

A Unified Network Coding Framework for LR-FHSS Headers and Payloads

Bruno Henrique Scandelari, João Luiz Rebelatto, Guilherme Luiz Moritz, Richard Demo Souza, Glauber Brante and Bartolomeu F. Uchôa-Filho

Abstract—Long-Range Frequency-Hopping Spread Spectrum (LR-FHSS) improves the upload capacity of LoRaWAN networks by fragmenting the payload and transmitting multiple header copies. This method, along with frequency hopping, helps towards mitigating interference. Previous works have identified headers as the primary bottleneck in LR-FHSS networks, and then proposed techniques to enhance header protection. However, that assumption is not universally valid and depends on factors such as payload length, number of end-devices, and channel conditions. In scenarios with small payloads, vulnerable links or high network density, the payload's error probability can become the dominant factor. This paper first identifies this gap, and then proposes a novel scheme, Full Network Coding (LR-FHSS-FNC), which extends the header network coding concept recently proposed in the literature also to the payload fragments. Our results show that LR-FHSS-FNC provides considerable performance gains precisely in these payload-dominant scenarios, further enhancing network reliability and scalability without requiring additional spectral or power resources.

Keywords—IoT, LoRa, LR-FHSS, Network Coding.

I. INTRODUCTION

Low Power Wide Area Networks (LPWANs) represent a set of technologies to enable long-range and low-power communication, crucial in the scope of Internet-of-Things (IoT) and widely employed in applications such as smart cities, industrial automation, healthcare, and precision agriculture [1]. Among the most prominent LPWAN technologies, Chirp Spread Spectrum (CSS)-based LoRa has emerged as a key solution [2], leading to the development of the LoRaWAN protocol by the LoRa Alliance® [3]. Although LoRaWAN is widely adopted, its ALOHA-based MAC layer presents scalability challenges in single-gateway dense deployments due to the inherent risk of packet collisions [4], [5].

To mitigate these scalability issues, the LoRa Alliance recently introduced the Long Range Frequency Hopping Spread Spectrum (LR-FHSS) technique [6] to the upload of LoRaWAN networks. This modulation improves network robustness by fragmenting data packets into smaller segments and distributing them across multiple frequency channels. Recent results have shown that this payload fragmentation of LR-FHSS, along with its capability to retransmit header copies,

leads to a significant increase in the number of supported devices compared to legacy LoRa systems [7]–[10].

Initial analysis, such as that in [8], suggested that the system's reliability is often dictated by the successful reception of the packet headers. Based on this premise, the work in [11] proposed an effective inter-header coding scheme, referred to as network-coded LR-FHSS (LR-FHSS-NC), that significantly improved header resiliency against collisions and erasures by means of network coding [12], thereby boosting the total packet success rate.

However, assuming the header is the main bottleneck in LR-FHSS is not always valid. A significant issue arises when the probability of payload error leads to system outages. This work finds that this occurs in complex scenarios that involve variables such as network load, payload length, and channel reliability. In particular, when the offered traffic approaches the system capacity, or when long payloads are transmitted over channels with non-negligible fading and interference, the likelihood that at least one payload fragment is corrupted can dominate the overall packet error rate. As a consequence, even perfectly decoded headers are not sufficient to guarantee successful end-to-end communication, and the system performance becomes payload-limited rather than header-limited.

To address this limitation, we conduct a detailed analysis of the interplay between these parameters, showing how variations in the number of devices, the payload length, and the underlying propagation conditions jointly impact the probability of payload failure. Motivated by these findings, we then propose expanding the network-coded scheme from [11], originally applied only to headers, to include payload fragments. By coding across multiple payload fragments and transmissions, the receiver can exploit additional redundancy not only in the control information but also in the user data, thereby increasing robustness against isolated errors and collisions. This generalized coding framework enables graceful performance degradation under heavy load or harsh channel conditions and more balanced protection of header and payload, improving reliability and availability in LR-FHSS-based systems.

The contributions of this work are summarized as follows:

- We identify the situations where the payload dominates the packet error rate in LR-FHSS networks, in terms of payload length, number of end-devices (EDs) and channel conditions. We conclude that while payload generally dominates in poor channel conditions and dense networks, its relationship to payload length is nontrivial and involves other factors;
- We extend the LR-FHSS-NC scheme from [11] by apply-

B. H. Scandelari, J. L. Rebelatto, and G. Brante, CPGEI, UTFPR, Curitiba-PR, e-mail: {brunoscandelari@alunos.utfpr.edu.br, jlrebelatto@utfpr.edu.br, gbrante@utfpr.edu.br}; G. L. Moritz, PPGSE, UTFPR, Curitiba-PR, e-mail: moritz@utfpr.edu.br; R. D. Souza, PPGEI, UFSC, Florianópolis-SC, e-mail: richard.demo@ufsc.br; B. F. Uchôa-Filho, IEET, IEE, ITA, São José dos Campos-SP, e-mail: bartolomeu@ita.br. This work was supported by CNPq, processes no. 300705/2026-3, 317368/2025-7, 306359/2025-1, 307222/2023-3, 403124/2023-9 and 409179/2024-8 (INCT-STREAM).

TABLE I: LR-FHSS main parameters (ETSI) [6].

		DR8	DR9
Operating Channel Width (OCW)		147 kHz	
Occupied Bandwidth (OBW)		488 Hz	
Usable Channels per ED		35	
Total Physical Channels	C	280 (8×35)	
Coding rate	R	1/3	2/3
Number of header replicas	N_H	3	2
Duration of each header replica [s]	T_H		0.233
Duration of each payload fragment [s]	T_{frag}		0.1024
Payload duration [s]	T_L	$T_{frag} \left\lceil \frac{PL+3}{2} \right\rceil$	$T_{frag} \left\lceil \frac{PL+3}{4} \right\rceil$
Number of payload fragments	N_L	$\left\lceil \frac{T_L}{T_{frag}} \right\rceil$	
Duration of a packet (time-on-air) [s]	ToA	$N_H T_H + T_L$	
Maximum duty cycle	ρ	0.01 (1%)	
Average pkts/hour/device	$\mathcal{P}_{hour}$	3600/ ρ /ToA	

ing NC combinations also to payload fragments, creating the so-called LR-FHSS-FNC scheme;

- We show that the proposed scheme achieves reduced error levels over LR-FHSS-NC without requiring additional bandwidth or delay.

II. LR-FHSS

LR-FHSS is a fast frequency-hopping spread spectrum (FHSS) modulation for the uplink of LoRaWAN networks, introduced in [6]. In LR-FHSS, the bandwidth is divided into several Operating Channel Width (OCW) channels, whose bandwidths depend on regional regulations [6]. The OCW channels are subdivided into Occupied Band Width (OBW) channels, each with a bandwidth of 488 Hz. An ED transmits in one OBW channel at a time, following a frequency hopping pattern from a pseudo-random number generator [7].

Each packet consists of a header, which carries the essential decoding information (including the hopping pattern), and a payload, which contains the ED data. The payload is channel-coded and divided into multiple fragments prior to transmission. Multiple header replicas and encoded payload fragments are then transmitted, with each packet element¹ hopping to a different channel within the OCW every $T_H = 233.472$ ms for headers and $T_{frag} = 102.4$ ms for payload fragments². The standard also includes two different data rates (DR8 and DR9), which, along with the number of payload bytes PL, influence the time-on-air (ToA) as [6]

$$\text{ToA} = N_H T_H + T_{frag} \left\lceil \frac{PL + 3}{6R} \right\rceil, \quad (1)$$

where R is the coding rate of the payload error correcting code, and N_H is the number of transmitted header replicas, whose values are presented in Table I for both data rates [6].

A. LR-FHSS Packet Error Probability (PEP)

Let μ be the average inter-arrival time of packet elements within a one-hour period, which depends on the number of EDs $\mathcal{N}$ and the average number of packets per hour per device $\mathcal{P}_{hour}$ [8]. In particular, one has that $\mu_i = 3600/(\mathcal{N} \mathcal{P}_{hour} N_i)$,

¹We refer to a packet *element* as a general term encompassing either a payload fragment or a header replica.

²For countries that follow the European Telecommunications Standards Institute (ETSI).

for $i \in \{H, L\}$, where the sub-index H refers to headers and L to payloads, and thus N_L is the number of payload fragments per packet.

Let us consider that packet elements are subject to erasures, assumed independent and identically distributed (i.i.d.) in time, frequency, or space, with an erasure probability ϵ . Note that such an erasure probability model has been extensively used in the analysis of ALOHA schemes [11], [13], providing a good balance between mathematical tractability and modeling of fading and shadowing losses. Then, the average number of packet elements arriving at the gateway during the header and the payload transmissions are, respectively³ [8],

$$A_H = \left[\frac{1}{\mu_H} (2T_H) + \frac{1}{\mu_L} (T_H + T_{frag}) \right] (1 - \epsilon), \quad (2a)$$

$$A_L = \left[\frac{1}{\mu_L} (2T_{frag}) + \frac{1}{\mu_H} (T_H + T_{frag}) \right] (1 - \epsilon). \quad (2b)$$

Let p_i represent the probability of successfully receiving a single packet element, for $i \in \{H, L\}$. Then, one has that

$$p_i = \left(1 - \frac{1}{C} \right)^{A_i - 1} (1 - \epsilon), \quad (3)$$

where C represents the number of channels within an OCW channel for frequency hopping (see Table I).

A packet is considered successfully received at the destination when two independent events occur simultaneously [8]: *i*) at least one among the N_H header replicas is received without collision, which happens with probability

$$P_H = 1 - (1 - p_H)^{N_H}; \quad (4)$$

and *ii*) at least $R N_L$ payload fragments are correctly received, whose probability of occurrence is calculated as

$$P_L = \sum_{n=R N_L}^{N_L} \binom{N_L}{n} p_L^n (1 - p_L)^{N_L - n}. \quad (5)$$

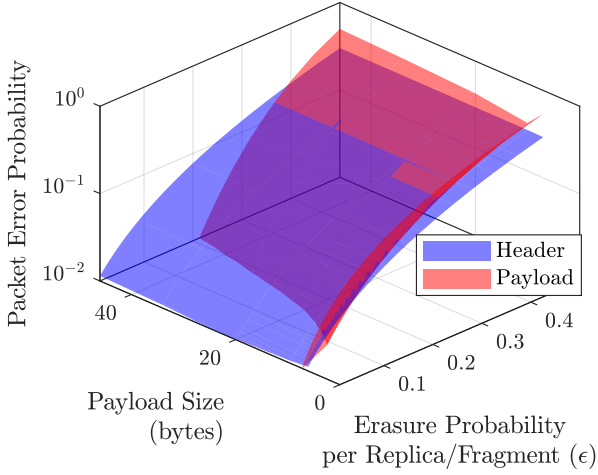
From (4)-(5), the packet error probability (PEP) is then

$$\text{PEP} = 1 - P_H P_L. \quad (6)$$

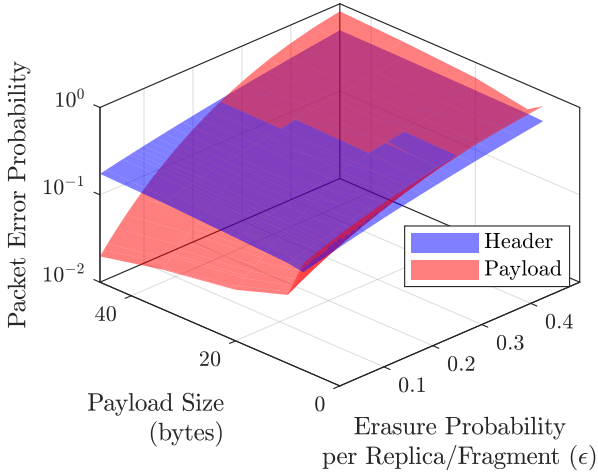
1) Individual Influence of Header and Payload in (6):

Fig. 1 presents the individual error probabilities of headers and payloads obtained respectively from the complements of (4) and (5), when considering the standard LR-FHSS framework under DR9. A comparison of the header error probability and the payload error probability reveals a clear trade-off that depends on both the payload length and the channel quality. For small payloads, the payload error is consistently the dominant factor. This occurs because with very few fragments, the payload is statistically volatile; the random loss of just one or two fragments due to channel erasure is enough to cause a decoding failure. As the payload length increases under good channel conditions (low ϵ), this trend inverts. The payload becomes extremely reliable due to the Law of Large Numbers, and its error rate drops to near zero. In this region, the header

³For simplicity, we consider that all the payload fragments have the same duration, which is achieved when PL is multiple of N_L .



(a) 1000 EDs.



(b) 5000 EDs.

Fig. 1: Comparison between the individual header and payload error probabilities of standard LR-FHSS (DR9), as a function of the payload length (PL) and erasure probability per packet element (ϵ), and considering (a) 1000 EDs and (b) 5000 EDs.

error, while small, is significantly larger and becomes the dominant bottleneck of the system.

This dynamic is reversed again under poor channel conditions (high ϵ). As the erasure probability for each fragment becomes severe (e.g., 40-50%), the payload error rate degrades far more rapidly than the header. This is because the payload is composed of many fragments, and the high probability of failure accumulates across all of them, making the entire payload statistically likely to fail. In these high-erasure scenarios, payload error once again becomes the dominant cause of packet loss, regardless of its size.

Scaling the network from 1000 (Fig 1a) to 5000 (Fig 1b) EDs shifts the bottleneck from the header to the payload. More devices increase congestion and collision probability, affecting the payload more due to its lower redundancy level. Thus, as collisions rise, the payload success rate declines more than

TABLE II: Summary of Scenarios for Dominant Error Sources.

Dominant error source	Scenarios where it dominates
Payload	small payloads (due to high statistical variance); large payloads in poor channel conditions; dense, collision-prone networks.
Header	large payloads in low-density networks, good-channel conditions.

the header's, expanding the error-prone region and making payload protection crucial for reliability in large deployments. Table II summarizes this discussion.

Nonetheless, it is important to note that when the performance of headers and payloads is comparable (*i.e.*, of the same magnitude), they both significantly impact the overall packet error rate. Also, a similar trend is observed when operating under DR8, and omitted here for brevity.

III. LR-FHSS-FNC: A UNIFIED NC FRAMEWORK

Based on [8], which indicated that headers may dominate the packet failure rate, the work in [11] introduced LR-FHSS-NC to improve header reliability using network coding [12]. In that proposed scheme, instead of transmitting the headers of each packet independently, an ED first accumulates a block of δ packets. It then transmits a total of δN_H (distinct) linear combinations of these δ headers.

Assuming that the coefficients are chosen in a way that all the combinations are linearly independent (which can be ensured through the use of a maximum distance separable - MDS - code [14]), one has a system of δN_H equations and δ variables. Thus, such a system can be solved by correctly receiving *at least* δ out of the δN_H (distinct) linear combinations. Since the probability of correctly receiving n individual coded replicas is equal to $\binom{\delta N_H}{n} p_H^n (1 - p_H)^{\delta N_H - n}$, it is shown in [11] that the probability of correctly receiving a header becomes

$$P_H(N_H, \delta) = \sum_{n=\delta}^{\delta N_H} \binom{\delta N_H}{n} p_H^n (1 - p_H)^{\delta N_H - n}, \quad (7)$$

where p_H is the individual probability of successfully receiving a coded replica from (3), and $\binom{a}{b}$ represents the binomial coefficient. The key advantage of this approach is its new decoding condition. In standard LR-FHSS, a header is lost if all its N_H replicas fail, as in (4). In LR-FHSS-NC, the receiver needs only any δ of the δN_H coded replicas to recover all δ original packets' headers. This provides significant diversity gain. For instance, with $\delta = 2$ and $N_H = 3$, the system sends six replicas but needs any two for successful decoding. This makes the header block highly resilient to partial collisions and channel erasures, as losing five of the six replicas is much less likely than losing all from three.

A. What About the Payload Fragments?

The LR-FHSS-NC scheme from [11] assumes headers cause most packet errors and ignores extra payload protection,

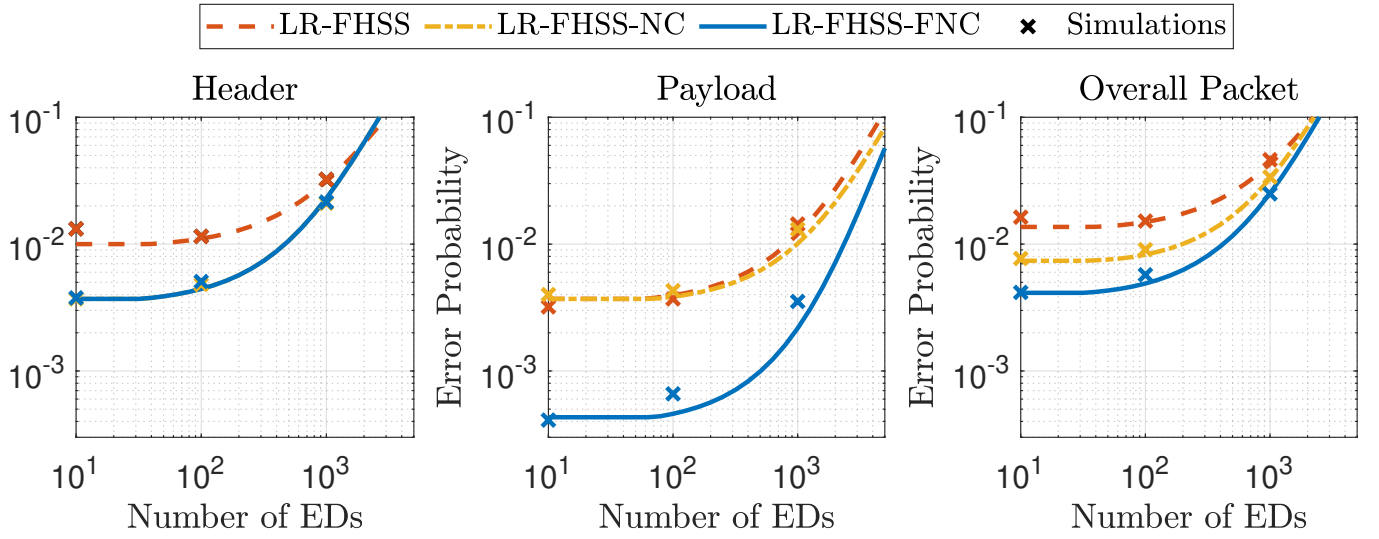


Fig. 2: Error Probability of Header (left), Payload (middle) and Packet (right) vs. number of EDs, for LR-FHSS, LR-FHSS-NC and LR-FHSS-FNC. $\delta=2$, $PL=9$, $\epsilon=0.1$.

though fragments from different packets are simultaneously available. These combinations could likewise apply to payload fragments without extra delay or throughput⁴.

In the herein proposed LR-FHSS-FNC, network coding is also applied to the payload, after it is channel encoded and split into N_L fragments. Combinations occur packet-by-packet, which need to have the same length: each packet's first fragment combines only with first fragments from other packets, and so on for all slots. This method allows efficient payload recovery by solving N_L independent equations.

1) *Analytical Performance of LR-FHSS-FNC*: The PEP of the unified LR-FHSS-FNC scheme is also obtained from (6), with the header success probability given by (7) and the success probability of the payload fragments now obtained as from Proposition 1.

Proposition 1. *The probability of correctly receiving the payload in LR-FHSS-FNC with parameters N_L , R , and δ is*

$$P_L(N_L, R, \delta) = \sum_{n=\delta RN_L}^{\delta N_L} \binom{\delta N_L}{n} p_L^n (1 - p_L)^{\delta N_L - n}, \quad (8)$$

where p_L is the fragment success probability from (3).

Proof. Each packet needs RN_L fragments to be decoded. Therefore, δRN_L successful coded fragments must be obtained from the pool of δN_L . The probability in (8) is the binomial sum for receiving at least this number of fragments. $\square$

Example: In a DR9 scenario, a 9-byte payload is split into three fragments ($N_L = 3$), with two required for decoding. In standard LR-FHSS, Packet A is lost if two fragments are erased, even if Packet B is perfectly received. In LR-FHSS-FNC, with $\delta = 2$, six combined fragments are generated, of

which any four suffice. For example, if only one fragment of Packet A but all three fragments of Packet B are correctly received, four valid fragments remain, enabling recovery of both payloads and showing resilience to localized errors.

IV. NUMERICAL RESULTS

In this section, we present some numerical results to evaluate the performance of the proposed scheme. Unless stated otherwise, we adopt the ETSI parameters presented in Table I.

Fig. 2 presents the error probability of headers (left), payload (middle) and entire packet (right). One can see that even though the error rate is dominated by the headers (comparing the figures on the left and in the middle), improving the payload protection by means of LR-FHSS-FNC also reduces the packet error probability (right), since the headers and payload individually experience an error in the same magnitude. Moreover, it is evident that the analytical results agree well with the simulations, reproducing the same overall trends with good accuracy.

The number of supported EDs for a target PEP is presented in Fig. 3, as a function of the erasure probability ϵ , when taking into account two different payload sizes, namely $PL \in \{5, 21\}$ bytes. As expected, LR-FHSS-FNC outperforms other schemes in the entire range for small payloads. When PL increases, the advantage of the proposed scheme is pronounced when the channel deteriorates (*i.e.*, when ϵ increases). For small ϵ values and large payload sizes, the partial recovery of independent standard packets may be more efficient than the strict, all-or-nothing success criterion of NC-aided schemes.

Finally, note that the proposed scheme adds no extra delay compared to LR-FHSS-NC [11], which, in turn, imposes an average additional delay of $(\delta - 1)T/2$ when compared to LR-FHSS, with T as the average interval between transmissions.

⁴One just needs the additional processing inherent to the network coding operation, which can be performed by means of Gaussian elimination similarly to the header replicas [11].

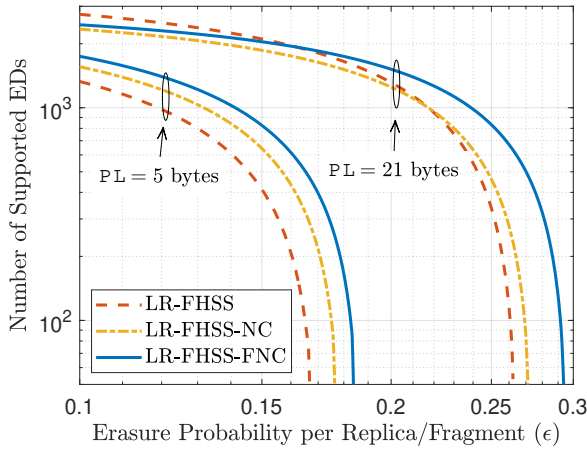


Fig. 3: Number of supported EDs vs. ϵ for a target $\text{PEP} = 0.1$, for standard LR-FHSS, LR-FHSS-NC (with $\delta = 2$) and LR-FHSS-FNC (with $\delta = 2$). Payload length $\text{PL} \in \{5, 21\}$.

V. CONCLUSION

In this work, we show that header failure is not always the main bottleneck in LR-FHSS networks, as commonly assumed in the literature. Then, we introduced LR-FHSS-FNC, a unified network-coded-aided scheme, in which both header replicas and payload fragments of multiple packets are linearly combined. Building on an erasure-based characterization, we derived the corresponding packet error probability and validated the analysis via simulations, showing a close match in the overall trends. The numerical results show that jointly protecting header and payload yields packet-level gains and that LR-FHSS-FNC supports more end devices for a given reliability target, especially under high erasure probability and with short payloads.

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