it is often impractical to implement complex or energy-intensive techniques on these devices. In this work, we explore whether LR-FHSS performance can be improved through alternative uplink transmission policies, specifically using techniques referred to as concatenation, embedded retransmission, and replication. To the best of the authors' knowledge, these

Table 2 – List of selected relevant LR-FHSS publications and covered topics.

Reference	Scalability analysis	Optimization & enhancements	Transceiver design	Channel conditions	Energy analysis	Concatenation	Embedded retransmission	Replication
(ULLAH <i>et al.</i> , 2022b)	✓	×	×	×	×	×	×	×
(MALEKI <i>et al.</i> , 2024b)	✓	×	×	×	×	×	×	×
(MALEKI <i>et al.</i> , 2023)	✓	×	×	×	×	×	×	×
(SOUZA SANT'ANA <i>et al.</i> , 2024a)	✓	×	×	×	×	×	×	×
(TESTI <i>et al.</i> , 2025)	✓	×	×	×	×	×	×	×
(SOUZA SANT'ANA <i>et al.</i> , 2024b)	✓	×	×	×	×	×	×	×
(BEN TEMIM <i>et al.</i> , 2023)	✓	×	✓	×	×	×	×	×
(JUNG <i>et al.</i> , 2023)	✓	×	✓	×	×	×	×	×
(JUNG <i>et al.</i> , 2024)	✓	×	✓	×	×	×	×	×
(BUKHARI <i>et al.</i> , 2024b)	✓	×	✓	×	×	×	×	×
(MALDONADO <i>et al.</i> , 2025)	✓	×	✓	×	×	×	×	×
(MALEKI <i>et al.</i> , 2024a)	✓	×	✓	×	×	×	×	×
(FARHAT <i>et al.</i> , 2025)	✓	✓	×	×	×	×	×	×
(FRAIRE, Juan Andres <i>et al.</i> , 2023)	✓	✓	×	×	×	×	×	×
(RATHI <i>et al.</i> , 2024b)	✓	×	×	×	✓	×	×	✓
This work	✓	×	×	✓	✓	✓	✓	✓

transmission strategies have not yet been thoroughly investigated in the context of LR-FHSS.

2.3 TRANSMISSION POLICIES

Several studies in the literature address transmission policies for SigFox and LoRa modulations. For example, (MO *et al.*, 2016) investigates the optimal number of message replications in a system model representative of a SigFox network. In (MONTEJO-SÁNCHEZ *et al.*, 2019), the performance of transmission schemes that embed coded redundant information into packets carrying new data is analyzed, considering a generic ALOHA network. Subsequently, (RATHI *et al.*, 2024a) extends this analysis to a LoRa network, evaluating both energy consumption and reliability. However, these works and others in the same context are not directly applicable to LR-FHSS, due to significant differences in ToA and packet structure. Notably, LR-FHSS inherently includes replication in the transmission of headers, while redundancy through coding is applied to the payload prior to fragmentation.

Network-coded header replication was proposed for LR-FHSS in (KNOP *et al.*, 2024), leveraging error-correcting codes to combine multiple headers from different packets, improving robustness against interference and packet erasures. This approach has been shown to reduce packet error rates by more than an order of magnitude in high-density networks. However, payloads are not additionally protected. Recently, the authors in (RATHI *et al.*, 2024b) proposed two message replication schemes aimed at enhancing the reliability of LR-FHSS. The first scheme employs conventional replication, where multiple copies of a message are transmitted separately as individual link-layer frames, leveraging time diversity to increase the probability of reception. The second scheme integrates fragment replication, where multiple copies of the mes-

sage are embedded within a single link-layer frame. The results demonstrate that both schemes improve reliability, but their effectiveness depends on the traffic conditions: frame replication performs better under low-traffic scenarios, while fragment replication is preferable in high-traffic conditions. However, the authors do not consider the impact of background interference or the trade-offs between latency and energy efficiency in dense environments.

Unlike (KNOP *et al.*, 2024; RATHI *et al.*, 2024b), this study focuses on conventional approaches to provide a comparative analysis of three techniques: concatenation, embedded retransmission, and replication. This work provides insights into which approach performs best under varying network conditions, allowing for a deeper understanding of the trade-offs and benefits of each method.

3 SYSTEM MODEL

This chapter outlines the system and traffic configurations used to create a comprehensive and varied approach for evaluating LR-FHSS performance. The configurations adhere to the limitations set by the EN300.220 standard (ETSI, 2020) for the EU863-870 MHz band, ensuring compliance with regional regulations (LORA ALLIANCE, 2022). Specifically, the system model considers a network containing U end devices, all under the coverage of a single terrestrial gateway. While LR-FHSS is suitable for both terrestrial and DtS scenarios, the model adopted here abstracts away satellite-specific effects such as Doppler shifts, which are outside the scope of this analysis. The end devices generate periodic data which need to be transmitted to a server, and the payload size is typically short. Since ALOHA-based multiple-access is employed, transmissions are subject to destructive collisions, while collided headers or payload fragments are assumed to be lost. Moreover, in terms of traffic density, we assume that each end device generates a message every $1/\lambda$ seconds on average.

3.1 ERASURE PROBABILITY

We consider the on-off fading model (PERRON *et al.*, 2003) in order to account for channel impairments that may lead to packets that have not collided with others but that are still not detected by the gateway. In such a model, each packet element is subject to an erasure probability ε , assumed to be independent and identically distributed either in time, frequency, or space. Note that such a model has been extensively used in the analysis of ALOHA-based multiple access schemes, as, for instance, in (PERRON *et al.*, 2003; LIVA *et al.*, 2019; MUNARI *et al.*, 2021; KNOP *et al.*, 2024; BERIOLI *et al.*, 2016; TONDO *et al.*, 2023), which describes well the behaviour of channels whose losses are mainly dominated by fading and short-term blocking due to the presence of obstacles (MUNARI *et al.*, 2021), and therefore being a meaningful choice for our particular analysis. Moreover, the on-off fading model brings the bonus of mathematical tractability without loss of generality.

3.2 BACKGROUND TRAFFIC

We assume that the network server is able to (or intends to) control only part of the end devices connected to the network. Therefore, a portion δ of the connected end devices always transmits with one of the regular LR-FHSS configurations listed in Table 1. From the point-of-view of our analysis, which focuses on transmitting strategies not included in Table 1, such end devices operating under regular LR-FHSS are seen as background traffic. In the scenarios studied, only a subset of the end devices is assumed to adopt the proposed transmission techniques. The remaining devices coexist

as background traffic and continue to use the standard LR-FHSS configuration. This represents real-world scenarios where certain devices are beyond the management of the network server being evaluated. These could include, for example, legacy LR-FHSS devices that were installed prior to the implementation of new protocols, or devices registered on another network server operating within the same frequency band. Such an assumption allows the performance evaluation of, for instance, situations where a few end devices are extremely crucial for the operation, and would greatly benefit from employing a redundancy technique, while others are not priority. Finally, we can answer whether these techniques could harm, for example, legacy end devices operating under regular LR-FHSS.

3.3 PERFORMANCE METRICS

To holistically evaluate the performance of different transmission schemes, we consider four complementary metrics. These metrics collectively assess not only the reliability and responsiveness of the network but also its energy efficiency and scalability

1. *Success Probability*: The likelihood that an uplink packet is successfully received by the gateway.
2. *Delay*: The time delay between message generation and its successful reception.
3. *Network Congestion*: The impact of background traffic on the performance of each technique (and vice-versa).
4. *Energy per Message*: The average energy consumed by an end device to successfully deliver a message.

These metrics allow for a detailed comparison of transmission techniques by understanding the trade-offs involved under various network conditions.

4 MESSAGE TRANSMISSION TECHNIQUES

This chapter introduces and evaluates the performance of the message transmission techniques employed in this work, detailing their impact on reliability, delay, and network congestion. The probability of successful packet delivery is derived based on channel conditions defined by erasure probability, redundancy mechanisms, and coding strategies. Key terms are defined to ensure clarity in the discussion:

- *Payload*: The portion of an LR-FHSS packet that contains encoded messages. A single payload may contain one or more messages generated by the same end device, depending on the transmission technique used.
- *Message*: The basic unit of information generated by end devices, such as sensor readings (e.g. temperature, humidity, pressure).
- *Packet*: The complete LR-FHSS transmission unit, consisting of all replicated headers and payload fragments.

4.1 CONCATENATION

Message concatenation operates by buffering messages generated by a single end device until a predefined number of c messages is reached. Such messages are then concatenated into a single payload and transmitted as one packet, as illustrated in Figure 4, while respecting the maximum payload length listed in Table 1. This technique increases both the average inter-transmission interval and the payload size per transmission, while reducing the total number of transmissions by a factor of c . Given that LR-FHSS networks are expected to be dense (SEMTECH CORP., 2022), network traffic plays a key role in collision probability and overall performance. The message concatenation would then be expected to be advantageous in reducing channel occupancy and improving network performance.

However, this method is only suitable for use cases that can tolerate increased latency, as the average delay before transmission grows with the number of accumulated messages and can be approximated by $(c - 1)/(2\lambda)$, where λ is the message generation rate. In addition to reducing transmission frequency, this scheme also reduces protocol overhead by consolidating multiple messages into a single transmission. For example, in DR8 with $CR = 1/3$, the header is transmitted three times per packet. Without concatenation, sending three separate uplink packets results in a total of 173 bytes of overhead. With concatenation, this is reduced to just 58 bytes. Consequently, this method is expected to contribute to improved energy efficiency and longer battery life for LR-FHSS end devices.

For concatenation to be effective, individual messages must be sufficiently short to allow multiple messages to fit within the payload limits. If messages are too large,

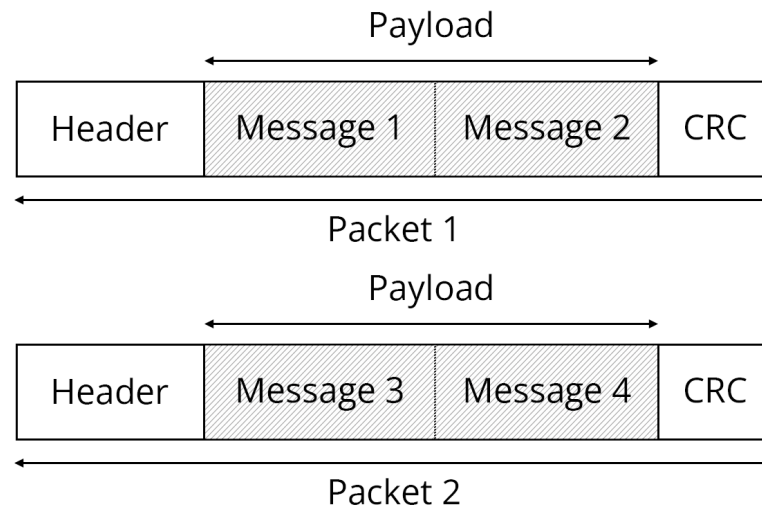


Figure 4 – Description of the LR-FHSS packet structure when concatenation is applied with $c = 2$. The cross-hatch pattern indicates that the messages were coded into a single payload.

concatenation may either offer a limited benefit or be infeasible. Moreover, this technique increases the risk of information loss: a single packet loss can lead to the loss of multiple messages, which is particularly problematic in environments with poor channel conditions (*i.e.* high erasure probabilities).

4.2 EMBEDDED RETRANSMISSION

The embedded retransmission method is conceptually similar to the Embedded Retransmission Technique (RT-E) introduced in (MONTEJO-SÁNCHEZ *et al.*, 2019). It introduces redundancy by transmitting each message p times across p successive packets, ensuring that the failure of any single packet does not necessarily result in message loss. This is achieved by concatenating the most recent p messages into each transmitted payload, as illustrated in Figure 5. Compared to simple concatenation, this approach provides the additional benefit of redundancy while maintaining a lower average delay, since each new message is transmitted at the next available opportunity.

However, this method increases network congestion due to the larger payload size per transmission, which results in a longer ToA. Since the average inter-transmission interval remains unchanged, the resulting higher channel occupancy may negatively impact overall network performance. Therefore, the benefits of redundancy must outweigh the congestion costs for it to be effective. As with concatenation, the practicality of embedded retransmission relies on the individual messages being short enough to allow multiple messages to fit within the payload constraints of LR-FHSS. If this condition is not met, the method may become inefficient or infeasible.

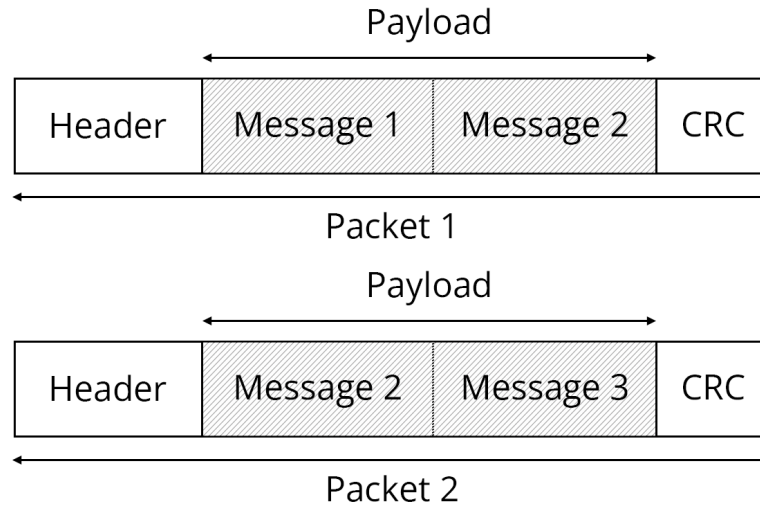


Figure 5 – LR-FHSS packet structure when embedded retransmission is applied with $p = 2$. The cross-hatch pattern indicates that the messages were coded into a single payload.

4.3 REPLICATION

Unlike the previous strategy, which embeds multiple messages within a single payload, replication, referred to as Independent Retransmission (RT-I) in (MONTEJO-SÁNCHEZ *et al.*, 2019), introduces redundancy at the packet level by ensuring that each packet carries only one message per payload. As illustrated in Figure 6, this technique involves transmitting each message n times in n separate packets. This improves the chances of successful reception and ensures the independence between transmissions. The key advantage is that each replica faces different channel conditions and collision scenarios, reducing the risk of systematic loss from interference or channel impairment. It is worth noting that this strategy is widely employed in LPWAN technologies such as NB-IoT (AZARI *et al.*, 2018) and Sigfox (ZÚÑIGA *et al.*, 2023), to compensate for the lack of downlink acknowledgments and enhance reliability in long-range, interference-prone channels.

The downside of replication is the increased network load, as it shortens the average time between transmissions and increases the total number of packets sent. This added traffic can exacerbate collisions, particularly in dense network deployments. Nevertheless, the decoupling of replicas into individual transmissions enhances robustness, as each replica encounters different propagation and interference environments, providing diversity and improving resilience against transient channel degradations and mitigating correlated losses.

To elucidate the impact of each technique on network traffic more effectively, Table 3 provides a summary of key characteristics: the number of packets required

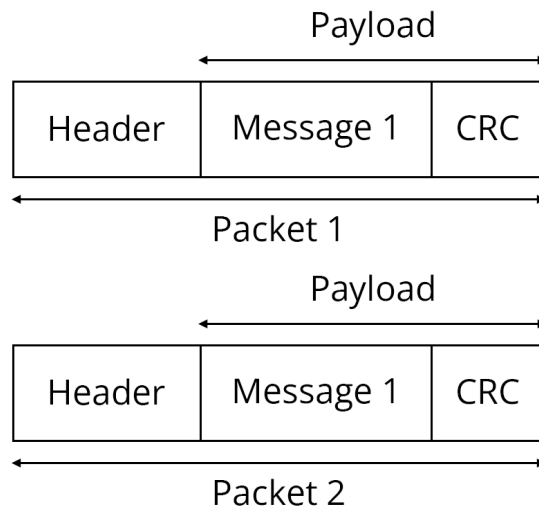


Figure 6 – Description of the LR-FHSS packet structure when replication is applied with $n = 2$.

Table 3 – Packets per message, redundancy per message, and messages per payload.

	Concatenation	Embedded retransmission	Replication
Packet transmissions	1	p	n
Redundant transmissions	0	$p - 1$	$n - 1$
Messages in each payload	c	p	1

for the transmission of each message, the redundancy level indicated by the number of redundant transmissions per message, and the number of messages incorporated within each packet payload. Concatenation reduces transmissions by combining multiple messages into one large packet. In contrast, embedded retransmission increases both packet size and transmissions by including multiple messages per packet, adding redundancy. Finally, replication increases the number of transmissions, keeping the packet size constant, as each packet carries a single message. Moreover, note that when $c = p = n = 1$, the system reduces to the standard LR-FHSS operation, without redundancy or message concatenation.

It is important to note that these techniques operate fully at the application server level, requiring no changes to the gateway or network server. This means that payloads containing multiple messages (as in concatenation and embedded retransmission) or replicated messages (as in replication) are interpreted and processed by the application server, without impacting the underlying network infrastructure. This design choice simplifies implementation and enhances the scalability of these techniques in real-world IoT deployments.

5 PERFORMANCE ANALYSIS

Chapter 4 presented the trade-offs of the evaluated transmission methods and how they influence channel robustness, network traffic load, and average delay. To allow a proper assessment and comparison of these techniques, we develop an analytical model, based on the framework presented in (ULLAH *et al.*, 2022a), to estimate the success probability associated with each approach. In addition, we analyze average and maximum transmission delays, as well as average energy consumption per message delivered.

With the aim of developing a general modeling framework, the following analysis allows for the concurrent use of multiple transmission schemes. For instance, one may adopt the embedded retransmission technique (e.g., with $p = 2$) along with the concatenation technique (e.g., with $c = 2$). In this case, $p = 2$ previously transmitted concatenated messages would be sent together with the $c = 2$ current concatenated messages, resulting in a total of $p \cdot c = 4$ messages per transmission. However, note that the total payload must not exceed 50 bytes.

5.1 SUCCESS PROBABILITY

First, note that the total number of frequency hops in a LR-FHSS packet is $S = N + F$, where N is the number of header replicas and F is the number of payload fragments within a packet. The number of payload fragments is influenced by the payload length, the concatenation factor, the embedded retransmission factor, and the coding rate. Adapted from the LoRaWAN specifications (LORA ALLIANCE, 2022), F can be expressed as

$$F = \left\lceil \frac{L \cdot c \cdot p + 3 + O}{6 \cdot CR} \right\rceil, \quad (1)$$

where c is the concatenation factor, p is the embedded retransmission factor, CR is the payload coding rate, L is the application layer payload length, and O accounts for the 13-byte overhead coming from the application and MAC layers as illustrated in Figure 2. Recall that replication does not change the payload length of each transmitted packet, thus it does not influence the number of frequency hops in a packet.

The minimum number of decoded payload fragments for successful packet reconstruction, denoted by γ , is:

$$\gamma = \lceil CR \cdot F \rceil. \quad (2)$$

Moreover, we define F_δ as the number of fragments for end devices using regular LR-FHSS, which is obtained from (1) by setting $c = p = 1$. Consequently, the minimum number of payload fragments for a successful transmission for end devices using regular LR-FHSS is $\gamma_\delta = \lceil CR \cdot F_\delta \rceil$.

Following the framework in (ULLAH *et al.*, 2022a), the average inter-arrival time for headers μ_H can be expressed as

$$\mu_H = \frac{\delta}{U \cdot (1 - \varepsilon) \cdot \lambda \cdot N} + \frac{(1 - \delta) \cdot c}{U \cdot (1 - \varepsilon) \cdot \lambda \cdot n \cdot N}, \quad (3)$$

and for payload fragments μ_F as

$$\mu_F = \frac{\delta}{U \cdot (1 - \varepsilon) \cdot \lambda \cdot F_\delta} + \frac{(1 - \delta) \cdot c}{U \cdot (1 - \varepsilon) \cdot \lambda \cdot n \cdot F}, \quad (4)$$

where $\delta \in (0, 1)$ denotes the proportion of end devices using standard LR-FHSS. When $\delta = 1$, all devices follow the regular LR-FHSS scheme; conversely, when $\delta = 0$, only alternative transmission strategies are employed, and no background traffic from regular devices is present.

The inter-arrival times are inversely proportional to both the number of users U and the effective packet generation rate, which is influenced by the concatenation factor c and the replication factor n . Since embedded retransmission does not alter the average transmission rate (each message is still transmitted once per opportunity), the factor p does not affect these expressions. The model incorporates an erasure probability ε to account for packet elements that fail to reach the receiver with sufficient power for decoding. The factor $(1 - \varepsilon)$ in the denominators of (3) and (4) adjusts for this effect, modeling the system as if the effective traffic originates from $U(1 - \varepsilon)$ users. Notably, a non-zero erasure probability ($\varepsilon > 0$) can lead to reduced perceived traffic at the gateway, thereby decreasing the collision probability from this point of view.

The average number of packet elements arriving during a header's vulnerable interval A_H is given by

$$A_H = \frac{2t_H}{\mu_H} + \frac{t_H + t_F}{\mu_F}, \quad (5)$$

and during a payload fragment's vulnerable interval A_F by

$$A_F = \frac{2t_F}{\mu_F} + \frac{t_H + t_F}{\mu_H}, \quad (6)$$

where t_H is the ToA for a single header, equal to 0.233472 seconds, and t_F is the ToA for a single payload fragment, equal to 0.1024 seconds (LORA ALLIANCE, 2022).

The probability P_H of the gateway successfully receiving at least one of the N transmitted headers of a given packet is

$$P_H(N) = 1 - \left(1 - \left(\frac{C-1}{C} \right)^{A_H-1} \cdot (1 - \varepsilon) \right)^N, \quad (7)$$

where C denotes the total orthogonal channels available and ε represents the signal erasure probability.

The probability P_F of successfully decoding at least γ payload fragments out of F is given by

$$P_F(\gamma, F) = P_r[F_{rx} \geq \gamma|F] = 1 - \sum_{k=0}^{\gamma-1} P_r[F_{rx} = k|F], \quad (8)$$

where the probability of receiving exactly k fragments is modeled as a binomial distribution:

$$P_r[F_{rx} = k|F] = \binom{F}{k} p_F^k (1 - p_F)^{F-k}, \quad (9)$$

with the success probability of a single fragment p_F defined as

$$p_F = \left(\frac{C-1}{C} \right)^{A_F-1} \cdot (1 - \varepsilon). \quad (10)$$

The factor $(1 - \varepsilon)$ in (7) and (10), as also used in (KNOP *et al.*, 2024), accounts for the probability that a header or fragment, although not suffering a collision, may still be lost due to insufficient received signal power. Consequently, while a non-zero erasure probability $\varepsilon > 0$ can reduce collision rates (as fewer packets reach the gateway), it also reduces the individual success probabilities of packet elements.

Using the header and payload success probabilities from (7) and (8), the overall packet success probability P_P is:

$$P_P(N, \gamma, F) = P_H(N) \cdot P_F(\gamma, F), \quad (11)$$

and the message success probability P_S is given by

$$P_S(N, \gamma, F) = 1 - \left(1 - P_P(N, \gamma, F) \right)^{p \cdot n}, \quad (12)$$

where the parameters p and n introduce time diversity by transmitting a message across multiple packets, in contrast to the concatenation factor c , which simply aggregates several messages into a single transmission without added diversity. For regular LR-FHSS transmissions, the message and packet success probabilities are identical and can be obtained from (11) by using the corresponding values γ_δ and F_δ .

To evaluate the overall average success probability in a network where both regular LR-FHSS and alternative transmissions coexist, we compute the weighted average as

$$P_S^{\text{total}} = (1 - \delta) \cdot P_S(N, \gamma, F) + \delta \cdot P_P(N, \gamma_\delta, F_\delta), \quad (13)$$

where $\delta \in (0, 1)$ denotes the fraction of end devices using regular LR-FHSS. This analytical model captures the trade-offs introduced by the parameters c , p , and n , which directly impact the network load, the average delay, and diversity. While concatenation (c) reduces traffic but may increase latency, embedded retransmission (p) introduces redundancy at the cost of increased congestion. Replication (n), in turn, improves reliability through diversity but significantly elevates the overall network traffic. The resulting success probabilities and network goodput are determined by the interplay of these mechanisms, as discussed in detail in the numerical results.

5.2 AVERAGE DELAY

Next, we analyze the average delay (or latency), defined as the time from message generation to the time the gateway receives the message successfully for the first time. In this paper, we use the terms delay and latency interchangeably. It should be noted that the transmission duration of an individual LR-FHSS packet is not included in this definition, as it is typically negligible compared to the inter-transmission intervals.

For concatenation, the delay arises from the need to accumulate c messages before transmission. The average delay d_c for a given message in this process is

$$d_c = \frac{\sum_{k=1}^c \lambda^{-1} \cdot (k-1)}{c} = \frac{\lambda^{-1} \cdot (c-1)}{2}, \quad (14)$$

since the k -th message waits $(k-1)\lambda^{-1}$ before transmission, and the average is taken over the c messages in the packet. The delay increases with c , making concatenation less suitable for latency-sensitive applications.

In the case of embedded retransmission, each message is included in multiple consecutive transmissions. The delay d_p depends on the number of failed transmissions before success. The average delay can be expressed as

$$d_p = \frac{\sum_{k=1}^{p-1} (1 - P_P)^k \cdot P_P \cdot \lambda^{-1} \cdot k}{P_S}, \quad (15)$$

where $(1 - P_P)^{k-1} \cdot P_P$ is the probability that the message is successfully received on the k -th attempt, and the delay is normalized by the overall message success probability P_S .

In replication, the message is sent n times using independent packets. The average delay d_n is computed similarly and since n transmissions happen sequentially before the next message, the result is normalized by n .

$$d_n = \frac{\sum_{k=1}^{n-1} (1 - P_P)^k \cdot P_P \cdot \lambda^{-1} \cdot k}{P_S \cdot n}. \quad (16)$$

This normalization reflects that n replicas are sent for each message, before a new message is transmitted for the first time. Unlike transmitting all replicas back-to-back, the replicas are spread within λ^{-1} , which helps mitigate correlated interference patterns that may arise from previous collisions. As with embedded retransmission, delay is influenced by the likelihood of early success, but division by n generally results in a lower average delay per message compared to embedded retransmission for the same P_P and λ .

A unified expression for the average delay $d_{c,p,n}$, considering all three transmission techniques, can be obtained by summing their respective contributions, as

presented in

$$d_{c,p,n} = \frac{\lambda^{-1} \cdot (c-1)}{2} + \frac{\sum_{k=1}^{p-1} (1-P_P)^k \cdot P_P \cdot \lambda^{-1} \cdot c \cdot k}{P_S} + \frac{\sum_{k=1}^{n-1} (1-P_P)^k \cdot P_P \cdot \lambda^{-1} \cdot c \cdot k}{P_S \cdot n}. \quad (17)$$

It is important to note that in both retransmission and replication, the time between packet transmissions is affected by the concatenation factor c , since each retransmitted or replicated packet will have its average interval between packets affected.

5.3 MAXIMUM DELAY

In contrast to the average delay, the maximum delay metric represents the longest possible latency a message may experience before being successfully decoded. While average delay provides insight into long-term expected performance, many applications, though tolerant to some delay, often impose strict limits on acceptable latency. Therefore, evaluating the maximum delay is crucial to ensure system reliability, especially when redundancy techniques are employed.

The maximum delay for concatenation occurs when the first message in the concatenation process needs to wait for the remaining $c-1$ messages to be generated before transmission. This delay is given by

$$d_c^{\max} = \lambda^{-1} \cdot (c-1). \quad (18)$$

For embedded retransmission, the worst-case scenario arises when a message is successfully decoded only on its last retransmission. Therefore, the maximum delay is

$$d_p^{\max} = \lambda^{-1} \cdot (p-1). \quad (19)$$

In replication, the worst-case delay also occurs when a message is successfully decoded on its last transmission, but all replications are transmitted before the next message is generated. As a result, the maximum delay for replication is

$$d_n^{\max} = \lambda^{-1} - \text{ToA}. \quad (20)$$

Similarly to the average delay equation, a unified expression for the maximum delay $d_{c,p,n}^{\max}$ can be calculated by the sum of the individual contributions of each technique, as

$$d_{c,p,n}^{\max} = \lambda^{-1} \cdot (c-1) + \lambda^{-1} \cdot (c+p-2) + \varphi \cdot (\lambda^{-1} \cdot c - \text{ToA}), \quad (21)$$

where the indicator variable φ equals 1 if $n > 1$, and 0 otherwise, since the maximum delay of replication should only influence if such transmission technique is used. Notice that c influences both the embedded retransmission and replication contributions

because, when these techniques are combined, concatenation directly determines the interval between successive transmissions, along with the initial delay before the first packet is transmitted, which is accounted for by the first factor of the equation.

5.4 ENERGY CONSUMPTION

To evaluate the energy efficiency of each transmission technique examined in this study, we developed a model based on real-world end device parameters. Specifically, energy consumption estimations are derived from the Semtech LR1121 transceiver (SEMTECH CORPORATION, 2023), a low-power, long-range end device that supports LR-FHSS modulation. Designed for sub-GHz ISM bands, the LR1121 targets DtS and terrestrial IoT applications, making it an appropriate reference for assessing energy-aware strategies in LR-FHSS networks.

The model incorporates three operational modes: transmission (TX), reception (RX1 and RX2), and sleep. The first reception window (RX1) lasts for a duration of T_{RX1} , the second (RX2) lasts T_{RX2} , and the transmission period lasts for T_{TX} . These durations depend on the specific DR used in each window (SANCHEZ-VITAL *et al.*, 2024).

The total period between transmissions, T , is defined as the average waiting time between packet transmission, which varies with λ and the transmission technique. With concatenation or replication, the period scales proportionally, and thus

$$T = \frac{\lambda \cdot c}{n}. \quad (22)$$

The ToA of a given transmission depends on the transmission method adopted (concatenation, embedded retransmission, replication, regular LR-FHSS), which leads to a given number of headers N and payload fragments F per packet

$$\text{ToA} = F \cdot t_F + N \cdot t_H. \quad (23)$$

Considering that the sleep period T_{Sleep} is

$$T_{\text{Sleep}} = \left(T - \text{ToA} - T_{RX1} - T_{RX2} \right), \quad (24)$$

the average current consumption I_{avg} over the transmission cycle, including the states (I_{RX1} , I_{RX2} , I_{TX} and sleep), becomes

$$I_{\text{avg}} = \frac{T_{\text{Sleep}} \cdot I_{\text{Sleep}} + \text{ToA} \cdot I_{TX} + T_{RX1} \cdot I_{RX1} + T_{RX2} \cdot I_{RX2}}{T}. \quad (25)$$

The Energy per Message (EPM) metric, adapted from the Energy per Packet (EPP) concept in (LIN *et al.*, 2024), quantifies the energy required to successfully deliver a single message:

$$\text{EPM} = \frac{V \cdot I_{\text{avg}} \cdot T}{P_S \cdot c} \cdot n, \quad (26)$$

where V is the supply voltage and P_S is the message success probability. It is important to note that only factors c and n appear in (26). The factor c divides the total energy because each transmitted packet contains c distinct messages, effectively amortizing the energy cost across those messages. In contrast, n multiplies the EPM because a redundant packet is transmitted n times under replication, linearly increasing the total energy required for a single message delivery.

While the factor p also involves transmitting a message multiple times, it does not scale the EPM expression directly. This is because, although each packet contains p messages, the same message is repeated across p different packets. Since we are measuring energy per successfully delivered message, the term P_S naturally reflects the cumulative effect of these repeated opportunities for successful reception.

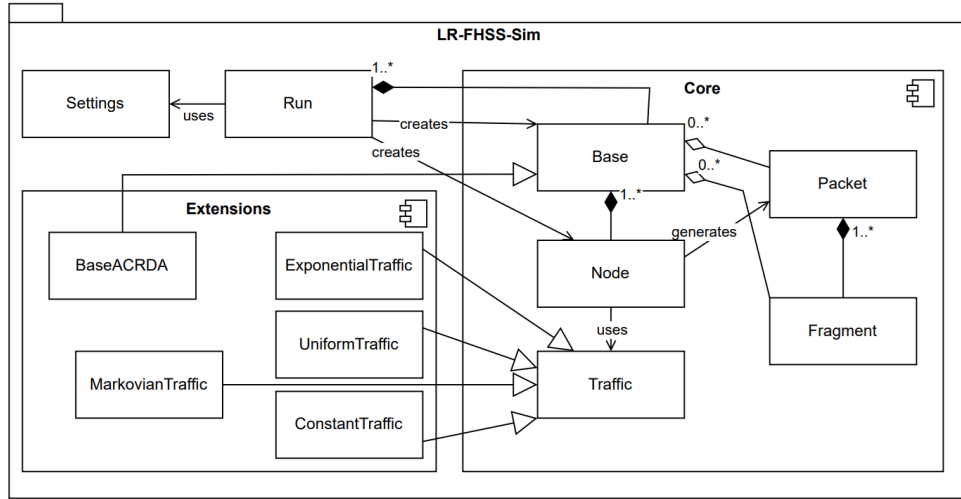
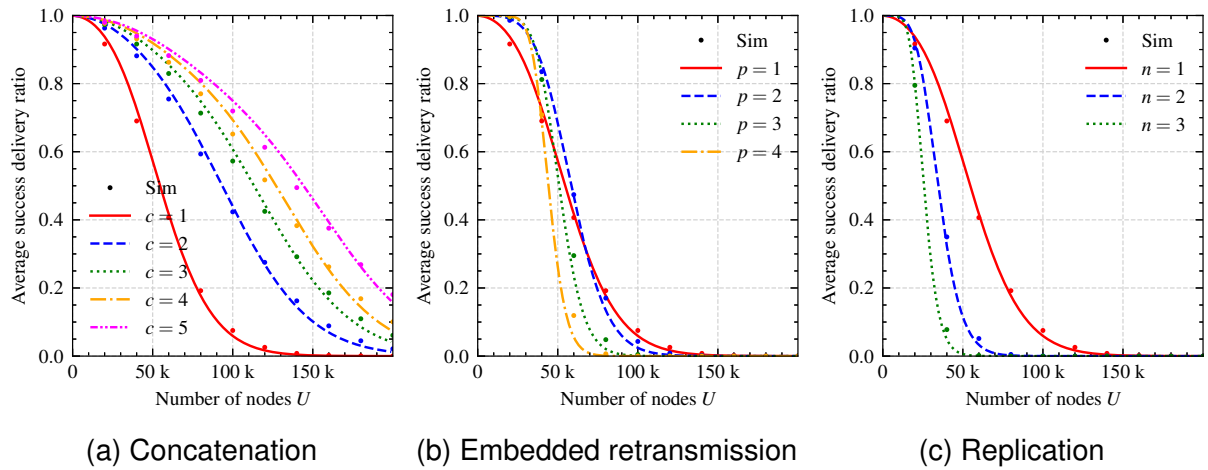
6 RESULTS AND DISCUSSION

This chapter evaluates the performance of the methods previously discussed. To validate the theoretical analysis, we also include computer simulations making use of LR-FHSS-Sim (SOUZA SANT'ANA *et al.*, 2024a), a free and open-source simulator written in Python for LR-FHSS networks. A diagram of main structures of the simulator can be found in Fig. 7. New features were included in the simulator, as to consider the three transmission techniques under investigation in this work.

Unless stated otherwise, we consider messages of $L = 10$ bytes, $\varepsilon = 0.1$ and the LR-FHSS DR8 configuration. We recall that DR8 is characterized by its high robustness due to a CR of $1/3$ and $N = 3$ header repetitions, which makes it suitable for scenarios requiring reliable communication in dense or interference-prone environments. Moreover, we assume that end devices generate traffic following an exponential distribution with an average interval of 900 seconds between transmissions, while the results consider a total of 18,000 seconds of simulation time.

6.1 SUCCESS PROBABILITY

We start by illustrating the individual performance, in terms of success probability, of concatenation, embedded retransmission, and replication for the case of no background traffic and erasure probability of $\varepsilon = 0.1$ in Figure 8. Note that for $c = p = n = 1$ we have the regular LR-FHSS. The goal is to show how the performance of such techniques varies as a function of their basic parameters c , p , and n . Although a 10% erasure probability might appear low in the context of satellite links, we also generated results for more severe conditions (e.g., $\varepsilon = 0.5$ and $\varepsilon = 0.9$), and the resulting behaviours and conclusions remained consistent. First, we note that concatenation improves with c , as long as the maximum payload size has not been reached. That is because the impact of traffic reduction dominates the potential reliability decrease due to a packet transmitting c messages. Embedded retransmission has an optimum parameter p depending on the number of users, showing that there is a trade-off between the increase in reliability offered by this technique and the additional traffic it imposes. Replication showed to be useful only in networks with very low-density of end devices. Moreover, simulation and theoretical results showed good agreement, keeping the same trends and validating the model. The small deviation arises because the theoretical model assumes independent transmissions, ignoring the correlation between header copies and payload fragments. In reality, when one fragment collides, others from the same message are also more likely to collide as well due to the sequential transmission of fragments and the potential overlap in time and frequency with interfering packets. Although different nodes adopt distinct hopping sequences, the constrained number of narrowband channels (each of $\text{OBW} = 488$ Hz) in an LR-FHSS channel and the comparable durations of packets

Figure 7 – Diagram of the LR-FHSS-Sim package (SOUZA SANT'ANA *et al.*, 2024a).Figure 8 – Average message success probability versus number of nodes U , for $\varepsilon = 0.1$ and no background traffic. Lines are obtained from equations, while markers represent simulation points.

increase the likelihood that two packets reuse the same OBW during successive hops, creating a temporal correlation between collision events. This effect is captured by the simulator but not by the collision-independence assumption of the analytical model, which justifies the slight overestimation of the analytical success probability. Finally, note that regular LR-FHSS outperforms replication in most cases, unless in networks with relatively few users (or traffic), while regular LR-FHSS outperforms embedded retransmission for dense networks. This result shows that, since header replication is already part of LR-FHSS configurations, further packet replications generally harm network performance.

A direct comparison of the average success of the three transmission methods is provided in Figure 9, considering only the best-performing parameter for each technique and a combination of the redundant techniques with concatenation. Concatenation outperforms other methods in high-density networks. Additionally, embedded retrans-

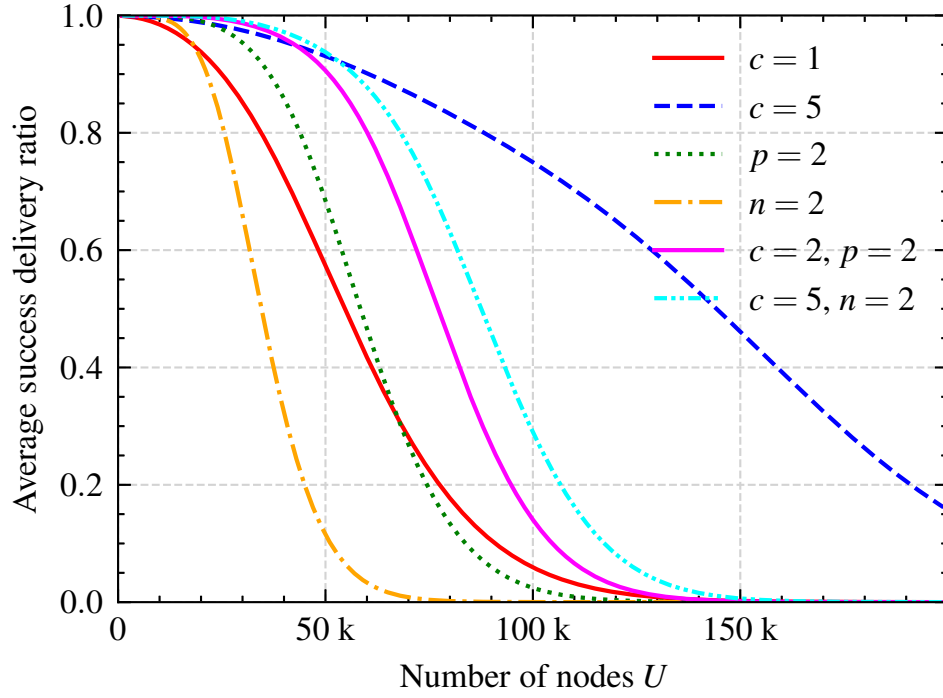


Figure 9 – Average message success probability with $\varepsilon = 0.1$ and no background traffic, considering the best parameter for each technique. Results for combinations of the three techniques are also shown. For instance, $c = 2, p = 2$ means that two messages are concatenated in a single packet and that the concatenated messages are transmitted again using the embedded retransmission technique in a subsequent packet.

mission is superior to replication as it better balances redundancy and network load. When combined with concatenation, both redundant techniques achieve better results than when in isolation, benefiting from the reduced transmission overhead. For instance, $c = 2, p = 2$ in which two messages are concatenated in a single packet and the concatenated messages are transmitted again using the embedded retransmission technique in a subsequent packet performs better than the case of only embedded retransmission with $p = 2$. Notably, replication with concatenation outperforms embedded retransmission with concatenation as it allows for higher c values without exceeding the maximum payload length.

Moreover, Figure 10 shows that the qualitative conclusions remain unchanged even for a longer payload length, such as $L = 25$ bytes. Concatenation significantly outperforms regular LR-FHSS, while replication and embedded retransmission struggle with increased channel traffic. In this figure, only the best performing parameter for replication is considered. Furthermore, note that $c = 2$ and $p = 2$ are the only viable options for concatenation and embedded retransmission, since the maximum payload size for DR8 is 50 bytes (LORA ALLIANCE, 2022). Next, we focus only on a message size of $L = 10$ bytes, which appears suitable for a wide range of IoT monitoring applications.

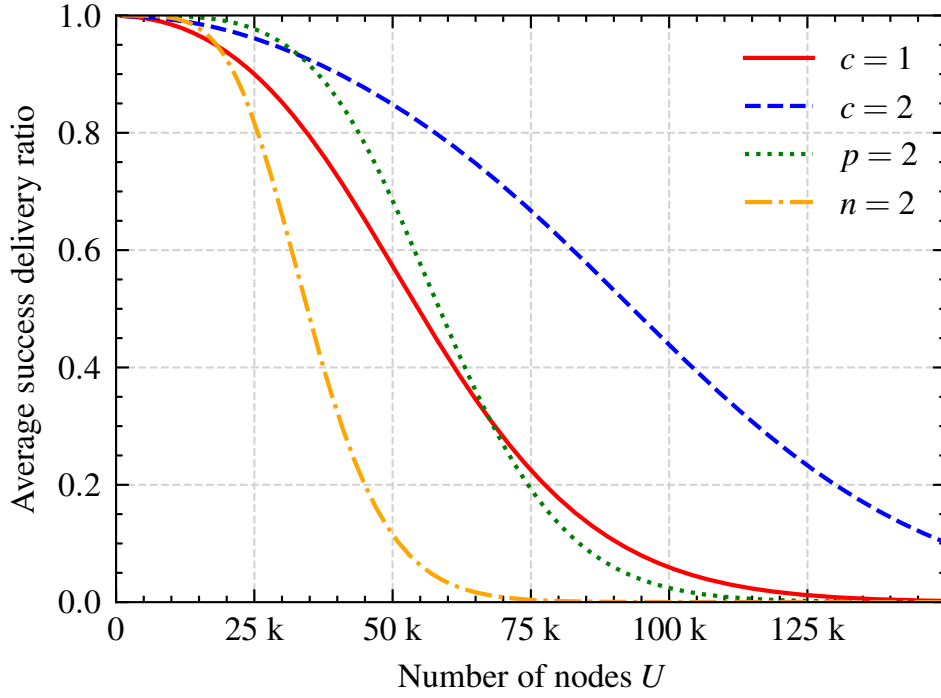


Figure 10 – Average message success probability for $L = 25$ bytes, $\varepsilon = 0.1$ and no background traffic, considering feasible parameters for each technique.

6.2 DELAY

Figure 11 provides a comprehensive comparison of the average and maximum message delay, for transmission techniques with the best parameter settings of Figure 9. As expected, the maximum delay for embedded retransmission and replication remains the same when their parameters have the same values. Furthermore, all maximum delays and the average delay for concatenation remain constant as U increases. In particular, concatenation incurs a significantly higher delay, primarily due to its larger parameter value ($c = 5$) for optimized performance. Its average and maximum delays are much greater than those of embedded retransmission and replication, indicating the trade-off to achieve high reliability. Finally, replication has a lower average delay than embedded retransmission, yet both share the same maximum delay, meeting identical application-specific delay constraints.

6.3 BACKGROUND TRAFFIC

Figure 12 and Figure 13 illustrate the message success probability for end devices applying the transmission techniques investigated in this work and those operating as background traffic for two proportions of background traffic: $\delta = 0.5$ in Figure 12 and $\delta = 0.9$ in Figure 13. Both embedded retransmission and replication exhibit egoistic behavior: they achieve a higher success probability for their own transmissions while causing congestion that degrades the performance of background traffic. As

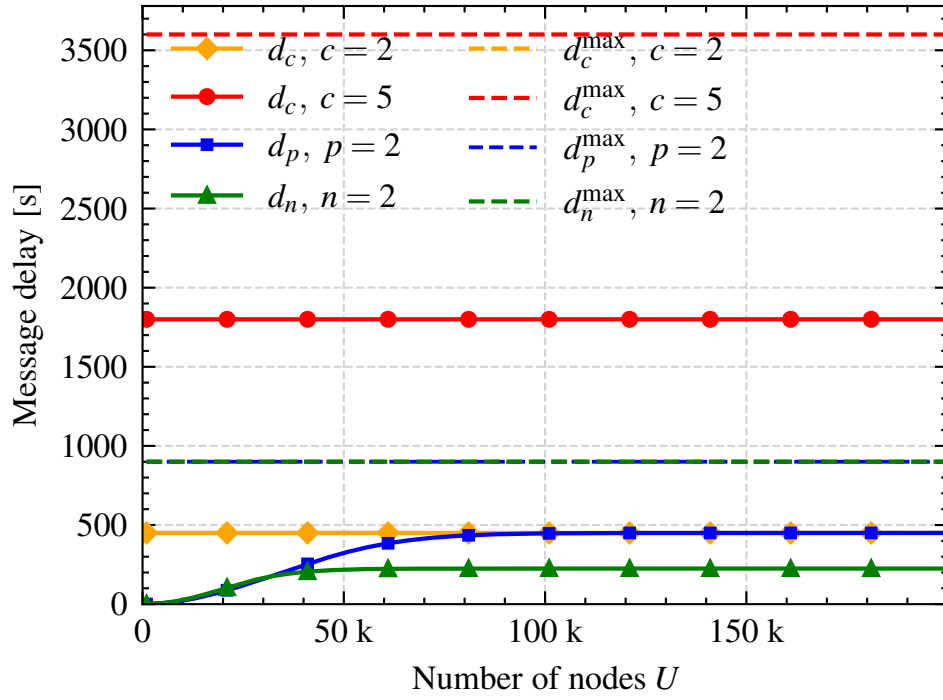
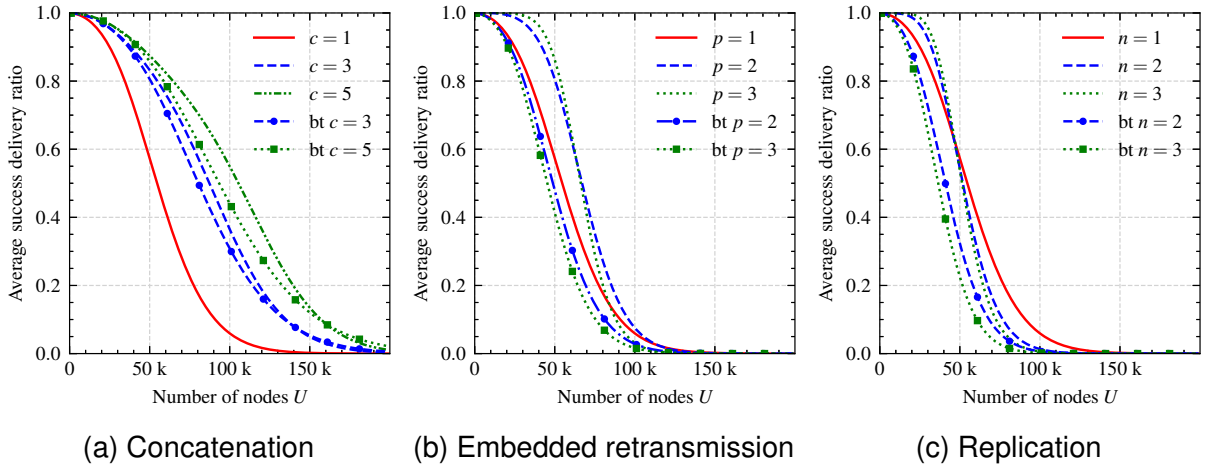
Figure 11 – Average and maximum delay, for $\varepsilon = 0.1$.

Figure 12 – Average success delivery ratio for different techniques with background traffic $\delta = 0.5$ and erasure $\varepsilon = 0.1$. Regular lines represent the performance of the end devices that use one of the transmission techniques discussed in this work, while lines with markers indicate the performance of the background traffic using regular LR-FHSS.

network congestion rises, even optimized end devices face reduced efficiency. Conversely, although concatenation may occasionally be outperformed by embedded retransmission and even replication under specific channel conditions, it consistently demonstrates superior performance compared to standard LR-FHSS transmissions. Importantly, background traffic also experiences improvements under these conditions. Among the examined techniques, concatenation stands out as it does not adversely affect background traffic while simultaneously offering benefits to the end devices that

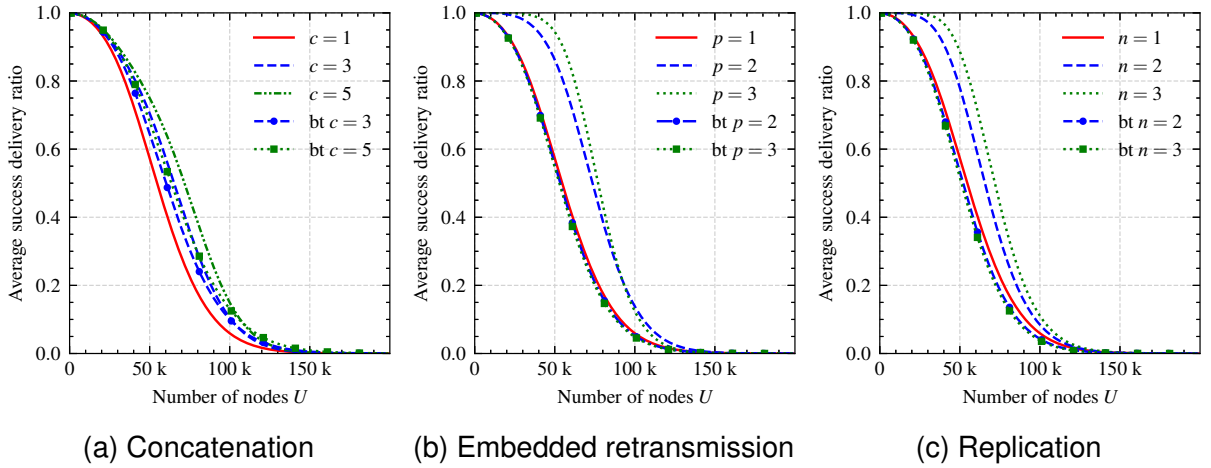


Figure 13 – Average success delivery ratio for different techniques with background traffic $\delta = 0.9$ and erasure $\varepsilon = 0.1$. Regular lines represent the performance of the end devices that use one of the transmission techniques discussed in this work, while lines with markers indicate the performance of the background traffic using regular LR-FHSS.

employ this method. Furthermore, when only a small fraction of end devices employ embedded retransmission (*i.e.* when δ is close to 1), this technique proves effective in ensuring good reliability for those end devices. Replication, however, exhibits poorer performance. It should be noted that while concatenation and embedded retransmission generally outperform replication, their applicability is limited by payload size limitations, which cannot exceed 50 bytes in some LR-FHSS configurations (LORA ALLIANCE, 2022). Consequently, for messages larger than 25 bytes, these techniques are not viable.

6.4 ENERGY CONSUMPTION

The energy model uses current consumption values taken from the LR1121 datasheet (SEMTECH CORPORATION, 2023). In transmission mode at +14 dBm using the low-power amplifier, the end device draws 28 mA during the ToA. Since we assume the use of DR8 in the uplink, and following the EU863-870 MHz regional parameters, the network employs DR1 for RX1 and DR0 for RX2, drawing 5.7 mA from the device in each window, which last for $T_{RX1} = 0.098304$ s and $T_{RX2} = 0.033024$ s, respectively (SANCHEZ-VITAL *et al.*, 2024). Between transmissions, the end device enters a sleep mode with a current draw of 1.6 μ A.

Figure 14 presents the estimated EPM for regular LR-FHSS, concatenation ($c = 5$), embedded retransmission ($p = 2$), and replication ($n = 2$). The results demonstrate that, despite a longer ToA for each transmission, concatenation consistently achieves the lowest EPM due to its ability to aggregate multiple messages into a single packet, thereby reducing the number of transmissions required while also saving on

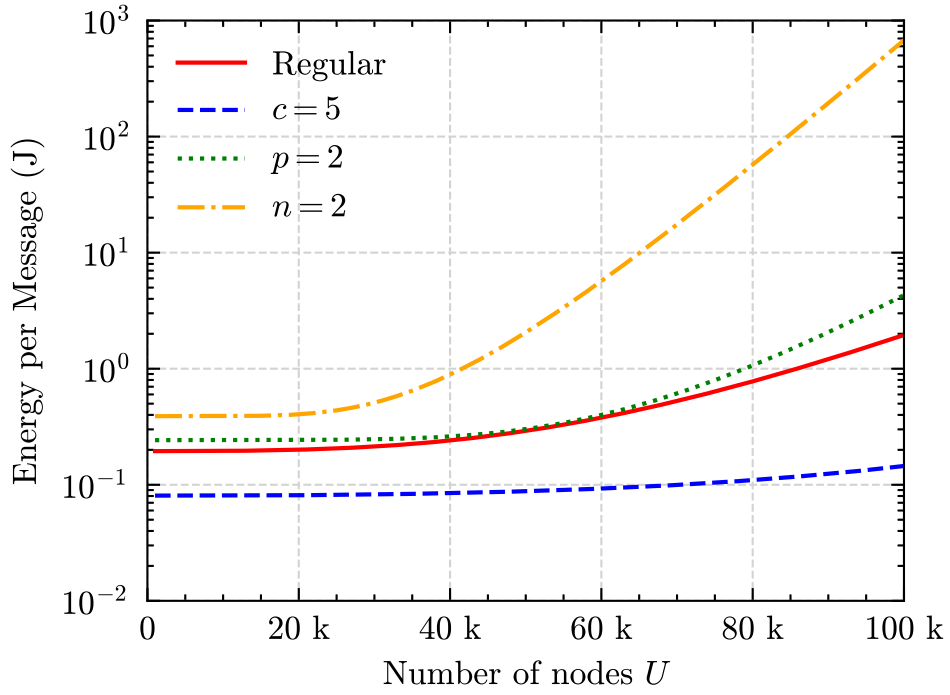


Figure 14 – EPM for regular LR-FHSS with $\varepsilon = 0.1$, concatenation ($c = 5$), embedded retransmission ($p = 2$), and replication ($n = 2$), as a function of the number of end devices.

overall ToA. As network density increases, the widening gap in success probability between concatenation and the other techniques further enhances its energy efficiency comparatively. Regular LR-FHSS performs competitively in low-density environments but gradually increases its energy cost per message as collisions become more frequent. In contrast, embedded retransmission and replication typically demonstrate the highest EPM values, particularly as network density increases, due to their inherently redundant transmission strategies. These approaches multiply the number of transmissions per message, substantially increasing energy consumption.

6.5 SUMMARY AND DISCUSSION OF RESULTS

Concatenation consistently achieves the highest message success probability across the evaluated scenarios while simultaneously reducing network congestion and energy consumption. This improvement is primarily attributed to its ability to aggregate multiple messages into a single packet, thereby reducing the total number of transmissions required for the same volume of data. By lowering channel occupancy and minimizing the protocol overhead per message, concatenation contributes to more efficient utilization of network resources. However, this advantage comes at the cost of increased latency, as messages must be buffered until their required number is accumulated before transmission. Consequently, concatenation is particularly suitable for LR-FHSS-based applications that allow aggregating and transmitting historical data,

such as wildlife tracking, where data can be stored and later transmitted (SOMMER *et al.*, 2018), waste management, and environmental monitoring (ALIPIO *et al.*, 2024). However, it is less appropriate for event-driven or near real-time applications, where each message needs to be transmitted upon generation. In such cases, even if latency requirements are not extremely stringent, the need for prompt delivery and the lack of benefit from buffering data make concatenation a less practical choice.

Embedded retransmission, in contrast, introduces redundancy directly into each payload by embedding previously transmitted messages alongside the new one. This design enhances reliability by increasing the likelihood that at least one copy of each message reaches the gateway successfully, even in the presence of erasures and collisions. The technique shows particular promise in networks with moderate traffic, where redundancy effectively mitigates channel impairments without overly saturating the network. However, in dense networks, the increased packet size and ToA elevate the probability of packet collisions. As such, the performance gains diminish in high-density environments, underscoring the importance of carefully tuning the p factor relative to network load and application requirements. Embedded retransmission is suitable for applications such as maritime traffic monitoring, where a few thousands of vessels send frequent short packets, and smart agriculture, where logging data are still of some importance.

Replication offers a different trade-off by transmitting independent copies of each packet across multiple time slots, leveraging time diversity to improve resilience against channel impairments. Although this strategy can improve reliability in highly dynamic environments, it significantly increases the network load and energy consumption. The simulations reveal that replication tends to perform poorly in dense deployments due to the compounded effect of increased packet traffic and collisions, often resulting in lower message success probabilities compared to the baseline LR-FHSS configuration. Moreover, the added energy burden makes replication a suboptimal choice for energy-constrained IoT devices that rely on long battery lifetimes. These results highlight the importance of matching transmission techniques with specific application requirements and network conditions. However, event-driven applications, such as precision agriculture, are better suited for replication, as it can increase the chances that messages are received without additional delays, like the other alternatives. Finally, repetition-based techniques like replication and embedded retransmission can be a good choice when high reliability is required for a limited number of devices.

7 CONCLUSION

The analysis of concatenation, embedded retransmission, and replication techniques in LR-FHSS networks has shown that each technique presents distinct strengths and weaknesses. Concatenation achieves the highest success probability while positively impacting channel traffic and reducing energy consumption, but its applicability is limited to use cases tolerant to higher delays. Most typical IoT applications can tolerate higher delays. Embedded retransmission improves resistance to erasures and collisions, though its effectiveness is highly dependent on the density of the network. Additionally, it introduces higher delays compared to regular LR-FHSS. Replication provides redundancy, but has not proven to be an efficient choice in any of the scenarios evaluated. In general, this study provides valuable insight into the trade-offs involved in optimizing LR-FHSS networks across various configurations. These findings can assist network designers and researchers in developing more efficient and resilient communication systems.

7.1 FUTURE WORKS

In future works, several directions can be explored to enhance LR-FHSS network performance. First, advanced hybrid transmission schemes that dynamically adjust transmission methods based on network conditions and delay requirements could be investigated. Additionally, experimental validation through real-world deployments and hardware-based testing is crucial to confirm the practical feasibility and effectiveness of the proposed techniques in large-scale LR-FHSS networks. Finally, we plan to design a message transmission technique which only sends highly relevant messages by taking into account the running application. With this approach, we intend to reduce traffic congestion and increase reliability, while also accounting for the impact at the application layer, which closely aligns with the emerging paradigms of Goal-Oriented Communications, where the transmission priority is not placed on raw throughput but on the value the delivered information. This prioritisation of the most informative or time-critical updates would allow the network to achieve better scalability without overwhelming the spectrum. Future work will, therefore, focus on integrating AoI or goal-oriented mechanisms into LR-FHSS, providing an approach that bridges message transmission techniques with application-level relevance. Such integration has the potential to yield significant performance gains in both reliability and efficiency, and we envision this as an important next step toward the practical deployment of LR-FHSS in massive IoT scenarios.

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