Robust LoRa via Repetition in Frequency through Signal Emulation using WiFi

Sascha Rösler, Anatolij Zubow, Falko Dressler

School of Electrical Engineering and Computer Science, TU Berlin, Germany

{roesler,zubow,dressler}@tkn.tu-berlin.de

***Abstract*—Low-Power Wide-Area Networks technologies like LoRa are essential for Internet of Things (IoT) applications, but their simple ALOHA-based channel access and low-power, narrow-band signals make them vulnerable to interference, especially when using the crowded 2.4 GHz band. We present `SolidWi-Lo`, a novel cross-technology communication (CTC) scheme that uses WiFi to emulate LoRa transmissions with frequency-based frame repetition. This method improves resilience against channel fading, external interference and jamming by leveraging WiFi's broader bandwidth and its listen-before-talk channel access scheme. Through link-level simulations, we demonstrate that `SolidWi-Lo` significantly increases the communication distance from 1 km to 1.5 km under the 3GPP urban micro propagation model and multipath fading. The resilience of the communication link in a scenario with external narrow-band interference is also dramatically increased showing an improvement in Packet Delivery Ratio (PDR) from 0.5 to 0.91 as compared to classical LoRa. Notably, `SolidWi-Lo` requires no changes to the existing LoRaWAN infrastructure, offering a practical solution to enhance communication resilience of LoRa in crowded wireless environments.**

***Index Terms*—Cross-technology communication, resilience, jamming, WiFi, LoRa, frequency diversity**

I. Introduction

Low-Power Wide-Area Network (LPWAN) technologies like LoRa are gaining increasing importance for Internet of Things (IoT) applications due to their energy efficiency and long-range communication capabilities. For LoRa, the use of the 2.4 GHz ISM spectrum is particularly promising, as it provides wider channels and avoids the duty cycle restrictions imposed in sub-GHz bands. However, this spectrum is heavily shared with other radio technologies such as WiFi, ZigBee and Bluetooth, leading to significant cross-technology interference. LoRa is particularly vulnerable to such interference due to its simple ALOHA-based channel access and its weak and narrow signal.

On the other hand, the spectrum shared with WiFi enables direct signal emulation of LoRa waveforms using WiFi hardware as we show in [1]. This Cross-Technology Communication (CTC) elaborates the wider bandwidth of WiFi, however, it also causes spectral inefficiency as parts of the wider WiFi spectrum remain unused. Nevertheless, the larger bandwidth of WiFi is an opportunity as emulated copies of the same LoRa packet can be sent in parallel on different frequencies within a single WiFi frame without requiring any additional hardware (Fig. 1). In this paper, we show this `SolidWi-Lo` approach for the first time. Our method makes the emulated LoRa transmissions more robust to channel fading and narrow-band interference and even active jamming. Furthermore, since WiFi employs a Listen Before Talk (LBT) mechanism via CSMA/CA, the emulated LoRa frames are better protected against collisions with strong interferer - an advantage over ALOHA used in classical LoRa. Results from link-level simulation reveal the benefits of frame repetition in frequency outweighing losses by imperfect waveform emulation. With `SolidWi-Lo` the tolerable distance allowing for a Packet Delivery Ratio (PDR) of 0.9 is increased from 1 km to 1.5 km in a multipath environment. In case of strong narrow-band interference the PDR is increased from 0.5 to 0.9 as compared to LoRa.

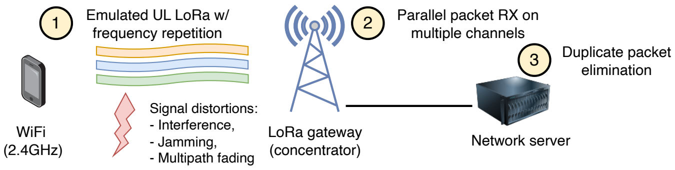

Figure 1. Envisioned system - signal emulation is used to create multiple parallel LoRa transmissions on different channels within a single WiFi frame.

Contributions: Using the example of WiFi to LoRa CTC, we show for the first time that the wider bandwidth of the emulating technology, here WiFi, can be utilized to make the transmissions of the emulated technology, here LoRa, more resilient to channel fading and interference. We introduce `SolidWi-Lo` and evaluate this approach by simulations. Moreover it is of practical use as it does not require any changes to LoRaWAN.

II. Background

A. Cross-Technology Communication

CTC enables direct communication among heterogeneous devices using different incompatible wireless technologies, e.g., WiFi with LoRa [2]. Existing CTC techniques operate either at packet-level or physical-level. The packet-level CTC utilizes the packet transmission as the carrier to convey messages to the receiver of another technology. More sophisticated approaches do physical-level CTC where the waveform of the target technology is directly emulated. WEBee [3] enables an unmodified WiFi device to transmit a ZigBee waveform by proper selection of its payload bits. WEBee enabled communication at native data rates of ZigBee but suffered from a high packet error rate due to the inherent distortions of the emulated signal. TwinBee [4] and WIDE [5] further improve the quality of signal emulation and hence the reliability of WEBee. Later, physical-level CTC between WiFi and BT [6],

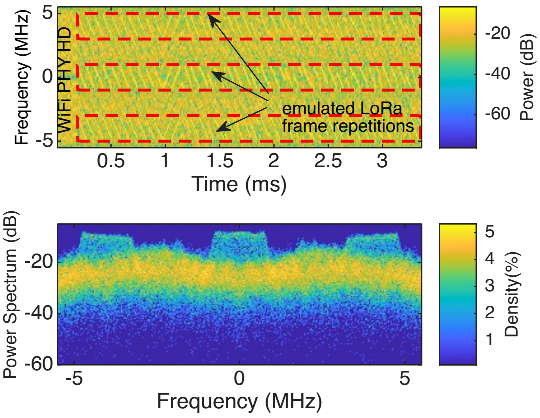

Figure 2. Spectrum of `SolidWi-Lo` frame with three emulated LoRa frames (SF5 (Spreading Factor), 1.6 MHz) on different frequencies within a single IEEE 802.11b frame.

WiFi and LTE [7], [8] are introduced. In [1], we showed that 802.11b WiFi can be used to emulate LoRa waveforms.

B. WiLo - WiFi to LoRa CTC

In this paper we present an extension of the method we termed as Wi-Lo [1]. Wi-Lo enables CTC from an 802.11b WiFi device to a LoRa receivers by emulating LoRa's chirp spread spectrum (CSS) waveforms through carefully crafting the WiFi payload. The approach exploits the Complementary Code Keying (CCK) modulation scheme, where payload bits are mapped to phase shifts in codewords (8-chip sequences). By reverse-engineering the CCK modulator's constraints, Wi-Lo approximates LoRa chirps. The emulated signal achieves functional parity with native LoRa, albeit with a minor Signal to Noise Ratio (SNR) penalty due to quantization effects in CCK modulation. Wi-Lo uses COTS hardware.

III. Proposed Approach

The envisioned scenario is shown in Fig. 1. We consider a LoRaWAN network where WiLo [1] as WiFi-to-LoRa CTC is used in the uplink. The key idea of `SolidWi-Lo` is the usage of the wideband transmission capability of WiFi to emulate not only a single, but R parallel LoRa frame repetitions in frequency in order to increase resilience towards multipath fading and interference. The sent multi-frame (Fig. 2) can be decoded at a standard LoRaWAN gateway consisting of a LoRa concentrator, which is capable of decoding multiple LoRa frames on multiple channels in parallel. The network server will eliminate duplicated packets (Fig. 1) while the gateway will drop corrupted packets. Hence, with our approach, a transmission will fail if all copies of the same LoRa packet are corrupted. No changes are required to the LoRaWAN network as the necessary components are already available.

IV. Performance Evaluation

A. Methodology

We evaluated `SolidWi-Lo` by means of link-level simulations in MATLAB using the WLAN toolbox and the LoRa implementation provided by Xu et al. [9] for accurate PHY layer processing. We consider a scenario with a single WiFi station transmitting `SolidWi-Lo` frames in the uplink (Fig. 1). We analyze the performance considering two different wireless channel models: i) flat fading and ii) multipath fading in a large indoor space (802.11ax model F delay profile). In both cases the noise is simulated using Additive White Gaussian Noise (AWGN). Moreover, the 3GPP urban micro pathloss model was used. Additionally, we analyze two different interference scenarios: i) clean channel without any interference and ii) 2 MHz OQPSK narrow-band interference with channel access probability of $I = 0.5$ on different center frequencies. The transmission power was set to maximum, i.e. 12.5 dBm for LoRa and 20 dBm for `SolidWi-Lo` respectively and the bandwidth of LoRa is set to 1.6 MHz giving LoRa a similar spectral power. We analyze the impact of frame repetitions (R) in `SolidWi-Lo` on the E2E PDR at the LoRaWAN network server. Classical LoRa and Wi-Lo are used as the baseline. In case of `SolidWi-Lo` the channel spacing for different R was selected to result in best performance for a flat channel.

B. Results

1) Emulation Loss: As preparation, we analyze the impact of R frame repetitions in frequency in `SolidWi-Lo` over an AWGN channel. From Fig. 3 we can observe that by increasing R the performance worsens as the emulation loss increases with R. This is caused by the multitude of LoRa waveforms that can no longer be optimally emulated by a 802.11b CCK waveform. The loss with two emulated LoRa channels is negligible, with 3, 4 and 5 channels the loss is 1, 2.5, 4 dB. Hence, there is no improvement from `SolidWi-Lo` in a flat channel environment without interference.

2) Multipath Fading Channel: Fig. 4 shows that in a multipath environment with higher R a larger communication distance is feasible. If a PDR=0.9 is tolerable, distances up to 1350 m with $R = 2$ and with $R = 3$ 1500 m can be achieved while Wi-Lo and classical LoRa are limited to only 1000 m. However, for $R > 3$ the performance decreases as the emulation loss becomes the limiting factor. Hence, in an environment

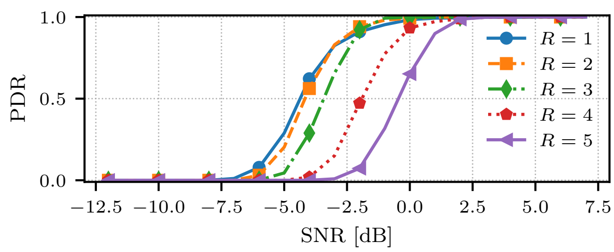

Figure 3. Impact of R in `SolidWi-Lo` in AWGN channel.

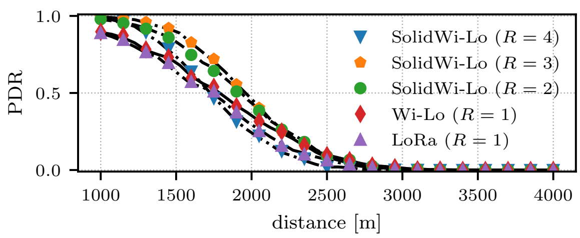

Figure 4. `SolidWi-Lo` under multipath fading and clean channel.

with strong multipath fading, using SolidWi-Lo with $R = 3$ repetitions provides the highest performance.

3) Narrow-band Interference: Fig. 5 shows how SolidWi-Lo improves the PDR in a scenario with narrow-band interference. While traditional approaches are limited to a PDR of 0.5 which correlates with I, using $R = 4$ within SolidWi-Lo increases this limit to 0.9 due to frame repetition. Even though the peak PDR for $R = 3$ is reduced, it achieves a larger distance for PDR$= 0.8$ of 1650 m compared to a distances below 1300 m for $R = 4$. With increasing R the peak PDR increases, however, the tolerable distance decreases.

4) Comparison with Classical LoRa: Our results also show that the resilience of classical LoRa and Wi-lo is comparable. Nevertheless, Wi-Lo performs a bit better, due to higher transmission power in the spectrum relevant for the LoRa receiver.

V. Related Work

Resilience and robustness for classical LoRa is already studied. Ahmar et al. [10] proposed a time-synchronized frequency hopping MAC protocol for LoRa. It reduces the contention by fairly exploiting the available frequency resources and also providing robustness against selective jamming attacks. Zorbas et al. [11] proposed a mechanism for optimal Spreading Factor (SF) selection for LoRa that improves the reliability compared to the standard adaptive data rate algorithm. In a later work [12], this approach is combined with time division multiple access to reduce latency and packet loss. The investigation of LBT mechanism like CSMA with LoRa was carried out in [13], [14]. The issue of jamming of LoRa was discussed by Hou et al. [15] where it was shown that LoRa is vulnerable to synchronized jamming chirps. They propose a protection method that can separate LoRa chirps from jamming chirps by leveraging their difference in power. Álamos et al. [16] improve the LoRa reception under collisions with the help of a Bayesian classifier approach which exploits the symmetry properties of the FFT of the dechirped signal and on the deviation of the expected magnitude of the FFT peak. Szafranski and Reinhardt [17] enhance the resilience of LoRa by creating constructive interference with concurrent transmissions from multiple nodes. Our work is the first one in enhancing resilience in LoRa by using the wider available spectrum of WiLo without the need for additional hardware.

VI. Conclusion

With SolidWi-Lo we showed that the degrees of freedom provided by CTC can be exploited for making transmissions of the emulated LoRa technology more resilient against channel fading and interference. This is achieved by means of parallel frame repetition in frequency domain, which becomes possible as WiFi uses a wider bandwidth. As future work we plan to prototype SolidWi-Lo using commodity hardware in order to evaluate it under real channel and interference conditions. Furthermore, we also want to study the possibilities of repetitive transmissions using different emulated technologies, e.g. LoRa with ZigBee and Bluetooth.

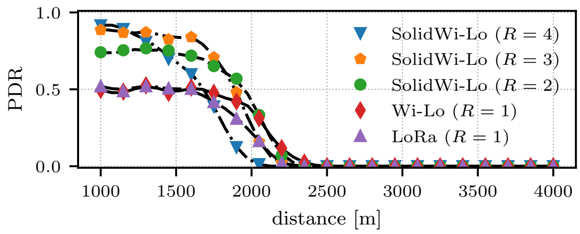

Figure 5. SolidWi-Lo under narrow-band interference and AWGN channel.

Acknowledgments

This work was supported by the German Research Foundation (DFG) within the projects Resilient Worlds under grant DR 639/30-1 and ZU 235/4-1.

References

[1] P. Gawłowicz, A. Zubow, and F. Dressler, "Wi-Lo: Emulation of LoRa using Commodity 802.11b WiFi Devices," in *IEEE ICC 2022*, Seoul, South Korea: IEEE, May 2022, pp. 4414–4419.

[2] Y. Chen, M. Li, P. Chen, and S. Xia, "Survey of cross-technology communication for IoT heterogeneous devices," *IET Communications*, vol. 13, no. 12, pp. 1709–1720, Jul. 2019.

[3] Z. Li and T. He, "WEBee: Physical-Layer Cross-Technology Communication via Emulation," in *ACM MobiCom 2017*, Snowbird, UT: ACM, Oct. 2017, pp. 2–14.

[4] Y. Chen, Z. Li, and T. He, "TwinBee: Reliable Physical-Layer Cross-Technology Communication with Symbol-Level Coding," in *IEEE INFOCOM 2018*, Honolulu, HI: IEEE, Apr. 2018, pp. 153–161.

[5] X. Guo, Y. He, J. Zhang, and H. Jiang, "WIDE: Physical-level CTC via Digital Emulation," in *ACM/IEEE IPSN 2019*, Montréal, Canada: ACM, Apr. 2019, pp. 49–60.

[6] W. Jiang, Z. Yin, R. Liu, Z. Li, S. M. Kim, and T. He, "BlueBee: A 10,000x Faster Cross-Technology Communication via PHY Emulation," in *ACM SenSys 2017*, Delft, Netherlands: ACM, Nov. 2017, pp. 1–13.

[7] P. Gawłowicz, A. Zubow, and A. Wolisz, "Enabling Cross-technology Communication between LTE Unlicensed and WiFi," in *IEEE INFOCOM 2018*, Honolulu, HI: IEEE, Apr. 2018.

[8] P. Gawłowicz, A. Zubow, S. Bayhan, and A. Wolisz, "Punched Cards over the Air: Cross-Technology Communication Between LTE-U/LAA and WiFi," in *IEEE WoWMoM 2020*, Virtual Conference: IEEE, Sep. 2020, pp. 297–306.

[9] Z. Xu, S. Tong, P. Xie, and J. Wang, "From Demodulation to Decoding: Toward Complete LoRa PHY Understanding and Implementation," *ACM Transactions on Sensor Networks*, vol. 18, no. 4, pp. 1–27, Jan. 2023.

[10] A.-U.-H. Ahmar, E. Aras, T. D. Nguyen, S. Michiels, W. Joosen, and D. Hughes, "Design of a Robust MAC Protocol for LoRa," *ACM Transactions on Internet of Things*, vol. 4, no. 1, pp. 1–25, Feb. 2023.

[11] D. Zorbas, P. Maillé, B. O'Flynn, and C. Douligeris, "Fast and Reliable LoRa-based Data Transmissions," in *IEEE ISCC 2019*, Barcelona, Spain: IEEE, Jun. 2019, pp. 1–6.

[12] D. Zorbas, K. Q. Abdelfadeel, V. Cionca, D. Pesch, and B. O'Flynn, "Offline Scheduling Algorithms for Time-Slotted LoRa-based Bulk Data Transmission," in *IEEE WF-IoT 2019*, Luimneach, Ireland: IEEE, Apr. 2019, pp. 949–954.

[13] Z. Xu, J. Luo, Z. Yin, T. He, and F. Dong, "S-MAC: Achieving High Scalability via Adaptive Scheduling in LPWAN," in *IEEE INFOCOM 2020*, Virtual Conference: IEEE, Jul. 2020, pp. 506–515.

[14] A. Gamage, J. C. Liando, C. Gu, R. Tan, M. Li, and O. B. A. Seller, "LMAC: Efficient carrier-sense multiple access for LoRa," *ACM Transactions on Sensor Networks*, vol. 19, no. 2, pp. 1–27, 2023.

[15] N. Hou, X. Xia, and Y. Zheng, "Jamming of LoRa PHY and countermeasure," *ACM Transactions on Sensor Networks*, vol. 19, no. 4, pp. 1–27, 2023.

[16] J. Álamos, T. C. Schmidt, and M. Wählisch, "CoRa: A Collision-Resistant LoRa Symbol Detector of Low Complexity," in *IEEE INFOCOM 2025*, London, United Kingdom: IEEE, May 2025, pp. 1–10.

[17] D. Szafranski and A. Reinhardt, "ELORA: Even Longer Range Sensor Networking Through Modulated Concurrent LoRa Transmissions," in *IEEE WoWMoM 2023*, Boston, MA: IEEE, Jun. 2023, pp. 388–393.