A Study on Packet-Level Index Modulation Using Frequency Offsets within a LoRaWAN Channel

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***Abstract*—Low Power Wide Area (LPWA), which is increasingly utilized in Internet of Things (IoT) systems, is attracting significant attention. In LPWA systems, Long Range Wide Area Network (LoRaWAN) is one of the most widely adopted communication methods for IoT systems. Since LoRaWAN relies on long range modulation, increasing the data rate poses significant challenges. Therefore, this study addresses the limitations in the number of channels owing to the restricted number of transmission bits by proposing a Packet-level index modulation (PLIM) scheme. The frequency bands allocated to the LPWA networks vary by region and country, and the number of channels is limited. To increase the number of transmission bits as effectively as possible, this study proposes the PLIM scheme, leveraging frequency offsets within the LoRaWAN channel.**

I. Introduction

In this study, we focus on a low-power wide area (LPWA) system, which is employed in Internet-of-Things (IoT) systems, and has become increasingly popular. In LPWA systems, various communication schemes have been proposed to achieve low power consumption and long-distance communication. LoRaWAN, which is used as an LPWA communication scheme, utilizes a chirp-spread spectrum modulation (CSS) called LoRa modulation. A higher spreading factor in LoRa modulation leads to longer transmitted signals, better tolerance to interference, and implements quasi-orthogonality between different spreading factors. LoRaWAN is a standard specified by the LoRa Alliance [**1**], [**2**].

Packet-level index modulation (PLIM) has been proposed to add transmission bits to the time-slot and channel indexes of packets with LoRaWAN [**3**]. In a PLIM system, time synchronization between the transmitter and receiver must be performed in advance when information is added to the time-slot index. If the start time of a frame in the PLIM system is not synchronized between the transmitter and receiver, the time-slot index cannot be correctly detected, resulting in PLIM symbol errors. Despite time synchronization, if the oscillator in the microcontroller regulating the timing of packet transmission at the node is inaccurate, the effect of clock drift accumulates over time, requiring its estimation and periodic correction of the clock drift. Clock drift estimation is performed on the base station side, where computational resources are less limited. The clock drift values generated at the node are modeled as a normal distribution with mean μ and variance σ^2, and the estimated values are calculated using the received packets [**4**].

However, it is widely known that oscillators generate clock drifts that vary with temperature. It has been suggested that the mean value of the normal distribution model of the clock drift varies significantly with changes in temperature, causing errors when demodulating the PLIM symbols [**5**]. When the interval between packet transmissions is long, estimation and correction become challenging, owing to the corresponding increase in packet reception intervals. However, the PLIM system requires an increase in the number of indexes and a longer frame length to increase the number of bits in the PLIM symbol. The number of frequency indexes cannot be easily increased, owing to the limitation in the number of channels to the originally allocated bandwidth. Although the number of time-slot indexes can theoretically be increased indefinitely, in practice, the data transmission interval of packets tends to be system-dependent. Therefore, the aforementioned clock drift estimation is most effective when performed at transmission intervals in which the temperature is kept constant.

As mentioned above, the number of time-slot indexes can be increased by increasing the frame time length, thereby increasing the number of bits that can be transmitted. However, processing tasks, such as time synchronization, are necessary, and studies have been conducted on estimation and correction techniques for addressing clock drift caused by inaccurate oscillators. Therefore, this study focuses on channel indexes that have been strictly limited by the number of channels, and we propose a new method to increase the number of indexes within each channel bandwidth. This study assumes that the transmitter and receiver use LoRaWAN to transmit packets. The proposed method realizes PLIM using frequency offsets within a LoRaWAN channel.

II. Previous Work

In this paper, a packet-level index modulation (PLIM) method is focused because the number of conveyed bits can increase. In PLIM, both the time-slot and channel indexes are assigned to different PLIM symbols. However, the detection of the time-slot index in PLIM is affected by inaccurate oscillators.

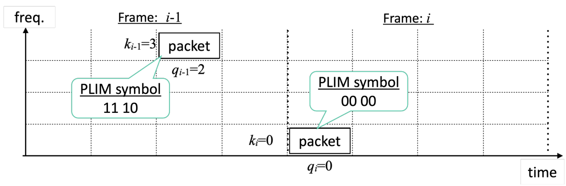

Fig. 1. Image of PLIM at a transmitter.

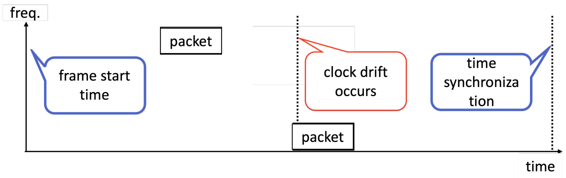

Fig. 2. Image of PLIM at a receiver.

A. Packet-Level Index Modulation (PLIM)

It is difficult to increase the data rate in a LoRaWAN using LoRa modulation by devising a modulation scheme owing to the low channel frequency, narrow bandwidth, and the fact that DC regulations must be strictly adhered to. In LPWA systems, when using modulation schemes such as LoRaWAN modulation, where data rate improvement is challenging, PLIM has been proposed as a method for increasing the number of transmission bits [**3**]. PLIM, wherein symbols are assigned to the time-slot and channel indexes as packets, enables nodes to increase the number of transmitted bits in addition to the amount of information in the packet. The time-slot and channel indexes to which a PLIM symbol is allocated can be designed as a frame such that the packet length to be transmitted relative to the frame length satisfies the duty cycle (DC) regulations.

As described above, the PLIM can transmit more information than the packet transmission volume without changing the modulation scheme of the packet itself, while satisfying DC regulation. Therefore, the practical application of PLIM is expected to be relatively simple. However, the nodes used in IoT and other applications are expected to be numerous and forming large networks, while also being cost-effective. Thus, it is expected that the circuit configuration or individual elements constituting a node will be affordable and have a minimum performance guarantee. In the PLIM system, a particular concern is regarding the accuracy of the oscillator in the microcontroller that controls the timing of transmission, which is a factor in PLIM symbol errors.

In PLIM, symbols are assigned to time slot and channel indexes. A PLIM frame is defined as a period in which a packet transmits in time domain and channel domain. Nodes transmit a packet at the corresponding time slot and channel to convey PLIM symbols.

B. Symbol demodulation in PLIM

Time synchronizations between a transmitter and receiver are performed in advance. Therefore, the receiver can demodulate PLIM symbols by detecting the time slot and channel indexes. The channel index is detected from the channel frequency of the received packet. In addition, the time slot index is detected from the frame start time and the packet reception time. In the time slot index detection, PLIM symbol in time domain is given by

$$\hat{q}_i = \frac{t_{\mathrm{r}} - t_{\mathrm{FST}}}{T_{slot}}, \tag{1}$$

where i is the frame number, t_{r} is the reception time of the packet, t_{FST} is the frame start time, and T_{slot} is the slot length.

In the time domain, a clock drift occurs because nodes are operated by a microcontroller without GPS system. The clock drift at the transmitter causes PLIM demodulation errors at the receiver. In general, the impact on the PLIM errors is greater for clock drift by the microcontroller than by the radio. Therefore, the receiver in PLIM periodically performs time synchronization.

III. PLIM Using Frequency Offsets with LoRaWAN

The proposed method is based on PLIM using LoRaWAN. LoRaWAN, which is an LPWA network, is used for IoT. In general, IoT nodes consist of inaccurate elements and devices owing to their large number of nodes. When using the PLIM, a clock drift is caused by the inaccurate oscillator of the transmit node because time synchronization is required to derive the PLIM time-slot index from the packet's received time.

However, IoT nodes are stricter on the frequency offset than on the clock drift because there are strict rules regarding microwave emissions. The signals were emitted by a wireless device equipped with a higher-precision oscillator than that of the microcontroller equipped for controlling the transmission timing. Therefore, we propose a PLIM method that uses frequency offsets without time synchronization, because it is assumed that the packet is modulated by LoRaWAN.

In the basic PLIM method, PLIM symbols is assigned to the time-slot and channel indexes. By contrast, in our proposed method, PLIM is performed by shifting the center frequency of a LoRaWAN signal within the channel bandwidth. In this proposed method, PLIM symbols assign to the amount of frequency offsets. This section presents the spreading and despreading methods, and the proposed method of frequency offset mapping using packet-level index modulation.

First, the basic LoRa modulation method is explained because it is an important technology for the method proposed in this study.

A. LPWA and LoRa Modulation

It is necessary to achieve low-power communication because IoT systems are assumed to be battery powered. Consequently, the LPWA is highly compatible with IoT systems, where it is difficult to ensure a sufficient power supply for each node because the LPWA has a small transmission power of approximately 20 mW and assumes low-power communication. Moreover, to achieve long-distance communication, LPWA systems are allocated a relatively low-frequency band of 800 MHz to 900 MHz, and the allocated frequency band differs

Preamble	Sync word	Payload (PHDR+CRC+PHY Payload)	CRC (only up link)

Fig. 3. Packet structure in LoRa PHY layer.

depending on the region or country. In the LoRaWAN, signal bandwidths of 125, 250, and 500 kHz were used, and when the bandwidth was 125 kHz, the channel center frequencies were specified at 200 kHz intervals.

LoRaWAN uses CSS, which continuously changes the frequency by performing a cycle within the channel bandwidth. The CSS in a LoRaWAN system is called LoRa modulation. The LoRaWAN system selects and uses a channel with a bandwidth of 200 kHz and can determine the LoRaWAN signal bandwidth at 125, 250, and 500 kHz. If the bandwidth of the LoRaWAN signal was 125 kHz, a guard band of 37.5 kHz was provided at both ends of each channel.

In LoRaWAN, packets are modulated using LoRa modulation, and the preamble of the signal is added to the head of the packets. The packet structure of the LoRa physical layer is illustrated in Fig. 3. LoRaWAN symbols are spread and modulated using CSS modulation. If the basic chirp is an up-chirp, the sync word consists only of down-chirps and the other symbols are up-chirps.

The received LoRaWAN signals were demodulated by de-spreading with an inverse-basic-chirp, and the LoRa symbols were then obtained by FFT or DFT processing. In this subsection, the theories of spread processing are explained.

1) Spreading on LoRaWAN: The transmission LoRaWAN signal is obtained by multiplying the waveform $w_{\mathrm{S}}(t)$ of the symbols before spreading by the basic waveform $w_b(t)$ while spreading. The baseband waveform is as follows:

$$w(t) = w_{\mathrm{S}}(t) \cdot w_b(t), \tag{2}$$

where, $w_{\mathrm{S}}(t)$ is the LoRaWAN signal and is also the target signal to be spread. By contrast, $w_b(t)$ is the waveform used to spread the target signal, that is, the basic chirp. $w_{\mathrm{S}}(t)$ is given by

$$\begin{aligned} w_{\mathrm{S}}(t) &= \exp(j2\pi \cdot D\frac{t}{2^{SF}T}) && (3)\\ &= \exp(j2\pi \cdot D\frac{B}{2^{SF}}t), && (4)\end{aligned}$$

where j is the imaginary unit, T is the sampling interval, and D is the index of the data that can be transmitted with the SF [bit]. D is expressed as follows:

$$D = 0, 1, .., 2^{SF} - 1. \tag{5}$$

Moreover, T is rewritten as $T = 1/B$ using the sampling frequency B, which is equal to the LoRaWAN signal bandwidth (i.e., the chirping bandwidth). In the LoRaWAN, the sampling frequency and the LoRa signal bandwidth were set equal to facilitate FFT processing and LoRaWAN symbol detection. Consequently, the length of one LoRaWAN symbol is equal to the length of 2^{SF} samples (one symbol length $= 2^{SF} \cdot T$), because the sampling frequency B determines the sample length T. When performing FFT processing for 2^{SF} points to the waveform of the baseband signal $w(t)$, the bin with the largest value is the Dth FFT bin, indicating that demodulation is possible by performing FFT processing of the signal before the spectrum spreads.

The LoRaWAN symbols to be transmitted are spread using an upchirp of 2^{SF} sample length. The up-chirp changes linearly in frequency from $-B/2\,[\mathrm{Hz}]$ to $B/2\,[\mathrm{Hz}]$ during the symbol length $2^{SF} \cdot T$. Therefore, the angular frequency at time t is expressed as follows:

$$\begin{aligned} \omega(t) &= 2\pi\left(\frac{B}{2^{SF}\cdot T}t - \frac{B}{2}\right) && (6)\\ &= 2\pi\left(\frac{B^2}{2^{SF}}t - \frac{B}{2}\right)\,[\mathrm{rad/s}]. && (7)\end{aligned}$$

Therefore, the phase of the baseband signal with an angular frequency $\omega(t)$ described in Eq. (7) is as follows:

$$\begin{aligned} \phi(t) &= \int_0^t \omega(t)\mathrm{d}t && (8)\\ &= 2\pi\left(\frac{B^2}{2\cdot 2^{SF}}t^2 - \frac{B}{2}t\right)\,[\mathrm{rad}]. && (9)\end{aligned}$$

In addition, the baseband signal of the waveform underlying the spread spectrum can be written as

$$\begin{aligned} w_b(t) &= \exp(j\phi(t)) && (10)\\ &= \exp\left\{j2\pi\left(\frac{B^2}{2\cdot 2^{SF}}t^2 - \frac{B}{2}t\right)\right\}. && (11)\end{aligned}$$

By Eq. (2), the transmitted LoRa signal is rewritten as

$$w(t) = \exp\left\{j2\pi\left(D\frac{B}{2^{SF}}t + \frac{B^2}{2\cdot 2^{SF}}t^2 - \frac{B}{2}t\right)\right\} \tag{12}$$

Note that when the frequency of the transmitted signal that is the up-chirp exceeds by $B/2\,[\mathrm{Hz}]$, it starts from $-B/2\,[\mathrm{Hz}]$ again, because the frequency bandwidth of the transmission signals is limited from $-B/2\,[\mathrm{Hz}]$ to $B/2\,[\mathrm{Hz}]$. However, if the sampling frequency is $B\,[\mathrm{Hz}]$, the sampling theorem allows the equation above to be used without modification.

2) De-spreading on LoRaWAN: The signal received at the receiver is the transmitted waveform plus the change in phase θ owing to the transmission path, as shown in the following equation:

$$\hat{w}(t) = w(t) \cdot \exp(j\theta). \tag{13}$$

Here, changes in amplitude were not considered.

In de-spreading, by multiplying the received LoRa signal, $\hat{w}(t)$, and the inverse of the baseband signal, $1/w_b(t)$, the receiver can obtain the desired waveforms, as shown in

$$\begin{aligned} \hat{w_{\mathrm{S}}}(t) &= w(t)\cdot\exp(j\theta)\cdot\frac{1}{w_b(t)} && (14)\\ &= w_{\mathrm{S}}(t)\cdot w_b(t)\frac{1}{w_b(t)}\cdot\exp(j\theta) && (15)\\ &= \exp(j2\pi\cdot D\frac{B}{2^{SF}}t)\cdot\exp(j\theta). && (16)\end{aligned}$$

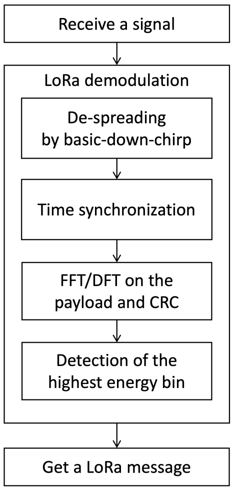

Fig. 4. Flow of the original LoRa demodulation at the receiver using LoRaWAN.

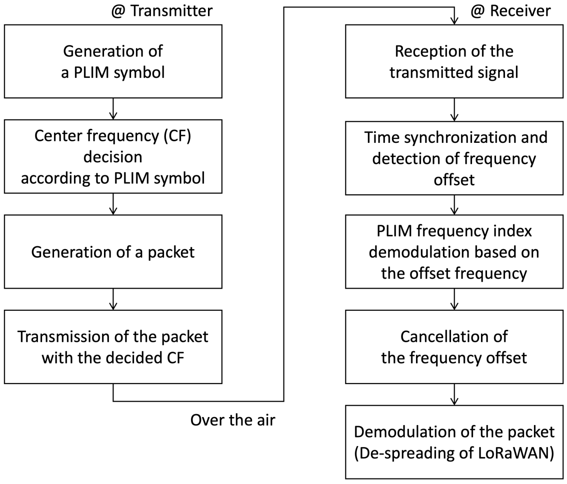

Fig. 5. Flow from the transmitter to the receiver, in the proposed method.

Note that $1/w_b(t)$ is a basic down-chirp because the positive and negative phases of $w_b(t)$ are reversed. Using the de-spread waveform expressed by Eq. (16), when performing the FFT for 2^{SF} points, the receiver obtains the result with the maximum absolute value in the Dth FFT bin, and the transmitted data can then be demodulated.

Fig. 4 illustrates the LoRa demodulation flow at the receiver. In LoRa demodulation, sync words consisting of basic-down chirps are used for synchronization in the time domain because the receiver can detect the peaks of the sync words by de-chirping the received signal.

B. Procedure of LoRaWAN with Frequency Offset Using PLIM

Fig. 5 illustrates the flow of the proposed method from the transmitter to the receiver. Fig. 6 illustrates the procedure for the proposed method at the receiver.

In the proposed scheme, the transmitter selects a channel and determines the offset according to the PLIM symbol. The signal was transmitted at the center frequency by considering the offsets. At the receiver, the PLIM symbol is demodulated by detecting the offset of the received signal. Moreover, the data transmitted by the packet can be obtained by processing LoRa demodulation after the cancellation of its detected offset.

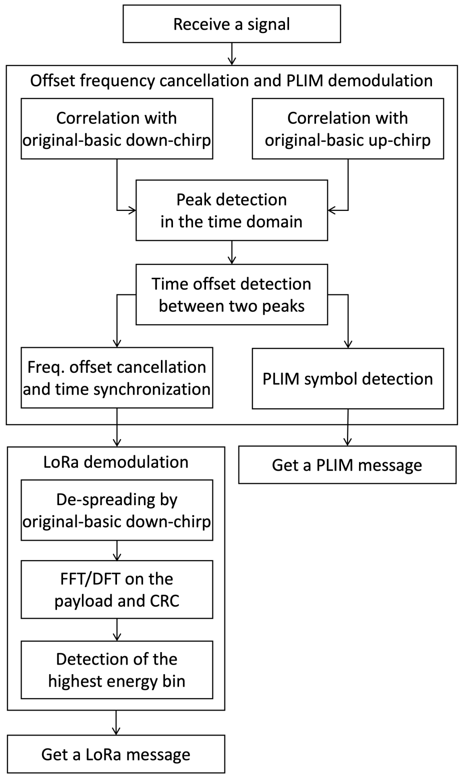

Fig. 6. Procedure of the proposed method.

C. Frequency Offset Acquisition by Correlation Peaks

The LoRa modulation scheme uses a basic-up-chirp in the preamble and basic-down-chirp in the sync word. In this subsection, we demonstrate that the offset of the transmission frequency can be obtained from the peak of the correlation function of the received up- and down-chirps.

The basic-up-chirp in the preamble is described by

$$w_u(t) = w_b(t) \tag{17}$$
$$= \exp\left\{j2\pi\left(\frac{B^2}{2\cdot 2^{SF}}t^2 - \frac{B}{2}t\right)\right\}. \tag{18}$$

The basic-down-chirp in the sync word is given by

$$w_d(t) = {w_b}^*(t) \tag{19}$$
$$= \exp\left\{j2\pi\left(-\frac{B^2}{2\cdot 2^{SF}}t^2 + \frac{B}{2}t\right)\right\}, \tag{20}$$

where * denotes the complex conjugation.

Fig. 7 shows an image of the original basic chirp and the shifted-chirps in the proposed method. The transmitter shifts the frequencies of the up-chirp and down-chirp by $f_{\rm os}$ [Hz]. Because $f_{\rm os}$ [Hz] is the frequency offset for transmitting the

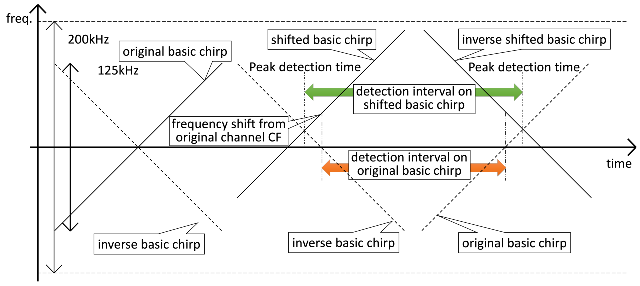

Fig. 7. Image of original-basic-chirp and shifted-chirp of the proposed method.

PLIM data, the transmission waveforms of the up- and down-chirps with offsets are as follows:

$$w_{u_{\rm os}}(t) = w_u(t)\cdot\exp(j2\pi f_{\rm os}t) \quad (21)$$
$$= \exp\left\{j2\pi\left(\frac{B^2}{2\cdot 2^{SF}}t^2-\frac{B}{2}t+f_{\rm os}t\right)\right\}, \quad (22)$$

and

$$w_{d_{\rm os}}(t) = w_d(t)\cdot\exp(j2\pi f_{\rm os}t) \quad (23)$$
$$= \exp\left\{j2\pi\left(\frac{B^2}{2\cdot 2^{SF}}t^2-\frac{B}{2}t+f_{\rm os}t\right)\right\}. \quad (24)$$

Moreover, the received signal of the up-chirp, whose frequency is offset by $f_{\rm os}$ [Hz] is described by

$$\hat{w_{u_{\rm os}}}(t) = w_{u_{\rm os}}(t)\cdot\exp(j2\pi f_{\rm os}t)\cdot\exp(j\theta) \quad (25)$$
$$= \exp\left\{j2\pi\left(\frac{B^2}{2\cdot 2^{SF}}t^2-\frac{B}{2}t+f_{\rm os}t\right)+j\theta\right\}. \quad (26)$$

The received signal of the downchirp, whose frequency is offset by $f_{\rm os}$ [Hz] is described as

$$\hat{w_{d_{\rm os}}}(t) = w_{d_{\rm os}}(t)\cdot\exp(j2\pi f_{\rm os}t)\cdot\exp(j\theta) \quad (27)$$
$$= \exp\left\{j2\pi\left(-\frac{B^2}{2\cdot 2^{SF}}t^2+\frac{B}{2}t+f_{\rm os}t\right)+j\theta\right\}. \quad (28)$$

Note that these waveforms exist in the range $0 \le t \le 2^{SF}/B$; however, for simplicity, the defined range is not considered.

The correlation function for the up-chirp is given by

$$R_u(t) = \int_{-\infty}^{\infty}\hat{w_{u_{\rm os}}}(\tau)\cdot {w_u}^*(\tau-t)\mathrm{d}\tau. \quad (29)$$

The correlation function $R_u(t)$ has a constant absolute value for $\hat{w_u}(\tau)$ and constant value for ${w_u}^*(\tau-t)$. Therefore, the absolute value of $R_u(t)$ is maximized at t where Eq. (31) holds, that is, when the following equation does not rotate on the complex plane according to τ.

$$\hat{w_{u_{\rm os}}}(\tau)\cdot {w_u}^*(\tau-t) \quad (30)$$

$$\frac{\partial}{\partial\tau}\arg(\hat{w_{u_{\rm os}}}(\tau)\cdot {w_u}^*(\tau-t)) = 0 \quad (31)$$

Solving for Eq. (31) as shown in the followings,

$$0 = 2\pi\left(\frac{B^2}{2^{SF}}\tau-\frac{B}{2}+f_{\rm os}\right)-2\pi\left(\frac{B^2}{2^{SF}}(\tau-t)-\frac{B}{2}\right) \quad (32)$$
$$= 2\pi\left(\frac{B^2}{2^{SF}}t+f_{\rm os}\right), \quad (33)$$

Time t is derived as follows:

$$t = -f_{\rm os}\frac{2^{SF}}{B^2}. \quad (34)$$

As a result, it ensures that when there is an offset of $f_{\rm os}$ [Hz] in the up-chirp, the correlation peaks appear at a time $f_{\rm os}\cdot 2^{SF}/B^2$ [s] earlier. In addition, the correlation function for the down chirp is given by

$$R_d(t) = \int_{-\infty}^{\infty}\hat{w_{d_{\rm os}}}(\tau)\cdot {w_d}^*(\tau-t)\mathrm{d}\tau. \quad (35)$$

Time t for which $R_d(t)$ is maximum, can be solved in the same manner, as shown in

$$t = f_{\rm os}\frac{2^{SF}}{B^2}. \quad (36)$$

From this result, when there is an offset of $f_{\rm os}$ [Hz] in the down-chirp, it is evident that the correlation peaks appear at a time $f_{\rm os}\cdot 2^{SF}/B^2$ [s] later.

Thus, the receiver can detect the offset frequency of the transmitted LoRaWAN signal in packets in wherein the up- and down-chirps are transmitted consecutively. That is, when the time difference between the respective correlation peaks of the consecutive up and down chirps is Δt, the offset frequency can be expressed by the following equation:

$$f = \frac{1}{2}\left(\Delta t-\frac{2^{SF}}{B}\right)\frac{B^2}{2^{SF}}. \quad (37)$$

The baseband signal of the transmitted signal when there is an offset of $f_{\rm os}$ [Hz] can be written as follows:

$$w_{\rm os}(t) = w(t)\cdot\exp(j2\pi f_{\rm os}t). \quad (38)$$

Therefore, the received signal with no offset can be obtained by multiplying $\exp(-j2\pi f_{\rm os}t)$ on the receiving side as follows:

$$\hat{w}(t) = w_{\rm os}(t)\cdot\exp(j\theta)\cdot\exp(-j2\pi f_{\rm os}t) \quad (39)$$
$$= w(t)\cdot\exp(j\theta). \quad (40)$$

This is equal to Eq. (13). In other words, to cancel the offset detected by the receiver, the received signal with the offset should be multiplied by $\exp(-j2\pi f_{\rm os}t)$.

IV. Simulation Result

This study confirmed that the offset frequency could be detected by the time difference between the peaks of the correlated up-chirp and down-chirp waveforms of the LoRaWAN preamble using simulation results. Table I lists the parameters used in the simulations.

In this simulation, the baseband signal that is the preamble of the LoRaWAN signal is constructed by consecutive chirp

TABLE I
SIMULATION PARAMETERS

Generation frequency of transmit waveforms	500 [ksamples/s]
Operation frequency of receive filter	500 [ksamples/s]
Down sampling frequency	125 [ksamples/s] $(= B)$
Receive filter	Raised-Cosine (FIR Filter: 27 taps)
Spreading factor (SF)	7
Number of FFT bins	128 [points]
Frequency offsets	0 [Hz] or 29297 [Hz]

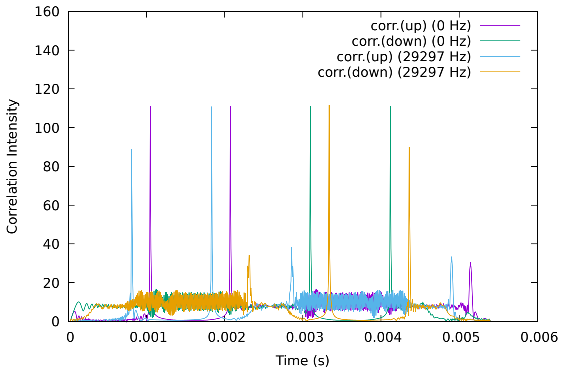

Fig. 8. Correlation peaks of basic-chirp and shifted-chirp in the time domain of the proposed method.

signals that consist of two up-chirps, two down-chirps. An up-chirp of 0.25 was used, as referenced in **[6]**.

The offset frequencies f_{os} were set to $0\,[\mathrm{Hz}]$ and $29297\,[\mathrm{Hz}]$. $f_{\mathrm{os}} = 0\,[\mathrm{Hz}]$ indicates that the signal is transmitted with the original LoRa modulation, and $f_{\mathrm{os}} = 29297\,[\mathrm{Hz}]$ indicates that the signal is shifted by the shifted basic chirp to the PLIM and then transmitted. $f_{\mathrm{os}} = 29297\,[\mathrm{Hz}]$ is derived from

$$f_{\mathrm{os}} = (D - 8 + 0.5) \cdot \left(4\frac{125\mathrm{k}}{128}\right) = 29297\,[\mathrm{Hz}]. \quad (41)$$

Here, D was set to 15. $D = 15$ implies that when the number of bits conveyed with the proposed PLIM is $4\,[\mathrm{bits}]$, the frequency offset has the maximum value. In this case, the width of FFT bins is $4 \cdot 125\mathrm{k}/128\,[\mathrm{Hz}]$, which is around $3.9\,[\mathrm{kHz}]$. When the channel frequency is $920\,[\mathrm{MHz}]$ and the oscillator accuracy of the transceivers is $\pm 1\,[\mathrm{ppm}]$, the range of the clock drift of the oscillator is twice the oscillator accuracy; therefore, we must consider that $\pm 2\,[\mathrm{ppm}]$ occurs between the transmitter and receiver. Then, the width of the FFT bins was set to approximately $3.9\,[\mathrm{kHz}]$, which is approximately equal to $4\,[\mathrm{ppm}]$ at $920\,[\mathrm{MHz}]$.

Fig. 8 shows the simulation results used to confirm the correlation peaks of each chirp. Based on Fig. 8, the simulation results indicate that the interval between the peaks when the offset frequency is $0\,[\mathrm{Hz}]$ is $1024.0\,[\mathrm{ms}]$ and the interval between the peaks when the offset frequency is $29297\,[\mathrm{Hz}]$ is $1504.0\,[\mathrm{ms}]$. These results indicate that frequency offsets can be detected when they are $0.0000\,[\mathrm{Hz}]$ and $29297\,[\mathrm{Hz}]$.

V. CONCLUSION

This study focused on LPWA, which is used in IoT systems. The LoRaWAN is a communication method for IoT systems. Because LoRaWAN uses LoRa modulation, it is difficult to increase the data rate. Therefore, we addressed the limitations in the number of channels owing to the restricted number of transmission bits by using the proposed PLIM scheme. To increase the number of transmission bits as effectively as possible, we propose a PLIM that leverages frequency offsets within the LoRaWAN channel. This paper presented simulation results to confirm that the channel offsets assigned to PLIM symbols can be detected using our detection algorithm.

ACKNOWLEDGMENT

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