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

Mai Ohta
Fukuoka University
Fukuoka, Japan

Hiroki Matsuura
NATANE eICT Lab.[1]
The University of Electro-Communications[2]
Tokyo, Japan[1, 2]

Takeo Fujii
Advanced Wireless & Communication Research Center, The University of Electro-Communications[3]
Tokyo, Japan[3]

***Abstract*—This paper focuses on Low Power Wide Area (LPWA), which is used for Internet of Things (IoT) systems because IoT becomes more and more popular. In LPWA, LoRaWAN (Long Range WAN) is known as one of the communication methods for IoT systems. Since LoRaWAN uses LoRa modulation, it is not easy to increase the data rate. Therefore, this paper addresses the issue of the number of channels due to the limitation of the number of transmission bits in increasing the transmission bits using the proposed PLIM scheme. The frequency bands allocated to PLWA vary by region and country, and the number of channels is limited. Then, in order to increase the number of transmission bits as much as possible, this paper proposes the PLIM to use frequency offsets within the LoRaWAN channel.**

***Index Terms*—Low Power Wide Area (LPWA), LoRaWAN, Packet-Level Index Modulation (PLIM)**

I. Introduction

In this paper, we focus on a low power wide area (LPWA), which is used in Internet-of-Things (IoT) systems as IoT becomes more and more popular. In LPWA, various communication schemes have been proposed to achieve low power consumption and long distance communication. The LoRaWAN scheme used as one of the LPWA communication schemes employs chirp spread spectrum modulation, which is called LoRa modulation. The higher the spreading code of LoRa modulation, the longer the transmitted signal length, the higher the tolerance to interference signals, and the quasi-orthogonality between different spreading codes. LoRaWAN is a standard specified by the LoRa Alliance [1], [2].

In addition, In a system with a large number of nodes, such as the IoT, it is necessary to achieve low-power communication because the system is assumed to be battery-powered. For this reason, LPWA is highly compatible with IoT systems, where it is difficult to ensure sufficient power supply for each node, because LPWA has a small transmission power of about 20 mW and assumes low-power communication. Moreover, in order to achieve long-distance communication, LPWA systems are allocated the relatively low frequency band of 800 MHz to 900 MHz, and the allocated frequency band differs depending on the region or country. In LoRaWAN, signal bandwidths of 125 kHz, 250 kHz, and 500 kHz are used, and when the bandwidth is 125 kHz, the channel center frequencies are specified at 200 kHz intervals.

Furthermore, one of the characteristics of LPWA is that the duty cycle (DC), which is a ratio of the packet transmission duration over the air to a specification period, is specified. In most countries and regions, the DC is specified as 1%. This means that communication between nodes and a base station is intermittent, limiting continuous channel occupancy by specific nodes, etc. The transmission data rate cannot be increased by increasing the number of transmissions because the nodes have to comply with the DC. However, since DC regulation is per channel, not per node, nodes can increase transmission opportunities by changing channels.

Therefore, it is not easy to increase the data rate in a LoRaWAN using LoRa modulation by devising a modulation scheme, because the channel frequency is low, the bandwidth is narrow, and the DC regulation must be strictly adhered to. In such LPWA systems, when using modulation schemes such as the LoRaWAN modulation scheme, where data rate improvement is not easy, a packet-level index modulation (PLIM) has been proposed as one method to increase the number of transmission bits [3]. The PLIM that symbols are assigned to the channel index and time slot index as a packet is transmitted enables nodes to increase the number of transmitted bits in addition to the amount of information in the packet. In the PLIM, the channel index and time slot index to which a PLIM symbol is allocated can be designed as a frame, so that the packet length to be transmitted relative to the frame length satisfies the DC regulation.

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 the DC regulation. For this reason, the practical application of PLIM is expected to be relatively easy. On the other hand, nodes used in IoT and other applications are expected to be huge and to make large networks, and the price of the nodes should be low. Thus, it is expected that the circuit configuration or individual elements constituting a node is inexpensive and have a minimum performance guarantee. In the PLIM system, there is particular concern about the accuracy of the oscillator in the microcontroller that controls the timing of transmission, which is a factor in PLIM symbol errors.

In the PLIM system, the 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 does not match between the transmitter and receiver, the time slot index cannot be detected correctly, resulting in PLIM symbol errors. Even with time synchronization, if the oscillator in the microcontroller that controls the timing of packet transmission at the node is inexpensive, the effect of clock drift accumulates over time, requiring estimation and periodic correction of the clock drift that is occurring. As shown in [4], clock drift estimation is performed at 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 received packets.

However, it is widely-well known that the oscillators generate clock drift that varies with temperature. Therefore, it has been suggested that the mean value of the normal distribution modeling the generated clock drift varies significantly as the temperature changes, which cause errors when demodulating PLIM symbols [5]. In particular, estimation and correction are difficult when the interval between packet transmissions is long, since the interval between packet reception is also long. On the other hand, the PLIM system requires an increase in the number of indexes and a longer frame length to increase the number of bits in a PLIM symbol. The number of frequency indexes cannot be easily increased because of the limitation of the number of channels to the originally allocated bandwidth. Although the number of time slot indexes can theoretically be increased indefinitely, in reality, 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 where the temperature is stationary.

Furthermore, there is a possibility that the temperature characteristics of the clock drift are insufficient for node-mounted air temperature sensor information. This is because the chip on which the oscillator is mounted is expected to become hotter according to the amount of processing. If it is difficult to use a chip equipped with a temperature measurement function from the viewpoint of price, it is likely that estimation of temperature characteristics will be difficult.

Therefore, this study focuses on the number of channel indexes, which has been strictly limited due to bandwidth constraints, and then we propose a new method to increase the number of channel indexes. In particular, this paper assumes that the transmitter and receiver use LoRaWAN to modulate the transmission packets. The proposed method realizes PLIM by using the frequency offsets within a LoRa channel.

II. Fundamental Technologies

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

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

Fig. 1. Packet structure in LoRa PHY layer.

A. Packet-Level Index Modulation (PLIM)

The packet-level index modulation (PLIM) adds some bits to packet communication with LoRaWAN [3].

B. LoRaWAN

LoRaWAN uses chirp spread spectrum modulation (CSS), which continuously changes the frequency by doing cyclic within a channel bandwidth. LoRaWAN system cheeses and uses a channel that its bandwidth generally is 200 kHz, and can decide a LoRa signal bandwidth from 125 kHz, 200 kHz, and 500 kHz. If the bandwidth of the LoRa signal is 125 kHz, a guard band of 37.5 kHz is provided at each end of each channel.

In LoRa modulation, CSS is used and the preamble of the signal is added to a head of packets. The packet structure in LoRa physical layer is shown in Fig. [**?**]. The LoRa symbols are modulated by CSS modulation and then the signals are spread. If the basic chirp is an up-chirp, Sync word only consists of down-chirps and the other symbols are up-chirps.

The received LoRa signals are demodulated by de-chirping with inverse-basic-chirp, and then the LoRa symbols are obtained by FFT or DFT processing. In this subsection, the theory of spread processing and de-spread processing is explained.

1) Spreading on LoRaWAN: When a spreading cord is the bandwidth of chirp is $B\,[\mathrm{Hz}]$, a LoRa modulated symbols before spreading spectrum represent waves length sampled by 2^{SF}, where the sampling frequency of baseband signals is set to $B\,[\mathrm{Hz}]$.

$$w_o(t) = \exp(j2\pi \cdot D\frac{t}{2^{SF}T}) \quad (1)$$

$$= \exp(j2\pi \cdot D\frac{B}{2^{SF}}t). \quad (2)$$

Here, j is the imaginary unit and $T = 1/B$ is the sampling frequency, D is the index of data to be transmitable with $SF\,[\mathrm{bit}]$. D is described by the following,

$$D = 0, 1, .., 2^{SF} - 1. \quad (3)$$

When to performing FFT for 2^{SF} points to this baseband waveform, the bin with the largest value is the D-th FFT bin, indicating that demodulation is possible by performing FFT to the wave before the spectrum spreading.

The LoRa signal to be transmitted is spreaded using up-chirp of 2^{SF} sample length. The up-chirp changes in frequency linearly from $-B/2\,[\mathrm{Hz}]$ to $B/2\,[\mathrm{Hz}]$ in time with symbol length $2^{SF} \cdot T$. Therefore, the angular frequency at a certain time t can be written as follows,

$$\begin{aligned} \omega(t) &= 2\pi \left(\frac{B}{2^{SF} \cdot T} t - \frac{B}{2} \right) && (4) \\ &= 2\pi \left(\frac{B^2}{2^{SF}} t - \frac{B}{2} \right) [\mathrm{rad/s}]. && (5) \end{aligned}$$

Therefore, the phase of the baseband signal with this angular frequency is as follows,

$$\begin{aligned} \phi(t) &= \int_0^t \omega(t) \mathrm{d}t && (6) \\ &= 2\pi \left(\frac{B^2}{2 \cdot 2^{SF}} t^2 - \frac{B}{2} t \right) [\mathrm{rad}], && (7) \end{aligned}$$

and the baseband signal of the waveform underlying the spread spectrum can be written as follows,

$$\begin{aligned} w_b(t) &= \exp(j\phi(t)) && (8) \\ &= \exp\left\{ j2\pi \left(\frac{B^2}{2 \cdot 2^{SF}} t^2 - \frac{B}{2} t \right) \right\}. && (9) \end{aligned}$$

The transmission signal is given by multiplying the waveform $w_o(t)$ of the symbol before spreading and the base waveform $w_b(t)$ of the spread, which is as follows,

$$\begin{aligned} w(t) &= w_o(t) \cdot w_b(t) && (10) \\ &= \exp\left\{ j2\pi \left(D \frac{B}{2^{SF}} t + \frac{B^2}{2 \cdot 2^{SF}} t^2 - \frac{B}{2} t \right) \right\} && (11) \end{aligned}$$

Note that, when the frequency of the transmit signal that is the up-chirp exceeds by $B/2\,[\mathrm{Hz}]$, that starts from $-B/2\,[\mathrm{Hz}]$ again, because the frequency bandwidth of the transmission signals are 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 above equation 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, due to the transmission path, as shown in the following equation,

$$\hat{w}(t) = w(t) \cdot \exp(j\theta). \quad (12)$$

Here, the change in amplitude is not taken into account. In de-spreading, by multiplying the received LoRa signal and the inverse of the baseband signal, $1/w_b(t)$, the receiver can obtain the de-spreaded waveforms, as shown in

$$\begin{aligned} \hat{w_o}(t) &= w(t) \cdot \exp(j\theta) \cdot \frac{1}{w_b(t)} && (13) \\ &= w_o(t) \cdot w_b(t) \frac{1}{w_b(t)} \cdot \exp(j\theta) && (14) \\ &= \exp(j2\pi \cdot D \frac{B}{2^{SF}} t) \cdot \exp(j\theta). && (15) \end{aligned}$$

Note that $1/w_b(t)$ is a down-chirp because the positive and negative phases are reversed. By using this de-spreaded waveform, when performing the FFT for 2^{SF} points, the receiver obtains a result with the maximum absolute value in the D-th FFT bin, and then the transmitted data can be demodulated.

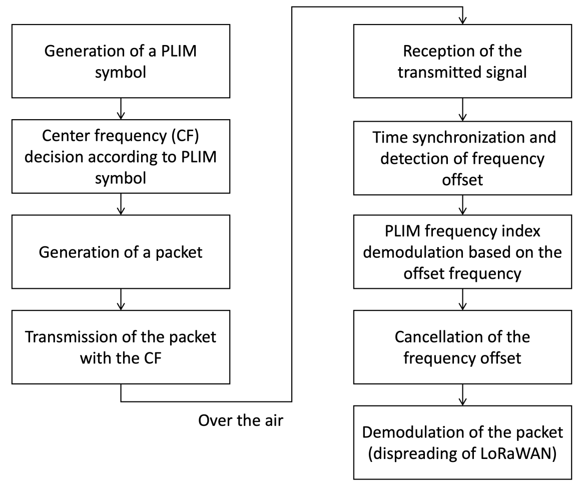

Fig. 2. Flow of the proposed method from the transmitter to the receiver.

III. PLIM Using Frequency Offsets with LoRaWAN

Our proposed method bases on the packet-level index modulation with LoRaWAN. LoRaWAN which is one of the low power wide area network (LPWAN) is used for the Internet of Things (IoT). In general, the IoT nodes consist of cheap elements and device because the number of nodes is huge. When using the PLIM, there is that the clock drift caused by the inexpensive oscillator of the transmit node because the time synchronization is needed to derive the PLIM time slot index from the packet's received time.

However, the IoT nodes are stricter on the frequency offset than on the clock drift because there are severe rules about the microwave emission. The signals are emitted by the wireless device equipped with a higher precision oscillator than an oscillator of microcomputer equipped for controlling the transmit timing. Therefore, we propose the PLIM method used the frequency offsets without the time synchronization as it is assumed the packet is modulated with LoRaWAN.

In the basic PLIM method, a PLIM symbol is assigned to the indexes of the time slot and channel. On the other hand, in our proposed method, PLIM is performed by shifting the center frequency of a RoLaWAN signal within the channel bandwidth. In this proposed method, PLIM symbols assign to the amount of frequency offsets. This section presents spreading method and de-spreading method, and a frequency offset mapping using packet-level index modulation which is our proposed method.

A. Procedure of LoRaWAN with Frequency Offset Using PLIM

Figure 2 shows the flow of the proposed method from the transmitter to the receiver. Figure 3 shows the procedure of the proposed method at the receiver.

B. Frequency Offset Acquisition by Correlated Peaks

The LoRa modulation scheme uses up-chirp in the preamble and down-chirp in the sync word. In this subsection, we show that the offset of the transmit frequency can be obtained from

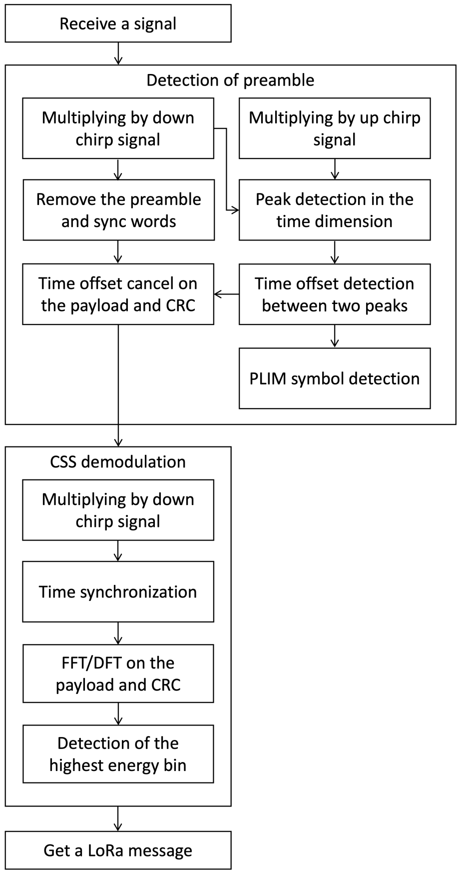

Fig. 3. Procedure of the proposed method.

the peak of the correlation function of the received up-chirp and down-chirp.

The up-chirp in the preamble is described by:

$$w_u(t) = w_b(t) \tag{16}$$
$$= \exp\left\{j2\pi\left(\frac{B^2}{2\cdot 2^{SF}}t^2 - \frac{B}{2}t\right)\right\}. \tag{17}$$

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

$$w_d(t) = w_b{}^*(t) \tag{18}$$
$$= \exp\left\{j2\pi\left(-\frac{B^2}{2\cdot 2^{SF}}t^2 + \frac{B}{2}t\right)\right\}, \tag{19}$$

where $*$ denotes complex conjugation.

Moreover, the received signal of the up-chirp whose frequency is offset by f [Hz] is described by:

$$\hat{w_u}(t) = w_u(t)\cdot\exp(j2\pi ft)\cdot\exp(j\theta) \tag{20}$$
$$= \exp\left\{j2\pi\left(\frac{B^2}{2\cdot 2^{SF}}t^2 - \frac{B}{2}t + ft\right) + j\theta\right\}. \tag{21}$$

The received signal of down-chirp whose frequency is offset by f [Hz] is described by:

$$\hat{w_d}(t) = w_d(t)\cdot\exp(j2\pi ft)\cdot\exp(j\theta) \tag{22}$$
$$= \exp\left\{j2\pi\left(-\frac{B^2}{2\cdot 2^{SF}}t^2 + \frac{B}{2}t + ft\right) + j\theta\right\}. \tag{23}$$

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

The correlation function for up-chirp is given by:

$$R_u(t) = \int_{-\infty}^{\infty}\hat{w_u}(\tau)\cdot w_u{}^*(\tau - t)\mathrm{d}\tau. \tag{24}$$

This correlation function has constant absolute values of $\hat{w_u}(\tau)$ and $w_u{}^*(\tau - t)$ are constant. When the following equation does not rotate on the complex plane according to τ, that is, the absolute value of $R_u(t)$ is maximized at t where the following Eq. (26) holds.

$$\hat{w_u}(\tau)\cdot w_u{}^*(\tau - t) \tag{25}$$

$$\frac{\partial}{\partial\tau}\arg(\hat{w_u}(\tau)\cdot w_u{}^*(\tau - t)) = 0 \tag{26}$$

Solving for this equation, t can be derived, as shown in Eq. (29),

$$0 = 2\pi\left(\frac{B^2}{2^{SF}}\tau - \frac{B}{2} + f\right) - 2\pi\left(\frac{B^2}{2^{SF}}(\tau - t) - \frac{B}{2}\right) \tag{27}$$
$$= 2\pi\left(\frac{B^2}{2^{SF}}t + f\right) \tag{28}$$
$$t = -f\frac{2^{SF}}{B^2}. \tag{29}$$

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

$$R_d(t) = \int_{-\infty}^{\infty}\hat{w_d}(\tau)\cdot w_d{}^*(\tau - t)\mathrm{d}\tau. \tag{30}$$

The t for which $R_d(t)$ is maximal can be solved in the same way, as shown in:

$$t = f\frac{2^{SF}}{B^2}. \tag{31}$$

From this result, when there is an offset of f [Hz] in the down-chirp, it can be seen that the correlation peak appears at a time $f\cdot 2^{SF}/B^2$ [s] later.

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

$$f = \frac{1}{2}\left(\Delta t - \frac{2^{SF}}{B}\right)\frac{B^2}{2^{SF}}. \tag{32}$$

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
Frequency offsets	0 [Hz] or 29297 [Hz]

The baseband signal of the transmitted signal when there is an offset of f [Hz] can be written as follows:

$$w_{offset}(t) = w(t) \cdot \exp(j2\pi ft). \tag{33}$$

Therefore, the received signal with no offset can be obtained by multiplying $\exp(-j2\pi ft)$ at the receiving side as follows:

$$\begin{aligned} \hat{w}(t) &= w_{offset}(t) \cdot \exp(j\theta) \cdot \exp(-j2\pi ft) \quad (34) \\ &= w(t) \cdot \exp(j\theta) \quad (35) \end{aligned}$$

This is equal to Eq. (12). In other words, in order for the receiver to cancel the detected offset, the received signal with the offset should be multiplied by $\exp(-j2\pi ft)$.

Figure 4 shows an image of the original-basic-chirp and the shifted-chirp of the proposed method.

IV. SIMULATION RESULT

This paper confirmed that the offset frequency can be detected by the time difference between the peaks of the correlated up-chirp and down-chirp waveforms of the LoRa preamble by simulation result. Table I shows the parameters for the simulation.

In this simulation, the baseband signal that the preamble of LoRa signal is constructed by consecutive chirp signals that consist of two up-chirp, two down-chirp, and 0.25 up-chirp, is used, as refer to [6]. Figure 5 shows the simulation result for confirming the peaks of the correlation of each chirp. From Fig. 5, the simulation result shows that the interval of peaks in case that offset frequency is 0 [Hz] is 1024.0 [ms] and the interval of peaks in case that offset frequency is 29297 [Hz] is 1504.0 [ms]. These results describe that the frequency offsets can be detected because the frequency offsets are 0.0000 [Hz] and 29297 [Hz], respectively.

V. CONCLUSION

This paper focuses on LPWA, which is used for IoT systems. In LPWA, LoRaWAN is one of the communication methods for IoT systems. Since LoRaWAN uses LoRa modulation, it is not easy to increase the data rate. Therefore, we address the issue of the number of channels due to the limitation of the number of transmission bits in increasing the transmission bits using the proposed PLIM scheme. In order to increase the number of transmission bits as much as possible, we propose the PLIM to use frequency offsets within the LoRaWAN channel. As a result, this paper shows the simulation result to confirm that the channel offsets assigned PLIM symbols can be detected by using our detection algorithm.

ACKNOWLEDGMENT

This research and development work was supported by the MIC/SCOPE #JP235004002.

REFERENCES

[1] LoRa Alliance Technical Committee, “LoRaWAN L2 1.0.4 Specification (TS001–1.0.4),” 2020. [Online]. Available: https://resources.lora-alliance.org/technical-specifications/ts001-1-0-4-lorawan-l2-1-0-4-specification.

[2] LoRa Alliance Technical Committee, “RP002-1.0.1 LoRaWAN Regional Parameters,” 2020. [Online]. Available: https://resources.lora-alliance.org/technical-specifications/rp2-1-0-1-lorawan-regional-parameters.

[3] Koichi Adachi, Kohei Tsurumi, Aoto Kaburaki, Osamu Takyu, Mai Ohta, and Takeo Fujii, “Packet-Level Index Modulation for LoRaWAN,” IEEE Access, vol.9, no.1, pp.12601–12610, Jan. 2021, DOI: 10.1109/ACCESS.2021.3051933.

[4] Kohei Tsurumi, Aoto Kaburaki, Koichi Adachi, Osamu Takyu, Mai Ohta, and Takeo Fujii, “Simple Clock Drift Estimation & Compensation for Packet-Level Index Modulation and its Implementation in LoRaWAN,” IEEE IoTJ, vol. 9, no. 16, pp. 15089–15099, Aug. 2022.

[5] H. Yamasaki, H. Matsuura, M. Ohta and M. Taromaru, “Impact of Inexpensive Oscillator in Wireless Sensor Node on Packet-Level Index Modulation Method under Real Environment,” The 15th International Conference on Ubiquitous and Future Networks (ICUFN 2024), July 2024.

[6] X. Tang, Y. Zhang, Y. Wang, D. Zhao, H. Li and X. Zhao, “Performance Analysis of Preamble Detection of LoRa System,” 2019 International Conference on Electronic Engineering and Informatics (EEI), pp. 175-180, 2019, doi: 10.1109/EEI48997.2019.00046.

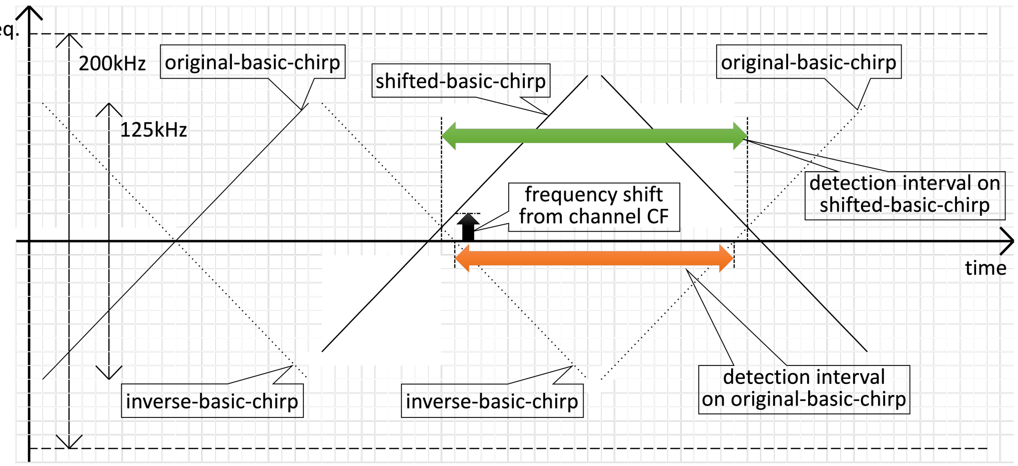

Fig. 4. Image of original-basic-chirp and shifted-chirp of the proposed method.

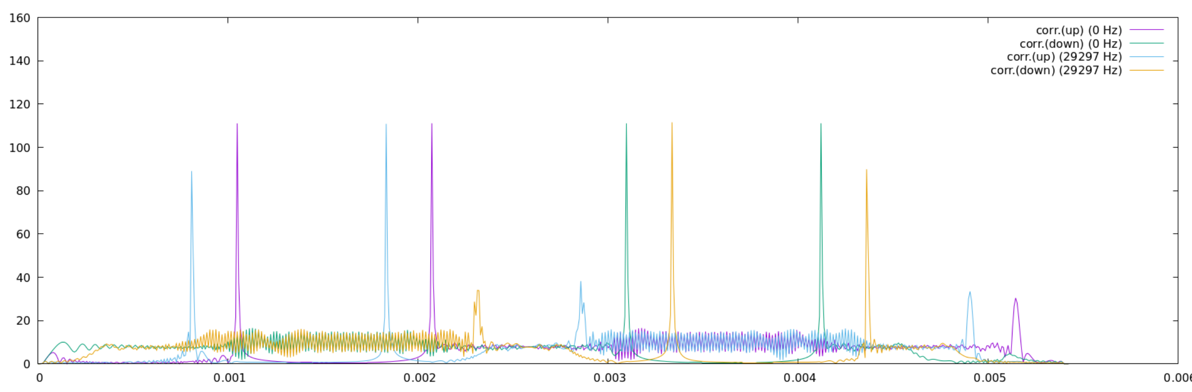

Fig. 5. Correlation peaks of basic-chirp and shifted-chirp of the proposed method in the time dimension.