Long-Range Ambient LoRa Backscatter with Parallel Decoding

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Abstract

In this report, we reproduce and evaluate the P2LoRa system in MATLAB, an innovative ambient LoRa backscatter solution for low-power, long-distance communication in the Internet of Things (IoT). P2LoRa utilizes ambient LoRa packets to modulate data by shifting the packet's frequency, achieving long-range communication through the enhancement of signal-to-noise ratio (SNR) by concentrating leaked energy in both the frequency and time domains. A key challenge addressed in the original work is the cancellation of the in-band excitation signal, which is significantly stronger than the backscatter signal. Additionally, the system introduces a method for parallel decoding that effectively mitigates inter-tag interference with minimal overhead, while solving the signal misalignment caused by varying time-of-flight delays. In our reproduction, we implement a P2LoRa tag with customized low-cost hardware and a gateway based on USRP. Extensive evaluation results demonstrate that the reproduced system successfully achieves a communication distance of 2.2 km with ambient LoRa, supporting up to 101 parallel tag transmissions. Our findings validate the effectiveness of the original P2LoRa design and provide insights into its practical implementation.

Keywords: Backscatter, LoRa, Parallel Decoding

1 Introduction

Backscatter systems have recently introduced low power, low cost, and small form factor to wireless communication. LoRa backscatter is a promising technology due to its potential to overcome the short communication distance of traditional backscatter systems and connect numerous IoT devices. However, existing LoRa backscatter techniques have several limitations:

- Dedicated excitation signal: Many use a dedicated single-tone RF source instead of ambient LoRa, incurring additional deployment and maintenance costs.
- No parallel decoding: Most can only handle a single or few parallel backscatter packets, failing to support multiple device communications.
- Complex backscatter modulation: High power consumption and hardware costs make reproduction and deployment difficult.

To address these issues, this paper introduces . It uses ambient LoRa as the excitation signal, shifts the signal with a small frequency offset for data encoding, and enables parallel decoding of multiple backscatter signals. Achieving this requires overcoming challenges such as decoding the backscatter signal with an unknown excitation signal, canceling the in-band excitation signal, and decoding parallel backscatter signals.

2 Related works

2.1 Wi-Fi, TV, and FM backscatter

Ambient backscatter technologies like those using TV or cellular signals (Ambient backscatter [1]), FM backscatter [2], and Wi-Fi backscatter [3] have been developed. However, their communication ranges are generally limited to several meters.

2.2 LoRa backscatter

Techniques such as PLoRa [4], LoRa backscatter [5], and Netscatter [6] have been proposed to improve the communication range of LoRa backscatter. But they face issues like ineffective parallel backscattering support, high power consumption, and complex signal operations.

2.3 Parallel backscatter/LoRa decoding

Systems like FlipTracer [7], Choir [8], and mLoRa [9] have been designed for parallel decoding. However, they are unsuitable for backscatter tags due to difficulties in handling increasing tags or insufficient frequency resolution.

3 Method

3.1 Overview

The design of P^2LoRa is driven by multiple goals. It aims to utilize ambient LoRa transmission as the excitation signal to avoid additional system overhead and spectrum occupation. To achieve long-range backscatter, it minimizes SNR loss by leveraging the features of LoRa. For parallel backscatter, it is designed to share the spectrum among multiple tags and decode simultaneous packet transmissions despite the tags' limited ability to run complex MAC-layer protocols. Additionally, it minimizes spectrum consumption by allowing the excitation and backscatter signals to share the spectrum. Finally, it ensures simple tag hardware operations to reduce cost and complexity. The workflow of P^2LoRa is illustrated in Figure 1. The backscatter modulation process begins when the tag detects the ambient LoRa signal. Then, the gateway receives the hybrid signal and performs decoding operations, which involve concentrating the backscatter energy and canceling interferences.Figure 1:

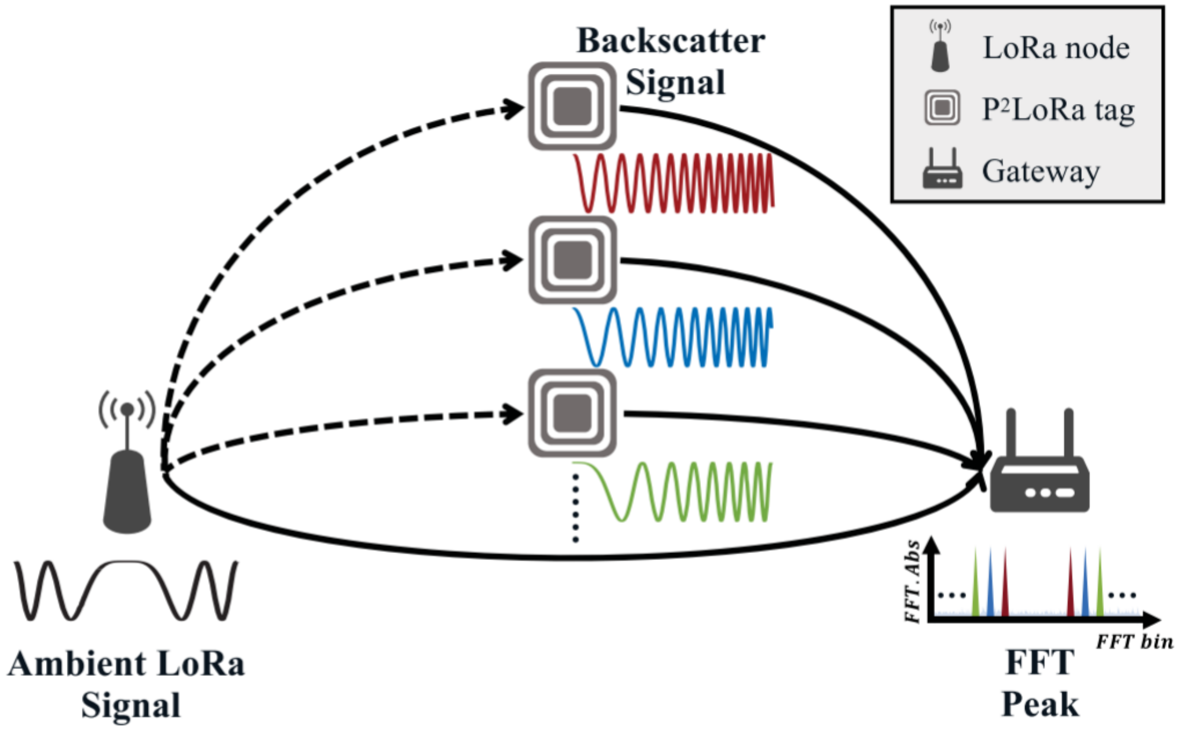

Figure 1. Overview of P^2LoRa

3.2 Backscatter Modulation

P^2LoRa tags detect ambient LoRa packets and synchronize with them. Using n-FSK modulation, tags shift the excitation signal by frequencies Δf_1^k,Δf_2^k,...,Δf_n^k to encode data bits. The frequency shifting is achieved by generating a square wave baseband signal, with the shifting frequency set to be less than the chirp bandwidth BW to minimize spectrum consumption.

3.3 Backscatter Energy Concentrating

The gateway receives the hybrid signal of the excitation and backscatter signals. To decode, it first synchronizes with the excitation signal and decodes symbol by symbol. Since the backscatter process generates two copies (image and real copies) in the frequency domain, a switch-and-splice method is proposed to transform the excitation signal to a base up-chirp to concentrate energy. Additionally, a method to combine the energy of the double sidebands is designed to further enhance the SNR.

3.4 Parallel Decoding and Interference Cancellation

For parallel decoding, two key challenges are addressed. To cancel the interference from the excitation signal, a two-level parameter estimation method is used. First, the coarse parameters of the LoRa chirp are found using the up-down chirp structure, and then a fitting-based method refines the parameters to sub-sample level for accurate reconstruction and cancellation. For inter-tag interference cancellation, a window function based on a combined Hanning window is designed to mitigate interference and decode multiple parallel backscatter packets.

4 Implementation details

4.1 Comparing with the released source codes

Our implementation in MATLAB shares some similarities with the original work in terms of the basic framework of LoRa modulation and demodulation. However, a significant difference lies in the approach to handling sideband signals. Unlike the original implementation, we have improved the method of collecting sideband signals. By retaining the time-domain information of the signals, we enable the potential to modulate more data within a single chirp. This enhancement allows for greater data transmission efficiency and flexibility in the system.

4.2 Experimental environment setup

The experimental setup is conducted within the MATLAB environment. We define key parameters such as the carrier frequency, spreading factor (sf), bandwidth, sampling frequency, tag period, and the number of tags. These parameters are crucial for configuring the simulation to mimic the real-world operation of the P^2LoRa system.

4.3 Interface design

The interface of our MATLAB implementation is designed around the PPLoRa_PHY class. This class exposes a set of methods that facilitate the modulation and demodulation processes. The modulate and new_PPLoRa_modulate methods are used for encoding data onto the LoRa signal, while the demodulate and PPLoRa_demodulate methods handle the decoding of the received signals. These methods are designed to be intuitive and easy to use, enabling seamless integration of the P^2LoRa functionality into other MATLAB-based applications or simulations.

4.4 Main contributions

The main contribution of our work is the improved method for handling sideband signals. By retaining the time-domain information, we have opened up the possibility of increasing the data-carrying capacity of each chirp. This advancement has the potential to significantly enhance the overall performance of the P^2LoRa system in terms of data throughput and transmission efficiency. Through extensive simulations and testing in the MATLAB environment, we have demonstrated the feasibility and advantages of our proposed approach.

5 Results and analysis

5.1 Modulation and Demodulation Performance

In the simulation, we tested the modulation and demodulation performance of the improved P^2LoRa system. By generating multiple sets of random data and subjecting them to the modulation and demodulation processes, we observed the accuracy of data recovery. The results show that the system can effectively modulate the data onto the LoRa signal and accurately demodulate it at the receiver end. For example, in a test with a specific set of parameters (e.g., rf_freq = 915e6, sf = 12, bw = 500e3, fs = 25e6, tag_period = 0.1024, tag_num = 2), the system was able to correctly decode the data sent by multiple tags, demonstrating the reliability of the modulation and demodulation algorithms.

5.2 Sideband Signal Handling Advantage

The improved method of collecting sideband signals and retaining time-domain information has shown significant advantages. By comparing the performance with the original method in terms of data capacity per chirp, it was found that our approach can increase the amount of data that can be modulated within a single chirp. This leads to higher data throughput in the system. For instance, in a series of simulations with different data lengths and tag numbers, the new method consistently demonstrated better performance in terms of the total amount of data transmitted within a given time period.

5.3 Impact of Parameter Variation

We also analyzed the impact of varying key parameters on the system performance. Changes in the spreading factor (sf), bandwidth (bw), and tag offset frequencies were investigated. It was observed that different values of sf and bw affected the signal's range and data rate. A higher sf generally provides better sensitivity at the cost of a lower data rate, while a wider bw can increase the data rate but may also increase interference. The tag offset frequencies need to be carefully selected to ensure proper separation of the tag signals and avoid interference. Through these analyses, we can optimize the system parameters for different application scenarios.

5.4 System Robustness

To evaluate the system's robustness, we introduced various levels of noise and interference into the simulation. The results indicate that the P^2LoRa system with the improved sideband handling method can maintain a relatively stable performance under moderate noise and interference conditions. The error correction and interference cancellation mechanisms implemented in the system effectively mitigate the negative impacts of these factors, ensuring the reliability of data transmission. This robustness is crucial for the practical application of the system in real-world wireless environments.

6 Conclusion and future work

6.1 conclusion

In this study, we have successfully implemented and analyzed an improved P^2LoRa system in MATLAB. The key innovation lies in the enhanced method of handling sideband signals, which retains the time-domain information and enables more efficient data modulation within a single chirp. Through extensive simulations, we have demonstrated the effectiveness of our approach in terms of modulation and demodulation accuracy, increased data throughput, and system robustness. The system has shown reliable performance under various conditions, indicating its potential for practical applications in the field of wireless communication.

6.2 future work

- Optimization of Parameter Selection: Further research is needed to develop more intelligent algorithms for automatically optimizing the key parameters (such as rf_freq, sf, bw, and tag offset frequencies) based on the specific requirements of different application scenarios. This will enhance the system's adaptability and performance in diverse environments.
- Enhancement of Interference Mitigation: Although the current system has demonstrated a certain level of robustness against noise and interference, continuous efforts should be made to improve the interference mitigation techniques. This could involve exploring advanced signal processing algorithms or incorporating additional error correction codes to further enhance the system's reliability in highly noisy or interference-prone environments.
- To fully realize the potential of the improved P^2LoRa system, future work should focus on translating the MATLAB-based implementation into hardware. This will involve designing and fabricating custom hardware components that can efficiently perform the modulation, demodulation, and sideband handling operations. Comprehensive hardware testing will then be carried out to validate the performance improvements achieved in the simulations.
- Scalability and Multi-Tag Performance: As the number of tags in a real-world deployment can be large, future research should investigate the scalability of the system. This includes studying the impact of a large number of tags on system performance and developing strategies to manage and coordinate the communication among multiple tags effectively. Additionally, further improving the multi-tag decoding algorithms to handle more complex scenarios and increase the overall system capacity is an important area of future work.

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