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LoFi: Enabling 2.4GHz LoRa and WiFi Coexistence by Detecting Extremely Weak Signals

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***Abstract*—Low-Power Wide Area Networks (LPWANs) emerges as attractive communication technologies to connect the Internet-of-Things. A new LoRa chip has been proposed to provide long range and low power support on 2.4GHz. Comparing with previous LoRa radios operating on sub-gigahertz, the new one can transmit LoRa packets faster without strict channel duty cycle limitations and have attracted many attentions. Prior studies have shown that LoRa packets may suffer from severe corruptions with WiFi interference. However, there are many limitations in existing approaches such as too much signal processing overhead on weak devices or low detection accuracy. In this paper, we propose a novel weak signal detection approach, LoFi, to enable the coexistence of LoRa and WiFi. LoFi utilizes a typical physical phenomenon Stochastic Resonance (SR) to boost weak signals with a specific frequency by adding appropriate white noise. Based on the detected spectrum occupancy of LoRa signals, LoFi reserves the spectrum for LoRa transmissions. We implement LoFi on USRP N210 and conduct extensive experiments to evaluate its performance. Results show that LoFi can enable the coexistence of LoRa and WiFi in 2.4GHz. The packet reception ratio of LoRa achieves 98% over an occupied 20MHz WiFi channel, and the WiFi throughput loss is reduced by up to 13%.**

I. INTRODUCTION

Recent years have witnessed the emergence of Low-Power Wide Area Networks (LPWANs) as attractive communication technologies for connecting a huge number of IoT (Internet-of-Things) devices. LPWANs enable low-power devices (e.g., milliwatts power consumption) to transmit at low data rates (kilobits per second) over long distances (several kilometers). Among many LPWANs, LoRaWAN [1] is a technology that has attracted many research interests [2], [3], [4], [5], [6], [7], [8], [9].

Recently, Semtech company has proposed a new LoRa chip SX1280 to provide long-range and low-power wireless communications over 2.4GHz [10]. Comparing with previous LoRa radios operating on sub-gigahertz (sub-GHz LoRa), the new one (2.4GHz LoRa) does not require a dedicated spectrum. In addition, it can receive LoRa packets without strict channel duty cycle limitations (e.g., 1% channel usage limitations [1]). In the meantime, the maximum available bandwidth is increased from 500kHz to 1600kHz, resulting in a faster data rate (i.e., from 21kbps to 70kbps) [10]. Therefore, 2.4GHz LoRa can provide wider support of IoT applications such as low latency health-care connections [11] and has attracted many attentions [12] (In the latter, we denote “LoRa” as 2.4GHz LoRa if not state.)

Prior studies have shown that LoRa packets may suffer from severe corruptions with WiFi interference [13], despite the built-in error recovery mechanisms, e.g., FEC and symbol interleaving [10]. There are many works on enabling the coexistence between ZigBee and WiFi [14], [15], [16], [17], [18], [19], which may be valuable references for the coexistence between LoRa and WiFi, e.g., exchanging coordination information to avoid collisions using cross-technology communication [14], [15], [16], [17], cancelling the cross-technology interference by adopting advanced wireless hardware such as MIMO [18], or performing accurate in-packet corruption estimation and lightweight partial packet recovery [19]. However, the above works generally fail when being applied to weak wireless devices equipped with LoRa, such as implanted biomedical devices [20] and embedded sensors [21] that are increasingly important in emerging application scenarios such as connected health-care and smart cities. They require too much power consumptions for continuously channel sampling, and sophisticated signal extraction and processing.

Recently, a new wireless PHY technology EmBee [22] has been proposed to shift the overhead from weak devices equipped with ZigBee to strong devices equipped with WiFi, to enable the cross-technology coexistence. The strong WiFi devices actively sense the spectrum occupancy of the weak ZigBee devices before transmissions using distinguishable features of Carrier Frequency Offset (CFO). The sensed spectrum is reserved for weak devices to perform collision-free transmissions while other subcarriers are still utilized by WiFi to allow concurrent transmissions.

However, EmBee cannot be applied for the coexistence of LoRa and WiFi. This is because LoRa devices can correctly receive packets at extremely low RSSI (e.g., -120dBm) level to achieve long range communication [23]. These low signals can easily be submerged in highly noisy environments (as shown in Section III) and hence cannot be detected by traditional approaches, e.g., CFO [22] utilized by EmBee. As such, WiFi transmitters cannot even notice the existence of LoRa transmissions, resulting in possible corruptions to LoRa transmissions.

In this paper, we propose a novel weak signal detection approach, LoFi, to enable the coexistence of LoRa and

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WiFi. LoFi utilizes a typical physical phenomenon Stochastic Resonance (SR) [24] to boost weak signals with a specific frequency by adding appropriate white noise. Although the SR system has been widely studied in physical areas [24], [25], it is still challenging to be applied to detect weak LoRa signals due to two reasons. *i)* LoRa employs the time varying frequency based modulation (e.g., chirp) and the existing SR system targeting for one specific frequency can not be directly utilized. *ii)* Existing SR systems can only detect periodic signals with AWGN (Additive White Gaussian Noise) environments instead of heavy WiFi interference [24].

To detect weak LoRa signals under heavy WiFi interference effectively, LoFi first carefully transforms one of the modulated frequencies of LoRa chirp into a smaller frequency using the trick of trigonometric identity, while the other modulated frequencies are shifted to larger frequencies. Then the lower pass filtering is performed to filter signals with larger frequencies, and the smaller frequency is reserved and fed into the SR system for weak signal detection. Note that the smaller frequency is carefully selected such that WiFi interference can also be moved to another frequency range that is separated from the above smaller frequency.

Based on the detected spectrum occupancy of LoRa signals, LoFi reserves the spectrum for LoRa transmissions. However, reserving spectrum can also degrade WiFi performance. To reduce the WiFi performance loss, we design a bandwidth-aware spectrum reservation approach to adaptively reserve the bandwidth for LoRa transmissions. On the other hand, the built-in error recovery functions of LoRa are utilized such that the performance loss can be further reduced.

We implement LoFi on the software-defined platform, USRP N210 [26]. Extensive experiments show that LoFi can improve LoRa detection accuracy by 63.1% and 66.2% on average compared with state-of-the-art approaches —- DOF [27] and EmBee [22]. When enabling the coexistence of LoRa and WiFi, LoFi can significantly improve LoRa packet reception ratio by 77.9% on average compared with EmBee. The WiFi throughput loss can be controlled by up to 13%.

The contributions of this paper can be summarized as follows:

- We conduct extensive experiments to identify the limitations of existing cross-technology coexistence approaches for detecting extremely weak LoRa signals under WiFi.
- We propose a novel weak signal detection approach, LoFi, which utilizes a typical physical phenomenon Stochastic Resonance to boost weak signals' SNR. The frequencies of weak signals are transformed carefully into a specific frequency leveraging the modulation characteristics of LoRa chirp, such that the resulting signals are distinguishable under heavy noise or interference in the frequency domain.
- We implement LoFi on USRP N210 and evaluate its performance extensively. Results show that LoFi can enable the coexistence of LoRa and WiFi. The packet reception ratio of LoRa achieves 98% over an occupied 20MHz WiFi channel, and the WiFi throughput loss due to the spectrum reservation is reduced by up to 13%. LoFi can significantly improve the signal detection accuracy compared with the state-of-art approaches.

The rest of this paper is organized as follows. Section II introduces the related work. Section III conducts extensive experiments to identify the limitations of existing approaches and then motivate our work. Section IV shows the key components of LoFi. Section V presents the evaluation results. Section VI discusses the deployments in existing networks and the generality to other wireless technologies and finally, Section VII concludes this paper.

II. Related Work

Cross-technology coexistence. EmBee [22] enables cross-technology coexistence by adaptively reserving spectrum from WiFi devices for ZigBee devices. Its coexistence performance is poor for the extremely weak LoRa signals. The features of LoRa are submerged in heavy noise or interference. Different from EmBee, LoFi utilizes the Stochastic Resonance to boost weak signals, which improves the probability of detecting weak signals.

WISE [28] enables coexistence by predicting the white space between WiFi frames, and then utilizing such white space for ZigBee transmissions. BuzzBuzz [29] improves the resilience of ZigBee transmissions over WiFi interference by customizing the Zigbee packet with an extra header to increase the packet reception rate. Different from the above approaches, LoFi can sense the occupied spectrum of LoRa, and then reserves a clear spectrum for LoRa to perform collision-free transmissions even under denser WiFi traffic load. Gsense [30] achieves cross-technology coexistence by customizing the Zigbee preamble to coordinate WiFi transmissions. However, the ZigBee throughput is degraded due to the additional overhead actively sending customized signals.

Cross-technology communication is another direction of enabling cross-technology coexistence by exchanging explicit coordination information among cross-technology protocols to avoid transmission collisions. FreeBee [14] conveys cross-technology information by adding a modulated beacon that can be demodulated from heterogeneous devices. WEBee [15] provides an analog emulation approach to let WiFi signals to emulate the wave of ZigBee signals, achieving up to 250kbps data rate. WIDE [31] provides a digital emulation approach to improve communication reliability. B2W2 [16] encodes cross-technology information by directly adjusting the adjacent BLE packets' transmission power to form a sine wave. The sine wave with varying frequency is modulated as different bits. However, all of the above approaches can only work in a very limited range with relatively higher RSSI, which is rare for LoRa transmissions as stated in existing works [23].

Spectrum sensing and interference detection. DOF [27] utilizes the autocorrelation of signals to sensing the spectrum occupancies of different types of signals. CrossZig [32] exploits the variations in demodulated results of signals (i.e., soft values) for interference type detection (i.e., intra- and

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cross-technology interference) and then enables an appropriate mechanism to recover the corrupted packet. SoNIC [33] classifying different interference sources (e.g., Bluetooth and WiFi) by extracting the distinct patterns in 802.15.4 packets, e.g., variances of in-packet RSSI series, link quality indication and etc. Smoggy-Link [34] maintains a link model to perform adaptive link selection and transmission scheduling. However, the effectiveness of the above approaches relies heavily on the relatively higher RSSI of the target signal. For weak signals like LoRa, the above works generally fail due to the submerged features.

Performance optimization for LoRaWAN. Charm [2] enhances the coverage of LoRaWAN and the battery life of client devices through multiple gateway combinations. Choir [3] is a collision decoding approach in LoRaWAN exploiting hardware imperfections. DaRe [4] recovers the lost data in LoRaWAN using the redundant information calculated from previous frames. Martin *et. al.* [6] develop a link probing based approach to automatically adjust the parameters for LoRa transmissions. Thiemo *et. al.* [7] propose to use a directional antenna and multiple gateways to deal with the inter-network interference. However, it requires heavy deployment and modification cost on all of the end-devices.

III. Background and Motivation

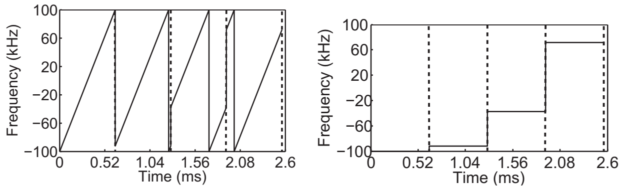
Before detailing the design of LoFi, we first provide the background of LoRa, which is a low-power long-range wireless technology operating on 2.4GHz. Then we give a brief introduction of the Stochastic Resonance (SR) system and use a simple example to show how SR can boost weak signals. Finally we discuss the limitations of detecting weak LoRa signals using existing approaches.

A. Preliminaries of LoRa Operating on 2.4GHz

The modulation scheme of LoRa is the same as sub-gigahertz LoRa, i.e., Chirp Spectrum Spread (CSS) [10]. A chirp is a sinusoidal signal of frequency increases or decreases over time. CSS uses its entire allocated bandwidth to broadcast a signal, making it robust to the noise and can be received at very low power [23]. LoRa provides a wider bandwidth, e.g., from 200kHz to 1600kHz, resulting in a larger raw data rate up to 87.5kbps [10]. While sub-gigahertz LoRa provides the bandwidth up to 500kHz (21.875kbps) [1].

To modulate a LoRa chirp, given the bandwidth B and the spreading factor S, a LoRa symbol y is modulated by shifting the initial frequency of the time varying frequency sequence. For example, Fig. 1(a) presents how to modulate the symbol 0, 5, 40 and 110 with the spreading factor S=7 and bandwidth B=200kHz. For the symbol 40, the initial frequency is set to $B \cdot y/2^S$ = $200kHz \cdot 40/2^7$ = 62.5kHz. In Fig. 1(a), the frequency is 62.5-100 = -37.5kHz.

To demodulate LoRa signals, LoRa first multiples original signals with a reverse chirp starting at the frequency zero. It results in a signal with a consistent frequency of the initial frequency. As shown in Fig. 1(b), the time varying frequencies are transformed into consistent frequencies, which are the initial frequency. Then the information is demodulated by mapping the initial frequency to the corresponding symbol. When there is interference on the modulated signals, e.g., WiFi interference on LoRa signals, the results of multiplying a reverse chirp will not be a single frequency but multiple possible frequencies. Then the symbols are corrupted.



(a) LoRa modulation. (b) LoRa demodulation.

Fig. 1: LoRa modulation and demodulation for symbol 0, 5, 40 and 110, SF=7, BW=200kHz.

B. Stochastic Resonance

A typical SR phenomenon can be described based on a second-order Duffing Holmes nonlinear differential equation. A Duffing Holmes Oscillator describes the trajectory of a particle's motion. In physical scenarios, suppose a particle with mass=1 is impressed with an outer force $F(t)$, damped force $\gamma\frac{dx}{dt}$ and a quartic double-well potential force $V(x)$, then Duffing Holmes differential equation can be formally expressed as follows [35]:

$$\frac{d^2x}{dt^2} + \gamma\frac{dx}{dt} + V(x) = F(t) \quad (1)$$

Where $\frac{d^2x}{dt^2}$ denotes the acceleration of the particle, $\frac{dx}{dt}$ denotes the damped force. And $V(x) = -ax + bx^3$, where a and b are parameters that describe the shape of the double-well potential force.

In existing works, the outer force can be expressed as the sum of the driven signal $A_g cos(2\pi f_g t)$, the target weak signal $s(t)$ and the noise $n(t)$, then Eq. 1 can be rewritten as:

$$\frac{d^2x}{dt^2} + \gamma\frac{dx}{dt} - ax + bx^3 = A_g cos(2\pi f_g t) + s(t) + n(t) \quad (2)$$

Where $n(t)$= $D\sigma(t)$, D is the noise intensity and $\sigma(t)$ represents Additive Gaussian White Noise (AGWN) with zero mean and unit variance. And $s(t) = A_w cos(2\pi f_w t)$, where A_w is the extremely weak amplitude, f_w is the frequency of the target signal. To boost the target weak signal $s(t)$ using the above SR model, f_w should be equal to f_g. In addition, A_g is the critical amplitude of the SR model and should be carefully estimated, so that when $s(t)$ is superimposed on $F(t)$ the SR model can produce large amplitude results.

We use a simple example to see how the target signal $s(t)$ can be boosted by the above SR model. Suppose a=10, b=5, and γ=0, then the particle trajectory motion function can be as shown in Fig. 2(a). The outer force power $F(t)$ is plotted in the y axis and normalized within (-20, 20). The particle moves following the trajectory system among (-2, 2). Note that there are two transition points A and C. When there is no $s(t)$ in $F(t)$, the resulted particle trajectory has very small

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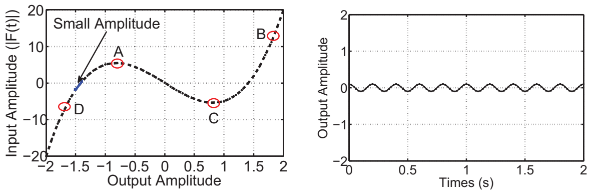
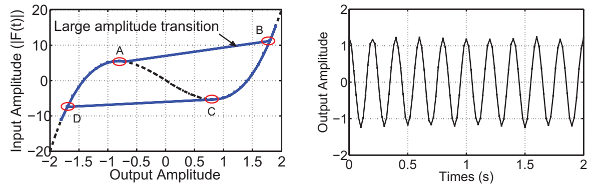


(a) Potential function. (b) SR output signal.

Fig. 2: Results of the SR model when the target signal $s(t)$ is not in the outer force $F(t)$ (frequency=4Hz).



(a) Potential function. (b) SR output signal.

Fig. 3: Results of the SR model when the target signal $s(t)$ is presented in the outer force $F(t)$.

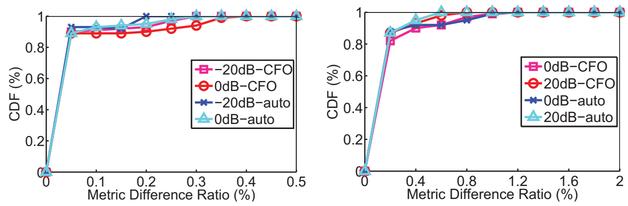
output amplitude (e.g., 0.2) as shown in Fig. 2(b). On the other hand, when the target weak signal $s(t)$ is imposed on $F(t)$, the resulted particle trajectory has a large amplitude transition thanks to the carefully estimated critical amplitude A_g (e.g., the transition from point A to point B and from point C to point D as shown in Fig. 3(a)). The resulted amplitude is strengthened and the frequency of the output signal is equal to f_w (as shown in Fig. 3(b)). The target weak signal is thus detected.

However, the LoRa signal is modulated based on CSS, i.e., the time varying frequency modulation. The most important two parameters (i.e., the target frequency f_g and the critical amplitude A_g) of the SR model are predefined or carefully estimated before detecting the weak signal. The SR model cannot always match the time varying frequency signal, resulting in inefficiency when detecting LoRa signals. To deal with this challenge, we carefully transform the time varying frequencies in a LoRa chirp into one specific frequency utilizing the trigonometric equations. Then the SR model can be used to effectively boost the weak signal with the specific frequency.

C. Why Existing Works Fail?

There are existing works for strong WiFi devices to detect weak ZigBee devices [27], [22], [36]. For example, EmBee [22] utilizes the Carrier Frequency Offset (CFO) to detect ZigBee signals from WiFi signals, and DOF [27] extract the periodic features of signals to differentiate different types of signals by calculating the autocorrelation metrics of signals. However, they both can not detect LoRa signals due to its extremely weak RSSI, for example, the receiver sensitivity of LoRa is -134dBm [37] that is much lower than -95dBm of ZigBee [38]. The signal features utilized by existing works are submerged in noise or dense interference, especially in crowded 2.4GHz unlicensed band.

We conduct experiments to validate the above observations. Two LoRa devices communicate with each other at a distance



(a) Impact of SNR. (b) Impact of WiFi tx gain.

Fig. 4: Effects of using existing metrics for detecting weak LoRa signals.

of 200m, with the transmission power of 10dBm, SF=7, and BW=200kHz. The WiFi interferer is placed at a distance of 1m. Two typical metrics (CFO [22] and autocorrelation [27]) are evaluated. In Fig. 4, 'auto' means using the autocorrelation approach. Given the metric value without LoRa signals m_w and with LoRa signals m_l, then the metric difference ratio is defined as $(m_w - m_l)/m_l$. The above indicator is utilized since existing works also use similar methods to evaluate their approaches [22], [27]. Fig. 4(a) shows that when SNR is lower than -10dB, the difference ratio of CFO between the signals with/without LoRa transmissions are too small to be used, i.e., lower than 0.1%. The results are similar to autocorrelation, i.e., lower than 0.3%. It is a common SNR for LoRa's long range transmissions [23]. Fig. 4(b) shows that when the WiFi transmission gain is larger than 10dB, the above features are also submerged in WiFi. We can conclude that existing approaches both fail to detect the extremely weak LoRa signals under heavy WiFi interference.

IV. Design

The goal of LoFi is to detect weak LoRa signals to enable the coexistence of LoRa and WiFi. Existing works suffer from low packet capture ratio due to the submerged and weak features sourced from the extremely low SNR and heavy interference on 2.4GHz. To tackle the above problem, LoFi utilizes a typical phenomenon in the physical area, i.e., Stochastic Resonance (SR) [35], [25], [24], which can be described by the SR model as stated in Section III.

However, the existing SR model can not be directly applied to detect weak LoRa signals due to 1) the time varying frequency modulation scheme of LoRa, i.e., there is a set of frequencies in LoRa signals (chirp) but not a specific frequency, while the existing SR model can only detect signals with a specific frequency. 2) On the other hand, the WiFi interference may further reduce the detection accuracy because the frequency of WiFi signals may be overlapped with LoRa, e.g., the overlapped channels with a 1600kHz LoRa band and a 312.5kHz WiFi subcarrier. Therefore, to design an effective LoRa detection system, LoFi carefully transforms the time varying frequency into one single frequency such that a specific frequency can be used to determine the existence of LoRa signals. And the SR model can thus be effectively utilized to pull the extremely low power signals with the specific frequency from heavy noise. On the other hand, WiFi

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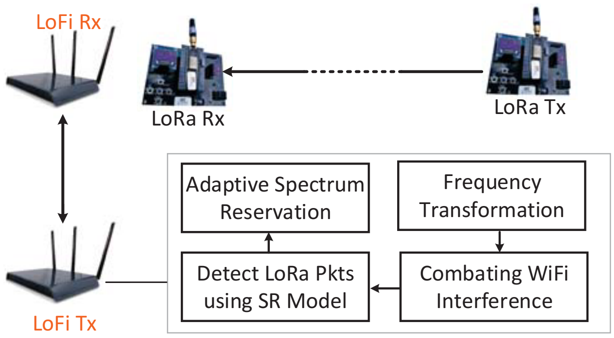


Fig. 5: Overview of LoFi.

signals are carefully moved to another frequency range that is separated from the above extracted frequency.

Fig. 5 presents an overview of LoFi. There are four main procedures: First, LoFi samples and records signals in a sliding window with length W. The signals from each channel are stored separately. LoFi carefully transforms the received signals into the signals with a specific frequency, which can only be transformed from a LoRa chirp. The low pass filter is performed to filter signals with larger frequencies, e.g., WiFi signals. Second, to mitigate the false detection problem caused by WiFi signals, we selectively skip the frequency transformations. After that, the pre-processed signals are fed into the SR model to perform weak signal detection. Once there are signals with specific frequency are found in the signals, the LoRa transmissions are captured. Finally, the detected spectrum is reserved by LoFi to allow concurrent transmissions of LoRa and WiFi.

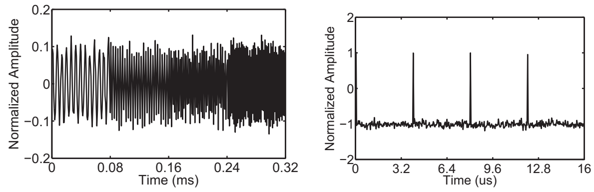
A. Obtaining One Specific Frequency utilizing Trigonometric Transformation

A straightforward way is to perform the LoRa demodulation to get one specific frequency (i.e., multiplying a reverse chirp). However, it will result in a initial frequency (as stated in Section II) that is unknown to the receiver and thus can not be utilized by the SR model. To address this challenge, we utilize the trigonometric identity to obtain a specific frequency that can be known by the receiver. In the next we present the basics of the trigonometric identity and how can we obtain the specific frequency.

Multiplication with a set of carefully selected frequencies. In the following, we use the following LoRa PHY parameter settings by default, where the spreading factor S is 7, and the bandwidth B of LoRa signals is 1600kHz. Then for the symbol "0000000", the sequence of the LoRa chirp starts from 12.5kHz to 1600kHz with the step of 12.5kHz, as shown in Fig. 6(a).

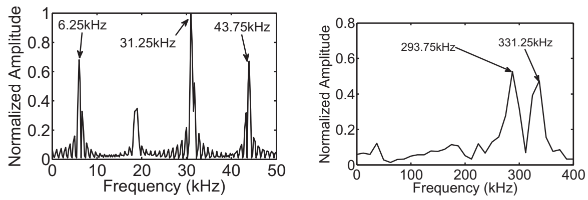
Based on the product-to-sum identities shown in Eq. 3, we can perform the multiplications to transform one frequency to others:

$$cos\theta cos\varphi = \frac{1}{2}[cos(\theta-\varphi)+cos(\theta+\varphi)] \quad (3)$$



(a) Received LoRa signals. (b) Received WiFi signals.

Fig. 6: The received signals. (a) The first four frequencies of the LoRa signal: 12.5kHz, 25kHz, 37.5kHz, and 50kHz. (SF=7, Bandwidth=1600kHz). (b) WiFi is the sum of frequencies from 312.5kHz to 20MHz.



(a) Spectrum of LoRa signals. (b) Spectrum of WiFi signals.

Fig. 7: Spectrum occupancy after multiplication with 18.75kHz signals.

Where θ denotes the frequency used in a LoRa chirp, and φ is one of the carefully selected frequencies. For example, suppose θ equals to 12.5kHz and φ equals to 2.5kHz, then after the multiplication we will obtain the sum of the two resulted frequencies, 10kHz and 15kHz. Then the next problem is how to select appropriate frequencies for multiplications to convert all frequencies modulated in a LoRa chirp to the target frequency f_g.

An intuitive approach is to transform the frequency one by one, however, it will cause many undesirable and redundant processing overhead. We propose an approach that can reduce the half of the processing overhead compared to the intuitive approach. i.e., we can transform two frequencies of a LoRa chirp into the specific frequency at a time. The key idea is to carefully select the target frequency f_g such that one processing operation can transform two frequencies simultaneously. In the LoRa signal, we select the half of the step frequency (e.g., 12.5kHz/2 = 6.25kHz in the above example) as f_g. Such that by multiplying the middle frequency of the two adjacent frequencies in a LoRa chirp, we can transform the two adjacent frequencies into the target frequency f_g. In addition, the target frequency is smaller than all frequencies in the LoRa chirp, which will ease the process of finally extracting the target frequency.

For example, using the LoRa symbol "0000000" as the example. the first two adjacent frequencies in the LoRa chirp are 12.5kHz and 25kHz (as shown in 6(a)). When multiplying the received signals with the middle frequency (i.e., 18.75kHz) of the about two adjacent frequencies, we will obtain the resulted frequencies (31.25kHz, -6.25kHz, 43.75kHz, and 6.25kHz). Note that -6.25kHz is actually the same with 6.25kHz (as shown in 7(a)). For the other frequencies in the LoRa chirp,

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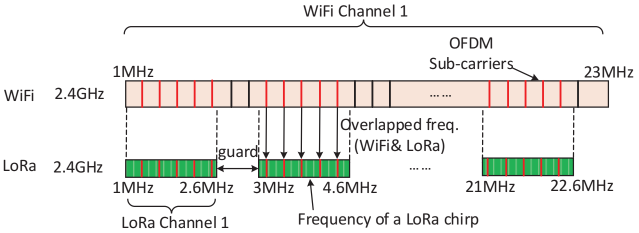

Fig. 8: The example channel allocation of LoRa (*B*=1600kHz). We directly skip the transformation of the frequencies that may cause the false detection (as shown in red line).

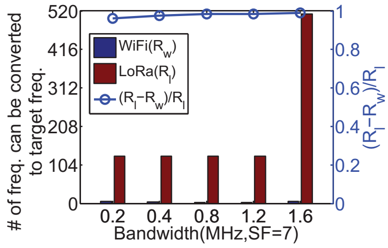

Fig. 9: The top-5 parameter settings that WiFi sub-carriers will be converted to the target frequency by mistake. Larger $\frac{R_l - R_w}{R_l}$ means there is a lower probability of causing false detection of LoRa signals.

the resulted frequencies will be larger than 6.25kHz. Then by performing the low pass filter with a cutoff frequency of 6.25kHz, only the signal with 6.25kHz will be retained and is stored into the transformation queue Q. The above operation is performed iteratively until all frequencies in the LoRa chirp are processed. The final resulted signals are the sum of the signals in Q that contains only one target frequency (e.g., 6.25kHz in the above example).

To be generative to other LoRa parameters, we have the following procedures to infer the set of frequencies F_φ to be multiplied. Given the spreading factor S and the bandwidth B, then the target frequency f_g that all frequencies of a LoRa chirp will be converted to is $\frac{B}{2^{S+1}}$. The set of appropriate frequencies to be multiplied can be expressed as $F_\varphi = \frac{B}{2^S} + \frac{B}{2^{S+1}} + i \cdot \frac{B}{2^{S-1}}$, for $i \in \{1, 2^{S-1}\}$. They are actually the middle frequencies between two adjacent frequencies of a LoRa chirp.

B. Combating with WiFi Interference

As for WiFi signals, Fig. 6(b) presents an example for WiFi signals (802.11n). The bandwidth is 20MHz, and there are 64 sub-carriers. Therefore a WiFi OFDM symbol is composed of the frequencies from 312.5kHz to 20MHz with the step of 312.5kHz. When performing multiplications with the 18.75kHz signals as stated in Section IV-A, the frequency of the 312.5kHz sub-carriers becomes 293.75kHz and 331.25kHz as shown in Fig. 7(b). Other sub-carriers can be calculated similarly.

In ideal, the resulted frequencies are both larger than 6.25kHz and will be filtered using the low-pass filter. However, few WiFi signals may be also converted to the target frequency by mistake. For example, the frequency of second WiFi sub-carrier (625kHz=312.5kHz×2) is the same to the 50-th frequency of the LoRa chirp when modulating the symbol "0000000" (625kHz=12.5kHz×50). By multiplying the frequency 618.75kHz, the target frequency (i.e., 6.25kHz) can also be transformed by the WiFi signal. It may cause the false detection case in LoFi (i.e., WiFi signals are mistakenly classified as the LoRa signal).

To combat with the WiFi interference, we directly remove the frequencies that may cause the false detection in the set F_φ. In the above example, we do not perform the multiplications with the frequency 618.75kHz. Note that LoFi knows the channel that WiFi occupies now, then given the channel allocation strategy of LoRa, the set of frequencies that should be removed from F_φ can be inferred off-line. Fig. 8 presents an example channel allocation strategy of LoRa, where B=1600kHz and SF=7. Under this parameter settings, there are at most five OFDM sub-carriers the same to the frequencies of the LoRa channel one, e.g., the first OFDM sub-carrier (312.5kHz=312.5kHz×1) and the 25-th frequency in the LoRa chirp (312.5kHz=12.5kHz×25). Then for the LoRa channel one, we do not perform the frequency transformation on the five overlapped OFDM sub-carriers. For other LoRa channels, LoFi does the similar operations.

However, eliminating too many frequencies in F_φ will degrade the signal detection performance of the SR model. Therefore, it is necessary to evaluate the ratio of the removed frequencies to all frequencies F_φ. The smaller the ratio, the less the impact on the weak sign detection performance. Formally, given the number of frequencies that can be converted to the target frequency as R_l and R_w for LoRa signals and WiFi signals, the optimization goal is find an optimal set F_φ to maximize the difference between R_l and R_w. It can also be expressed as:

$$\max_{F_\varphi} \frac{R_l - R_w}{R_l} \tag{4}$$

Currently, we still use the F_φ introduced in Section IV-A since this empirical approach can already obtain a satisfactory result (as shown in the evaluation section). And we leave the approach to find the optimal frequency set F_φ to minimize the interference from WiFi as the future work. We have conducted extensive experiments to investigate the difference between R_l and R_w using the empirical approach. Fig. 9 shows the results under different parameter settings. Results show that the ratio of R_l to R_w is 3.1% at most, indicating the effectiveness of the empirical approach.

C. LoRa Signal Detection using the SR Model

Once we have set the target frequency, we can estimate the parameters of the SR model that can best boost the weak signals with the target frequency. The parameters are estimated using a typical approach, i.e., the fourth-order Runge-Kutta (RK4) method [35]. After performing RK4, we can get the boosted signals with the target frequency f_g. Then when a clear peak is presented at the target frequency f_g in the frequency domain, LoRa signals are detected. To determine

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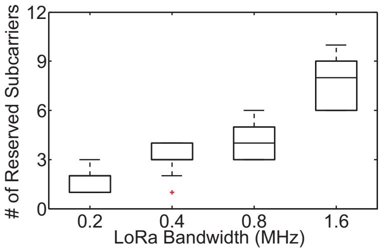

Fig. 10: The number of reserved subcarriers for LoRa.

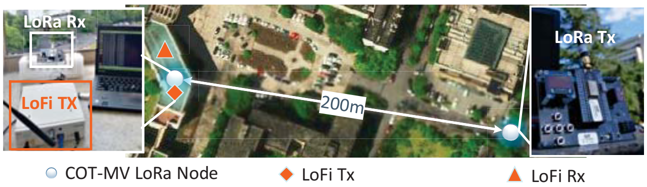

Fig. 11: Experimental testbed.

which channel is occupied by LoRa, we iteratively perform the channel sampling, frequency transformation on each LoRa channel overlapped with WiFi channels.

D. Bandwidth-Aware Spectrum Reservation and WiFi Throughput Loss Minimization

When LoRa signals are detected, the spectrum can be reserved by LoFi for LoRa's transmissions. However, when the whole spectrum is reserved for LoRa transmissions, it will also cause the throughput loss of WiFi. For example, in a 20MHz WiFi channel, each OFDM subcarrier occupies 20M/64 = 312.5kHz spectrum. Therefore, in theory the minimum number of needed OFDM subcarriers is $\lceil 1600/312.5 \rceil$=6 when the occupied LoRa bandwidth is 1600kHz. On the other hand, reserving a fixed spectrum will also waste the opportunity to reduce the WiFi throughput loss due to the alterable LoRa bandwidth (e.g., from 200kHz to 1600kHz). Fig. 10 show that the number of reserved OFDM subcarriers for LoRa is averaged at 7 and could be up to 10 in extreme cases for 1600kHz bandwidth.

According to Fig. 10, the perfect spectrum reservation approach results in up to 21% throughput loss in WiFi. To reduce the throughput loss, LoFi first selects a proper number of subcarriers to be reserved according to the detected bandwidth occupied by LoRa, e.g., one subcarrier for 200kHz and three subcarriers for 400kHz. To further reduce the WiFi throughput loss, LoFi utilizes the built-in error correction capability in LoRa [10]: the spread factor, FEC and symbol interleaving. For example, a LoRa symbol lasts for 80μs with spreading factor seven and bandwidth 1600kHz, then only 4 OFDM symbols with 4μs each needed to be reserved for LoRa transmissions. And the throughput loss can be reduced by up to 13%. The reserved OFDM symbols can be synchronized similar to EmBee [22].

V. Evaluation

In this section, we evaluate the accuracy of detecting LoRa signals under various noise levels and WiFi traffic load. Then we evaluate the effectiveness of utilizing LoFi to enable the coexistence of LoRa and WiFi. Finally, we investigate the trade-off WiFi throughput loss and LoRa performance.

A. Experimental Methodology

We implement LoFi on USRP N210 [26]. Based on existing 802.11g modules [39], new components are created to perform spectrum scanning and LoRa signal detection using the SR model. The USRP N210 running LoFi is connected via wired port to desktop PC with an Intel 3.6GHz and 12GB of RAM for hardware configuration and data processing. As shown in Fig. 11, we use two COT-MV development boards [40], the commercial LoRa platform embedded with SX1280 [37] chips, as a pair of LoRa transmitter and receiver at a distance of 200m. The LoRa transmitter is placed on the ground and connected with a laptop to record transmitted packets, and the LoRa receiver is placed next to the window of the fifth-floor building. The LoFi transmitter is placed near the LoRa receiver at a distance of 0.5m, and at a distance of 5m away from the LoFi receiver. LoFi is set to transmit 1400-byte WiFi packets at channel one (e.g., the center frequency is 2.412GHz). The LoRa transmitter is set to transmit 50-byte packets at the same center frequency 2.412GHz, and the bandwidth can be adjusted from 200kHz to 1600kHz.

To evaluate the impact of SNR and WiFi traffic load on LoRa detection accuracy, we vary the transmission power LoRa transmitter to generate the SNR within the range -25$\sim$0dB, which is a common SNR interval for long range transmissions [23]. We set the WiFi data rate to 54Mbps and vary the packet transmission interval to generate different traffic load from 0Mbps to 25Mbps. We compare LoFi with two most related works, EmBee [22] and DOF [27], in terms of the LoRa detection accuracy. The results are shown in Section V-B.

To investigate the effectiveness of enabling cross-technology coexistence, we evaluate the impact of the WiFi transmission power (e.g., -10dB to 22dB gain), WiFi traffic load and SNR on the LoRa packet reception ratio, LoRa throughput and power consumption. We compare LoFi with the most related work EmBee. The reserved channels in EmBee are modified to fit the bandwidth of LoRa, such that EmBee can also perform spectrum reservations when LoRa signals are detected. Note that both LoFi and EmBee enable the perfect spectrum reservation but not relies on the error recovery functions in LoRa. The LoRa data rate of 70kbps (SF to seven and bandwidth to 1600kHz) and 0.486kbps (SF to 12 and bandwidth to 200kHz) are achieved by setting proper parameters. To evaluate the power consumption, we add a fixed duty cycle of 20% to perform transmissions and reception on LoRa devices. Additional retransmissions with a maximum retry number 10 are required when packets are corrupted. We set LoRa data rate to 70kbps with 50-byte length packet. Different WiFi traffic load is achieved by varying the packet transmission interval and WiFi data rate is set to 36Mbps. The packet length of WiFi is 1400 bytes. There are at most two

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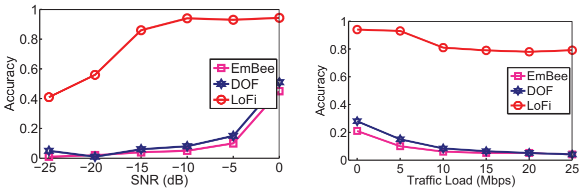


(a) Impact of SNR (5Mbps). (b) Impact of WiFi traffic (-5dB).

Fig. 12: Performance of LoRa detection accuracy.

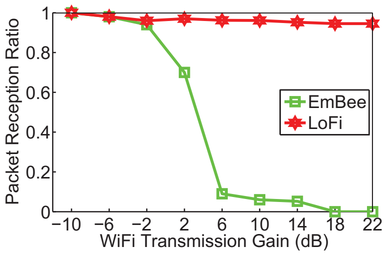


Fig. 13: Impact of WiFi transmission gain on LoRa packet reception ratio (SNR=-10dB).

LoRa packets can be received or transmitted in the fixed 20% duty cycle. Results are presented and analyzed in Section V-C.

To evaluate the impact of LoFi on WiFi throughput loss, we vary the MCS settings of 802.11g to achieve WiFi throughput from 4.3Mbps to 22Mbps. LoFi utilizes the built-in error recovery functions of LoRa to further reduce the WiFi throughput loss, given the occupied bandwidth of LoRa is 1600kHz. We also evaluate the impact of the number of reserved WiFi subcarriers on the LoRa packet reception ratio and WiFi throughput in terms of the occupied bandwidth (e.g., 200kHz, 800kHz, 1600kHz). Results are presented in Section V-D.

B. Accuracy of LoRa Detection

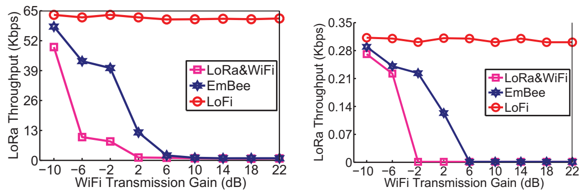
Fig. 12 shows the impact of SNR and WiFi traffic density on the LoRa packet capture ratio. Fig. 12(a) shows that LoFi improves the LoRa detection accuracy by 63.1% and 66.2% on average compared with DOF and EmBee in terms of varying SNR. Specifically, LoFi achieves the largest improvements (e.g., 89.1% improvements) at specific SNR, e.g., about -10dB, since at this SNR LoFi can still capture most LoRa packets thanks to the extracted signal features and the SR model. But DOF and EmBee miss most LoRa packets due to the extremely low received power, and the features are buried in noise. Fig. 12(b) presents that LoFi can consistently achieve the highest LoRa detection accuracy when varying WiFi traffic load from 0Mbps to 250Mbps, and the improvements are 72.8% and 75.4% on average compared to DOF and EmBee.

C. LoRa Performance

1) LoRa Packet Reception Ratio: Fig. 13 presents the impact of WiFi transmission power on LoRa packet reception ratio. Results show that LoFi can significantly improve LoRa packet reception ratio by 77.9% on average compared with EmBee [22]. When WiFi transmission gain is larger than 7dB, the improvements to EmBee achieved by LoFi reach about 92% because the characteristics of LoRa are submerged in WiFi signals with larger transmission power. LoFi can still pull out LoRa signals' features because of the careful frequency transformation and the weak signal boosting with SR model.

TABLE I: Impact of SNR on LoRa packet reception ratio (WiFi transmission gain=-2dB).

SNR (dB)	-25	-20	-15	-10	-5	0
LoRa w/ WiFi	0	0	0	0	0	0.04
LoRa w/ EmBee & WiFi	0	0	0.01	0.03	0.1	0.15
LoRa w / LoFi & WiFi	0.94	0.95	0.97	0.98	1	1



(a) 70Kbps LoRa data rate. (b) 0.486Kbps LoRa data rate.

Fig. 14: LoRa throughput with different WiFi transmission gain (SNR=-5dB).

Table I shows the impact of SNR on LoRa packet reception ratio. Results show that LoFi consistently achieves the highest LoRa packet reception ratio with SNR from -25dB to 0dB compared with EmBee. It presents that LoFi maintains a good performance in a wide range of SNR.

2) LoRa Throughput: Fig. 14 shows the impact of WiFi transmission gain on the throughput of LoRa. Results show that LoFi can maintain a consistent LoRa throughput with WiFi transmission gain changing from -10dB to 22dB. However, EmBee can not protect LoRa throughput when WiFi transmission gain is larger than 6dB due to the missing of LoRa signals.

Fig. 15 presents the impact of SNR on LoRa throughput. Results show that LoFi can effectively detect weak LoRa signals and achieve successful concurrent transmissions for LoRa and WiFi. With LoFi, the throughput differences under WiFi interference or not are subtle, e.g., lower than 5.9% and 6.9% for LoRa data rate 70Kbps and 0.486Kbps respectively. EmBee fails to detect weak LoRa signals when SNR is lower than -10dB, e.g., the throughput is lower than 3Kbps and 0.01Kbps for LoRa data rate 70Kbps and 0.486Kbps respectively.

3) Power Consumption: Fig. 16 presents the impact of SNR and WiFi traffic load on LoRa power consumption. Fig. 16(a) shows that LoFi can reduce the duty cycle by 42.3% on average compared with EmBee. Specifically, LoFi achieves the best improvements (e.g., 48.9%) over EmBee when SNR is about -20dB, because LoRa signals are too weak to be detected by EmBee but LoFi can still pull them out. As shown in Fig. 16(b), LoFi can consistently reduce the duty cycle compared with EmBee when WiFi traffic load varying from 5Mbps to 25Mbps. Note that with denser traffic load, the improvements of LoFi are larger (e.g., 23% improvements). Because more retransmissions are needed for LoRa to ensure reliable transmissions, resulting in larger duty

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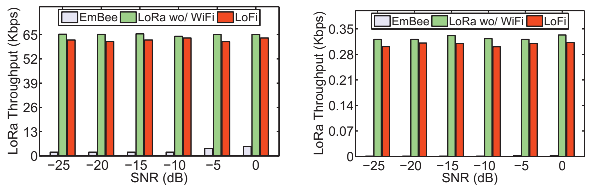
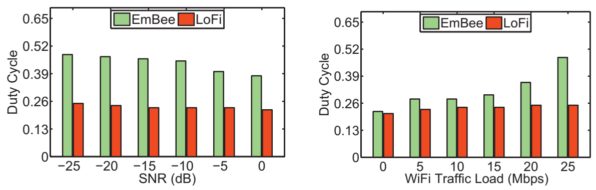


(a) 70Kbps LoRa data rate. (b) 0.486Kbps LoRa data rate.

Fig. 15: LoRa throughput with different SNR (WiFi transmission gain=5dB).



(a) Impact of SNR (25Mbps). (b) Impact of WiFi load (-5dB).

Fig. 16: Power consumption (20% default duty cycle).

cycles for EmBee. Then on the other hand, the improvements of LoFi are more significant.

D. Impact of WiFi Performance

Table II shows the impact of LoFi on the WiFi throughput loss in terms of WiFi traffic load. Results show that LoFi can control the loss within 13% with 1600kHz LoRa bandwidth. Note that the throughput loss is smaller with lossy traffic density since the collision probability is smaller.

Fig. 17 presents the tradeoff between enabling LoRa transmissions and WiFi throughput loss. We investigate the impact of the number of reserved WiFi symbols on the LoRa packet reception rate and WiFi throughput loss. With wider bandwidth used by LoRa, more WiFi symbols are needed to let LoRa achieve larger than 98% packet reception ratio. For example, the number of needed WiFi symbols increase from one to ten when the bandwidth of LoRa changes from 200kHz to 1600kHz. Despite that, results still show that LoFi can control the WiFi throughput loss within 13% with minor LoRa performance loss (5.3% packet reception loss). On the other hand, when LoRa's transmission desire more frequently, more WiFi symbols can be reserved to satisfy this goal.

VI. Discussion

Deployment in existing networks. In current implementation, LoFi requires modifications on existing WiFi devices to perform frequency transformation. Actually, LoFi can also be implemented as a stand-alone device to be deployed in existing works. For example, the device running LoFi can be placed near the LoRa receiver to detect whether there are ongoing LoRa transmissions. When LoRa transmissions are detected, LoFi can send a high power WiFi signal to force nearby WiFi devices to back off. Note that the high power WiFi signal is carefully designed to not affect LoRa's transmissions, e.g., reserving the spectrum used by LoRa. Then, with the stand-alone LoFi, the transmissions of WiFi and LoRa can be coordinated appropriately without any hardware modifications on existing devices.

TABLE II: WiFi throughput loss caused by LoFi.

Data Rate (Mbps)	**54**	**48**	**36**	**24**	**18**	**12**	**9**	**6**
Orignal WiFi (Mbps)	25.87	22.34	16.89	15.12	13.11	8.98	5.11	4.65
WiFi w/ LoFi (Mbps)	22.34	20.11	14.69	13.87	12.12	8.23	4.67	4.31
Throughput loss (%)	13.64	9.98	13.02	8.26	7.55	8.35	8.61	7.31

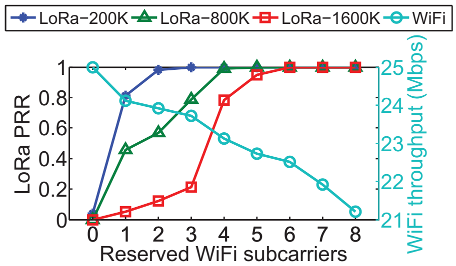


Fig. 17: Tradeoff between LoRa and WiFi performance.

Generality for other wireless technologies. In this paper, we mainly focus on detecting the extremely weak LoRa signals. It can also be utilized to detect other wireless technologies with little modifications to the signal preprocessing procedure. For example, to detect weak ZigBee signals modulated with O-QPSK (Offset Quadrature Phase-Shift Keying), it can be directly applied to the SR model to perform weak signal boost because of the fixed frequency of ZigBee signals. As for BLE signals modulated with GFSK (Gaussian Frequency-Shift Keying), we can first multiply the received signals with an up-chirp. In this way, the known modulated frequency can be transformed into a smaller frequency by at least one of the frequencies in the up-chirp signal. Then after performing low pass filtering, the smaller frequency is kept and can be applied to the SR model.

VII. Conclusion

In this paper, we propose a novel weak signal detection approach, LoFi, to enable the coexistence of LoRa and WiFi. LoFi utilizes a typical physical phenomenon Stochastic Resonance (SR) to boost weak signals. LoFi first carefully transforms the frequencies of a LoRa chirp into a smaller frequency using the trick of trigonometric identity, while other modulated frequencies are shifted to larger frequencies. Results show that LoFi can enable the coexistence of LoRa and WiFi in 2.4GHz. The packet reception ratio of LoRa is able to achieve 98% over an occupied 20MHz WiFi channel. and the WiFi throughput loss due to the spectrum reservation is reduced by up to 13%. There are multiple directions for future works. First, we can extend this approach to support other wireless technologies. Second, we can optimize the speed of spectrum scanning by taking the relationship among LoRa parameters into consideration.

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