On the Support of the 2.4 GHz Band in the LoRaWAN Standard

Giampaolo Cuozzo, Riccardo Marini, Chiara Buratti, and Konstantin Mikhaylov

Abstract

The introduction of LoRa chipsets operating in the 2.4 GHz band paves the way to unprecedented performance enhancements compared to their sub GHz counterparts, attributed to factors such as the absence of duty cycle constraints and higher data rates. Despite its potential benefits for Internet of Thing (IoT) applications, the LoRa Alliance has not yet proposed the integration of this new frequency spectrum into the LoRaWAN standard. Addressing this gap, this article proposes a roadmap for the evolution of the LoRaWAN standard, outlining three stages for seamless integration of the 2.4 GHz LoRa version. These stages are sequenced based on implementation complexity, starting from the current LoRaWAN standard (Stage 0), moving to the coexistence of two separate LoRaWAN networks (Stage 1), and ending with a single LoRaWAN network capable of supporting both sub GHz and 2.4 GHz bands (Stage 2). Additionally, the document enumerates all possible implementation options for each stage and outlines the main modifications required in the documents of the LoRaWAN standard. Through LoRaWAN-compliant simulation results, we demonstrate the performance advantages of the proposed multi-band approach over the existing LoRaWAN standard for the first stage of the suggested roadmap. Finally, the article discusses the challenges associated with the proposed roadmap and identifies corresponding research gaps to be addressed in the future.

Introduction

LoRaWAN is the prominent Low Power Wide Area Network (LPWAN) technology and one of the most widely spread solutions for Internet of Things (IoT) applications [1], where sensors and/or actuator boards, referred to as End Devices (EDs), communicate with the Network Server (NS) by means of fixed radio stations, also known as Gateways (GWs) [2]. The success of LoRaWAN stems from its design, which utilizes LoRa technology at the Physical (PHY) layer [3] to minimize complexity, cost, and energy consumption while maximizing transmission range. The standardization of LoRaWAN was initiated by Semtech, an American company holding the patent for the synthesizer used to generate the modulated signal, and later adopted by the LoRa Alliance, an organization of companies that leads the standardization and harmonization processes of LoRaWAN.

LoRaWAN works in the sub GHz Industrial, Scientific and Medical (ISM) spectrum, where the bands are allocated on a country-by-country basis (Fig. 1). Despite its widespread adoption, LoRaWAN currently faces limitations for highly demanding IoT applications (e.g., smart manufacturing) due to the relatively narrow bands available in the sub GHz spectrum and duty cycle constraints. As a first step to overcome these issues, in 2017, Semtech introduced LoRa chipsets operating in the 2.4 GHz ISM spectrum [4]. However, at the time of writing, this frequency range is not included in the standard LoRaWAN frequency plans, despite its potential benefits given by the larger bandwidths, absence of duty cycle constraints, and improved miniaturization properties [5]. Furthermore, this technology might have the potential to outperform other state-of-the-art solutions operating in the same band, such as Wi-Fi and 802.15.4, thanks to its inherent flexibility and robustness against interference provided by chirp-based modulation [3].

This key contribution of this work is the roadmap for evolving the LoRaWAN standard to incorporate the 2.4 GHz LoRa version as an additional frequency range to be used. The proposed roadmap comprises three stages based on implementation complexity and integration simplicity. Stage 0 corresponds to the current LoRaWAN standard operating solely in the sub GHz ISM spectrum. In Stage 1, we envisage the deployment of 2.4 GHz GWs as hot-spot coverage extensions to address the shorter transmission range associated with this frequency band. Subsequently, Stage 2 leverages the concept of Relays (RLs) recently introduced by the LoRa Alliance [6], while enabling and extending it to 2.4 GHz band. This empowers EDs to operate in this frequency as forwarding entities to maximize network performance. Moreover, the article outlines all possible implementation options for each stage, spanning from architectural to protocol aspects, and identifies the main modifications required in the current LoRaWAN standard documents to support the proposed roadmap. Through LoRaWAN-compliant simulation results, and as a means to support our claims, we demonstrate the illustrative performance advantages of the proposed multi band approach over the existing LoRaWAN standard for Stage 1 of the roadmap. As a further notable contribution, the document finally discusses the challenges associated with the proposed roadmap and identifies research gaps for future exploration.

ISSN: 2576-3180
Digital Object Identifier: 10.1109/IOTM.001.2400054

Giampaolo Cuozzo and Riccardo Marini are with CNIT, Italy; Chiara Buratti is with the University of Bologna, Italy; Konstantin Mikhaylov is with the University of Oulu, Finland.

The structure of the article is as follows. First, we provide a brief introduction to the fundamental principles of LoRa and LoRaWAN. Building upon this foundation, we review the current literature concerning solutions for deploying LoRaWAN and LoRa at 2.4 GHz together. Subsequently, we detail the proposed roadmap, enumerate implementation options, and identify necessary modifications to the existing LoRaWAN standard. We then employ a standard-compliant simulator to demonstrate the potential benefits of integrating the 2.4 GHz band into the LoRaWAN standard. Finally, we list the research topics prompted by the proposed roadmap and draw conclusions.

Technical Background and Recent Developments

LoRa and LoRaWAN

In the LoRa modulation scheme, a set of M distinct chirp signals covers a designated frequency sweep interval, referred to in LoRa terminology as Bandwidth (BW). Specifically, the relationship $M = 2^{SF}$ holds, where Spreading Factor (SF) is an integer defining the temporal characteristics of each chirp. The larger the SF, the longer the transmission time, or Time on Air (ToA), while simultaneously boosting receiver sensitivity. LoRa also incorporates Forward Error Correction (FEC) techniques to balance reliability and transmission times. In precise terms, the LoRa frame, that is, the LoRa PHY Protocol Data Unit (PDU), comprises, in addition to the Cyclic Redundancy Check (CRC) bits, a preamble (for detection and synchronization), an optional header, and the payload (i.e., the useful data).

Coming to the upper layers, the LoRaWAN protocol is based on ALOHA, thus an ED randomly selects one of the available frequency channels and sends a LoRa frame whenever it has new data ready. Rather than being associated with a specific GW, EDs are linked to a NS, hence their transmissions are received by all the reachable GWs. The NS is responsible for generating Acknowledgments (ACKs), eliminating potential duplicates, managing join requests, and overseeing and optimising the overall network. The two additional components are Application Servers (ASs) and Join Server (JS). The ASs fetches the decoded application data from the NS, and the JS manages authentication.

As far as the LoRaWAN network architecture is concerned, EDs can also work as RLs and act as network extenders [6], improving even more the coverage of LoRaWAN networks. RLs operate by receiving messages from EDs and subsequently retransmitting them to a GW. This functionality enables far EDs to communicate with the GW, overcoming distance limitations.

LoRaWAN is recognized for its sub GHz versions, operating in license free ISM bands, such as EU868 and US915 for Europe and the US, respectively [7]. As shown in Fig. 1, these bands are not harmonized around the globe, which complicates production and hampers roaming. There are also regional specific limitations that affect the LoRaWAN performance, for example, the EU868 MHz spectrum (the sub GHz reference spectrum in this work) mandates the implementation of three default channels in each ED. Additionally, within this spectrum, regulatory constraints impose a duty cycle limitation of 1% for the default channels to mitigate potential interference caused by devices.

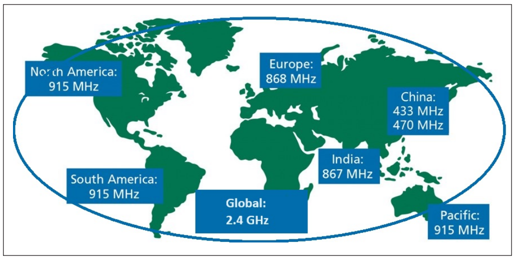

FIGURE 1. Comparison of LoRa bands across the world according to the regional parameters specification [7] and 2.4 GHz ISM band.

On the other hand, the 2.4 GHz band is available almost everywhere around the globe and features fewer restrictions on its use than sub GHz band which are compatible with the LoRaWAN working principle, thereby motivating the contribution contained in this article.

State of the Art

There exist a few works in the literature, mostly experimental, which envision the introduction of the 2.4 GHz PHY layer and its cooperation with already existing sub GHz bands into the standard. In [8], an experimental comparison between LoRa sub GHz and LoRa 2.4 GHz in both indoor and outdoor scenarios is carried out, and a discussion on the research challenges that need to be addressed to fully take advantage of this new technology is given. In [9], an experimental setup evaluating the LoRaWAN protocol stack on top of the LoRa 2.4 GHz is analyzed and a new Time Slotted Channel Hopping protocol is proposed. Authors in [10] exploit the well known ns-3 simulator to analyze network performance in different frequency bands. However, none of the above cited works discuss how integration of the 2.4 GHz in the specification can be done. This is the gap we focus on in the following.

Multi-Band LoRaWAN

Motivation

The introduction of a multi band LoRaWAN technology, that is, a LoRaWAN network that can work both in the sub GHz and 2.4 GHz band, presents an exciting opportunity to elevate mobile radio networks within the IoT landscape. This innovation heralds new horizons for enhancing network performance and augmenting deployment flexibility, accounting for the evolving needs of IoT applications. Thanks to its characteristics [5], LoRa 2.4 GHz is particularly well suited for applications with stringent traffic requirements (e.g., real time data collection in industry plants). Additionally, it allows for the reduction in antenna size, further enhancing deployment flexibility, along with an improved energy efficiency due to transmit power limitations and smaller transmission times. Remarkably, dual band solutions also help improve the network scalability and better tailor to propagation conditions and application requirements. Given these compelling advantages, it is worth investigating approaches that facilitate the seamless coexistence of both the regulated sub GHz version and the new 2.4 GHz iteration within a unified LoRaWAN standard. By leverag-

Coming to the upper layers, the LoRaWAN protocol is based on ALOHA, thus an ED randomly selects one of the available frequency channels and sends a LoRa frame whenever it has new data ready.

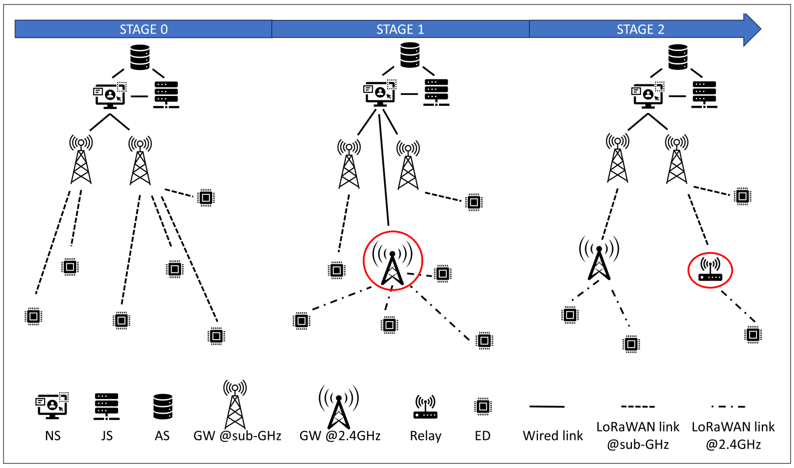

FIGURE 2. Suggested roadmap of the LoRaWAN standard to enable support of the 2.4 GHz LoRa version. Multiple links between EDs and GWs are not considered (even if possible) for simplifying the figure, and only the shortest ED-GW link is shown. Red circles identify the main additional components of Stages 1 and 2 in comparison to the state of the art Stage 0.

ing the strengths of this technology, LoRaWAN stands poised to revolutionize IoT connectivity and drive innovation in various industries, leading to a general increase in network performance.

Roadmap

Figure 2 depicts our vision of how the LoRaWAN standard should evolve to support the 2.4 GHz LoRa version. In particular, we envision three main stages:

- **Stage 0:** This stage aligns with the existing LoRaWAN standard [7], wherein EDs communicate with GWs using LoRa technology in the sub GHz band. The GWs then conveys this information through wired connections to and from the NS (it is worth noting that, to maintain simplicity throughout the text, we will refrain from detailing the various components of the NS, including the home, serving, and forwarding NS). The NS, in turn, can be linked to the JS and AS for managing security, authentication, and other relevant aspects;
- **Stage 1:** This is the first evolution of Stage 0, where GWs and EDs can also embed 2.4 GHz radio modules to properly exploit the benefits of this band.
- **Stage 2:** This is the final stage, where the concept of RL at 2.4 GHz is further introduced, to also forward LoRa frames in this band.

Implementation Options

In light of the macroscopic view of the proposed roadmap, we hereby present the different implementation options for Stages 1 and 2 only, as Stage 0 represents the current LoRaWAN standard.

Stage 1: The addition of the 2.4 GHz radio module in both, EDs and GWs, can be done in different ways. We enumerate the implementation options (which can also be considered as development steps) in ascending order of difficulty of integration:

- *Option 1.1:* Both GWs and EDs communicate via LoRaWAN at 2.4 GHz. Remarkably, this is not foreseen by the current LoRaWAN specification, as only the PHY layer at sub GHz is envisioned;
- *Option 1.2:* There are two types of GWs and EDs, one working at sub GHz and the other at 2.4 GHz, so that there exist separate GW-ED links that can be managed either by a single or multiple NSs.
- *Option 1.3:* There are two types of EDs, one working at sub GHz and the other at 2.4 GHz, whereas GWs are equipped with both radio modules to provide connectivity to all categories of EDs;
- *Option 1.4:* There are two types of GWs, one working at sub GHz and the other at 2.4 GHz, whereas EDs are equipped with both radio modules and properly select (or are forced to choose) the frequency spectra to be used. This is the version illustrated in Fig. 2;
- *Option 1.5:* Both GWs and EDs are equipped with both radio modules, that is, sub GHz and 2.4 GHz, and some logic at the NS determines which one to use;

Stage 2: The concept of RLs in the current LoRaWAN standard [6] requires that EDs, RLs, and GWs always operate in the same frequency spectrum. Differently, in this article, we foresee that GWs operate in the sub GHz band, whereas there are different possible options for RLs and EDs:

- *Option 2.1:* RLs are equipped with 2.4 GHz and sub GHz radios, whereas there are two types of EDs, each supporting only one frequency band. EDs working at 2.4 GHz communicate with RLs that, in turn, communicate with GWs via LoRaWAN at sub GHz. The EDs at sub GHz communicate with the GW directly.
- *Option 2.2:* Same as option 2.1, but RLs also forward data from/to EDs working in the sub GHz band. This option sets overhead on the sub GHz band, as it should account for two radio links, namely RLs-GWs and EDs-RLs;
- *Option 2.3:* RLs and EDs are equipped with radio modules for both frequencies so that all possibilities foreseen by the previous options are feasible.

Standard Modifications

In this following, we highlight the essential modifications needed for the LoRaWAN standard to align with the roadmap proposed in this article.

Specifically, Table 1 offers a summary of the primary modifications to the chapters of the current LoRaWAN standard required to implement Stages 1 and 2 for the various implementation options previously outlined. Obviously, the LoRaWAN regional parameters [7] should be adjusted to introduce the 2.4 GHz band, by specifying both the possible range of values (e.g., channel frequencies, data rates, transmit powers, maximum payload size, receive windows, etc.) and the corresponding PHY layer characteristics [4]. However, for both stages, the major changes in [11] are required, as the responsibilities of EDs, RLs, GWs, and NS should be extended to elucidate who determines the utilization of dual radios, the methodology employed for such decisions, and the collection of data to support them. Moreover, the modified standard should also describe the role of the multi bands in association and roaming procedures. In particular, from the network architecture viewpoint and considering Stage 2, the locations of EDs acting as RLs can either:

- Be chosen a priori to provide sufficiently high performance, that is, statically creating links between EDs, RLs and GWs

- A logic might be implemented in one of the network elements to dynamically transform EDs into RLs and create EDs-RLs links whenever it is needed. Additionally, the ED activation procedure, both Over-the-Air-Activation (OTAA) and Activation By Personalization (ABP) mode, should be properly modified as the NS should also acquire the knowledge on the bands supported by EDs, despite the rationale of such procedures can be seamlessly transitioned to the 2.4 GHz spectrum.

Another important modification of [11] refers to the criteria for communication mapping. Indeed, data communication may be allocated to either one frequency band or both (e.g., to increase reliability at the expense of additional complexity in managing duplicates), as well as it is possible to foresee a possible frequency split between uplink and downlink. Finally, the L2 and Relay specifications (i.e., [2] and [6]), should account for implementation details such as the introduction of new Medium Access Control (MAC) commands to switch between the two bands, or to keep the NS informed of the bands currently used by EDs.

Selected Numerical Results

In the following, some exemplary numerical results will be discussed to highlight how the proposed roadmap can improve network performance compared with the current LoRaWAN standard (i.e., Stage 0). For the sake of brevity, we will consider only Stage 1, Options 1.1 and 1.2, but the discussion can be extended to the other cases as well.

Simulations have been realized exploiting the open source LoRaWANSim simulator described in [12], properly modified to match the context of this work.

System Model and Simulation Setup

Scenario: We consider a scenario where a GW is located at the center of a square area with side length of A and N EDs are randomly and uniformly distributed around. The simulation lasts T seconds.

Channel Model: We assume the 3rd Generation Partnership Project (3GPP) Urban Macro (UMa) channel model described in TR 38.901 [13], which is valid for frequencies from 0.5 to 100 GHz.

Traffic Model: We focus on uplink traffic, which we assume to be periodic with period T_U and a payload of B bytes.

End Device Configuration: EDs work in *class A* mode [2]; hence, following an uplink transmission, they initiate two downlink receive slots, labelled Receive Window 1 (RX1) and Receive Window 2 (RX2), after specific fixed intervals of 1 second and 2 seconds (as per standard practice). For a more fair comparison, we assume that EDs exploit just three channels in both bands (specifically, we assume sub GHz EDs work in the EU868 MHz band). EDs employ the Adaptive Data Rate (ADR) algorithm [14], designed to dynamically configure the SF and transmit power used by EDs during their transmissions. We assume that the entire set of SFs is available at the ED side, which is 7–12 for sub GHz EDs and 5-12 for 2.4 GHz EDs, respectively. Finally, they operate in *unconfirmed mode*, so their transmissions do not require an ACK sent by the NS via GWs.

	LoRaWAN documentation	Options	Chapters
Stage 1	Regional Parameters [7]	1.1–1.5	2, 4
	Main Specifications [2]	1.2, 1.4–1.5 1.2-1.5	5 6
	Backend Specification [11]	1.1–1.5	3, 6–9, 11, 18
Stage 2	Regional Parameters [7]	2.1–2.3	3, 4.4
	Backend Specification [11]	2.1–2.3	3, 6–9, 18.3
	Relay Specification [6]	2.1–2.3	3, 8, 10

TABLE 1. Main modifications to the chapters of the current LoRaWAN standard to implement Stages 1 and 2 of the proposed multi band roadmap as a function of the chosen implementation option.

Simulator Working Principle: In the simulation, an uplink packet is considered correctly received, taking into account two impairments: noise and interference. Regarding the former, we model the entire transmitter-receiver chain. Therefore, based on the PHY layer parameters and the Signal to Noise Ratio (SNR) characterizing a specific link, the PHY layer part of the simulator determines whether the currently transmitted packet is received accurately. As for the interference, we take into account the possibility that colliding LoRa frames may still be correctly received if the corresponding Signal to Interference Ratio (SIR) exceeds a given threshold (which changes according to the SFs used for the transmissions), hence accommodating for the capture effect. This model has been largely used in the literature, as described in detail in Section V of [12].

Numerical Results

Network performance is evaluated in terms of success probability and network throughput as a function of the offered traffic, O [bit/s], defined as

$$O = \frac{B \cdot N}{T_U}.$$

The success probability, P_S, represents the percentage of frames correctly received by the GW and it is the ratio between the number of correctly received frames over the number of transmitted ones. The network throughput, S, has been defined as the number of data bits correctly received by the GW from all EDs throughout the simulation, measured in bit/s.

Parameters used during simulation are reported in Table 2. The selected results are depicted in Fig. 3 and Fig. 4. For each figure, three possibilities are presented: Stage 0 (i.e., the current LoRaWAN standard); Stage 1, Option 1.1; Stage 1, Option 1.2.

Figure 3 shows the success rate, P_S, as a function of the offered traffic, O. As one can notice, as the offered traffic increases, the success probability decreases. The reason behind such behavior is twofold: on one hand, increasing the number of EDs, N, will impact the number of collisions during frame transmissions in the network; on the other hand, with a larger B, the ToA of the frame will increase, leading to a longer vulnerability interval, hence more collisions. Moreover, the reduced data rate and the duty cycle constraints of LoRaWAN at EU868 MHz (Stage 0) produce even longer ToA, resulting in more collisions and fewer transmissions for the same amount of

Despite the inclusion of an additional transceiver is a consolidated procedure that does not significantly increase the overall price of the device, justifying this effort requires substantial performance improvements.

Parameter	Value
Area side length (A)	1 km
LoRa Frame Periodicity (T_U)	10 s
LoRa Frame Size (B)	10 B
Simulation duration (T)	120 s
Frequency Sweep Interval (BW)	125 (@EU868 MHz) kHz 203 (@2.4 GHz) kHz

TABLE 2. Simulation parameters.

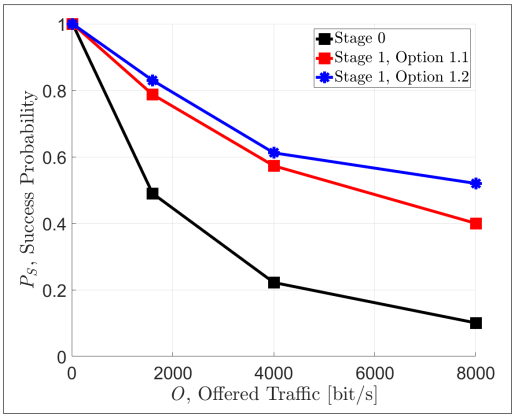

FIGURE 3. Success probability as a function of the offered traffic, O.

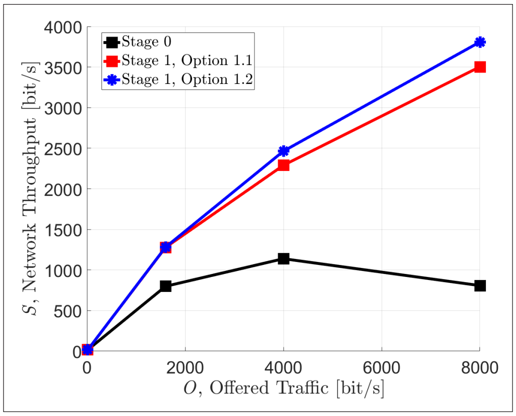

FIGURE 4. Network throughput, S, as a function of the offered traffic, O.

time w.r.t. the other cases, making the standard solution the worst possible choice. On the other hand, introducing the 2.4 GHz band (Option 1.1), the success rate increases thanks to the reduced ToA. The joint solution (Option 1.2) results in even better performance since sub GHz and 2.4 GHz EDs' transmissions do not collide, reducing the overall number of collisions in the network.

The success probability has a direct impact on the network throughput, as shown in Fig. 4. As it can be seen, Stage 0 shows the usual ALOHA behavior, with a peak around O = 4000 bit/s. Again, moving towards Stage 1, the network performance increases and the peak shifts further right, showing the benefit of the 2.4 GHz band introduction. As can be seen, for O = 8000 bit/s the suggested Stage 1 modifications enable supporting 3.5 higher overall network throughput.

Open Challenges and Research Directions

The proposed roadmap presents a promising avenue for mobile radio networks. However, it also introduces multiple challenges for design and optimizing the operation both from a network perspective (e.g., the development of dual band ADRs) and from the ED point of view (e.g., determining the starting band to use for OTAA). These challenges underscore the necessity to explore new avenues of research. In the following, we will outline the primary research directions that the proposed roadmap unveils.

Optimal Configurations for 2.4 GHz LoRaWAN: One of the first challenges to be solved is the optimal selection of communication configurations to be used for LoRaWAN 2.4 GHz operation, that is, determining the number and frequency of channels, specification of the bandwidth(s), SFs, and transmit power levels, the number of RX windows and respective delays, etc. Depending on the application and the level of integration with sub GHz LoRaWAN, there can even be several different configuration options.

Interference Mitigation: One further significant challenge lies in potential interference from existing networks operating within the 2.4 GHz band, such as Wi-Fi or Bluetooth. The coexistence of these networks is likely to happen in different scenarios (e.g., smart homes), impacting the performance and reliability of the proposed technology. In this regard, there already exist studies (e.g., [15]), that provide indications of the resilience of LoRa at 2.4 GHz from co-channel interference. However, further work may be directed toward implementing advanced interference mitigation strategies at the network and MAC levels.

Cost/Performance Tradeoffs: The proposed approach may incur higher costs due to the addition of radio modules operating in the 2.4 GHz band at EDs and/or GWs. Despite the inclusion of an additional transceiver is a consolidated procedure that does not significantly increase the overall price of the device, justifying this effort requires substantial performance improvements. Without tangible benefits, market viability may be compromised. Notably, our numerical findings demonstrate a remarkable improvement in network throughput when comparing Stage 1, option 1.2 with the state of the art LoRaWAN technology (refer to Fig. 4). Nevertheless, future studies, potentially including experimental trials, are needed to further confirm these preliminary observations and to bolster the proposed roadmap for the LoRaWAN standard.

Dynamic Allocation of End Devices to Relays: Another crucial research direction involves the dynamic allocation and handovers of EDs to RLs based on different factors, such as, traffic load, channel conditions, and proximity to RLs. Adaptive allocation strategies, including multi band adaptive data rate (ADR) can enhance network efficiency and resource utilization, ensuring optimal performance under diverse operating conditions and by mitigating the downsides of both LoRaWAN and LoRa at 2.4 GHz.

MAC Protocol Design: Designing more efficient MAC protocols than the approach similar to ALOHA of LoRaWAN for communication between EDs and RLs at 2.4 GHz (e.g., with specific application needs in mind), presents an intriguing research opportunity. Despite potential deviation from standard compliance, such protocols must offer substantial advantages to justify their adoption.

Multi-Hop Design Complexity: Designing the network architecture becomes intricate when considering wide scenarios requiring more than a single hop (i.e., more than one RL), to connect EDs with GWs. Managing multiple hops while maintaining sufficiently high performance levels (e.g., in terms of energy efficiency, reliability, and network throughput) poses a significant and unprecedented challenge in the routing strategies of LoRaWAN networks. We advocate for the comparison of LoRaWAN architectures incorporating multiple hops with, at minimum, the performance offered by the Stage 0 version. This comparison is essential to ascertain any potential advantage associated with the proposed approach. Nevertheless, even when considering a single level of RLs, the development of efficient RL selection algorithms is mandatory. These procedures should intelligently and dynamically identify RLs based on factors such as signal strength, interference levels, and network topology to optimize performance and reliability.

Security: The introduction of dual-band devices imposes some security concerns. First, it becomes mandatory to ensure transparent sequence numbering across interfaces for dual-mode EDs to mitigate replay attacks in alternate bands. Additionally, the introduction of additional network elements, i.e., GWs at 2.4 GHz and RLs, extends the number of devices that are physically accessible from malicious users. Hence, enhancing defenses against denial-of-service attacks and safeguarding against physical tampering or hijacking of equipment is imperative.

Conclusions

This article has reported how the potential integration of LoRa chipsets operating at 2.4 GHz into the existing LoRaWAN standard can be enabled. By proposing a roadmap consisting of three distinct stages, starting from the current LoRaWAN standard (Stage 0), moving to the coexistence of two separate LoRaWAN networks (Stage 1), and ending with a single LoRaWAN network capable of supporting both sub GHz and 2.4 GHz bands (Stage 2), we have elucidated the feasibility and benefits of this proposed approach.

Specifically, for Stages 1 and 2, we discussed the different implementation options and necessary modifications to Stage 0 documentation, spanning from architectural to protocol aspects, with the objective of providing practical insights for stakeholders involved in the standardization process. By leveraging LoRaWAN compliant simulation results, we have empirically demonstrated the performance advantages of the proposed multi band approach, particularly in Stage 1 of the roadmap, where GWs equipped with radio modules at 2.4 GHz can be deployed to boost success probability and network throughput.

Looking ahead, our work also highlights several research directions and open questions that warrant further investigation for the research community. These include optimal selection of configurations for 2.4 GHz LoRaWAN, interference mitigation strategies, cost/performance tradeoffs, dynamic allocation of EDs to RLs, MAC protocol design, and multi hop network architecture. As the IoT landscape continues to evolve, addressing these challenges and opportunities will be essential for unlocking the full potential of LoRaWAN technology.

References

[1] A. Ikpehai *et al.*, "Low-Power Wide Area Network Technologies for Internet-of-Things: A Comparative Review," *IEEE Internet of Things J.*, vol. 6, no. 2, 2018, pp. 2225–40.

[2] LoRa Alliance, LoRaWAN® L2 1.0.4 Specification (TS001-1.0.4), 2020.

[3] G. Pasolini, "On the LoRa Chirp Spread Spectrum Modulation: Signal Properties and Their Impact on Transmitter and Receiver Architectures," *IEEE Trans. Wireless Commun.*, vol. 21, no. 1, 2021, pp. 357–69.

[4] S. Corporation, "SX1280/1281 Data Sheet DS.SX1280-1.W.APP," 2018.

[5] R. Marini and G. Cuozzo, "A Comparative Performance Analysis of LoRaWAN in Two Frequency Spectra: EU868 MHz and 2.4 GHz," *2023 Joint European Conf. Networks and Commun. & 6G Summit (EuCNC/6G Summit)*, 2023, pp. 1–6.

[6] LoRa Alliance, LoRaWAN® Relay Specification TS011-1.0.0, 2022.

[7] —, LoRaWAN® Regional Parameters RP002-1.0.4, 2022.

[8] G. H. Derevianckine *et al.*, "Opportunities and Challenges of LoRa 2.4 GHz," *IEEE Commun. Mag.*, 2023, pp. 1–7.

[9] M. Schappacher, A. Dant, and A. Sikora, "Implementation and Validation of LoRa-Based Systems in the 2.4 GHz Band," *2021 IEEE 4th Int'l. Conf. Advanced Information and Commun. Technologies*, 2021, pp. 106–11.

[10] Masek, Pavel *et al.*, "Performance Analysis of Different LoRaWAN Frequency Bands for mMTC Scenarios," *2022 45th Int'l. Conf. Telecommun. and Signal Proc.*, 2022, pp. 417–20.

[11] LoRa Alliance, LoRaWAN® Backend Interfaces Technical Specification (TS002-1.1.0), 2020.

[12] R. Marini *et al.*, "LoRaWANSim: A Flexible Simulator for LoRaWAN Networks," *Sensors*, vol. 21, no. 3, 2021.

[13] 3GPP, "Study on Channel Model for Frequencies from 0.5 to 100 GHz (Release 16)," TS 38.901, 2019.

[14] R. Marini, W. Cerroni, and C. Buratti, "A Novel Collision-Aware Adaptive Data Rate Algorithm for LoRaWAN Networks," *IEEE Internet of Things J.*, vol. 8, no. 4, 2021, pp. 2670–80.

[15] G. Cuozzo, C. Buratti, and R. Verdone, "A 2.4-GHz LoRa-Based Protocol for Communication and Energy Harvesting on Industry Machines," *IEEE Internet of Things J.*, vol. 9, no. 10, 2021, pp. 7853–65.

Biographies

Giampaolo Cuozzo [M'23] (giampaolo.cuozzo@wilab.cnit.it) received from the University of Bologna a B.S with honors in electronics and telecommunications engineering in 2017, an M.S with honors in telecommunications engineering in 2019, and a Ph.D. degree in electronics, telecommunications, and information technologies engineering (ET-IT) in 2023. He is currently Head of Research at the National Laboratory of Wireless Communications (WiLab) of CNIT (the National, Inter-University Consortium for Telecommunications). His research activity is focused on the study, development, and validation of 6G networks for the Industrial Internet of Things.

Riccardo Marini [M'23] (riccardo.marini@wilab.cnit.it) received the M.Sc with honors in Telecommunications Engineering and got the Ph.D. in Electronics, Telecommunications and Information Technologies Engineering (ET-IT) at the University of Bologna in 2019 and 2023, respectively. He is currently Head of Research at the National Laboratory of Wireless Communications (WiLab) of CNIT (the National Inter-University Consortium for Telecommunications). His research activities focus on urban and rural Internet of Things, with emphasis on LPWAN technologies and UAV networks, as well as Machine Learning techniques for wireless networks.

Chiara Buratti [M'06] (c.buratti@unibo.it) received the Ph.D. in Electronics, Information Technologies and Telecommunications Engineering at the University of Bologna in 2009. She is Associate Professor at University of Bologna. Her research interests are on wireless sensor networks and IoT, with emphasis on MAC and routing protocols and on 3D networks. She co-authored approx. 120 papers. She has been PI of the COST Innovators Grant, Immunet. She was the main proponent of the Cost Action CA20120, INTERACT, and she is currently the Vice-Chair and Grant Holder of the Action.

Konstantin Mikhaylov [S'10, M'18, SM'19] (konstantin.mikhaylov@oulu.fi) received Dr.Sc. (Eng) in Telecommunication from the University of Oulu, Finland, in 2018. Currently he is an Assistant Professor (Tenure Track) for Convergent IoT Communications for Vertical Systems with the Centre for Wireless Communications at the University of Oulu. The major focus of his research is on the radio access and beyond-access technologies for massive and dependable IoT, and the matters related to the design and use of IoT systems. He has authored and co-authored over one hundred research papers on wireless connectivity for IoT, IoT devices and systems design, and applications.

Open Access funding provided by University of Bologna within the CRUI CARE agreement.