Proposal of System-specific Period Superimposed Chart for Visualization of Communication Status of HD-PLC System

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***Abstract*—Power line communications (PLC) is a communication technology that uses a power line as a transmission medium. This study focuses on HD-PLC systems and proposes a system-specific period superimposed chart (SSP-SC) that visualizes the steady-state communication state using packet capture data. The conventional method of directly observing PLC signal waveforms in power lines using an oscilloscope makes it difficult to visualize signals over the long term. In addition, the number of burst signal inclusion packets is difficult to evaluate from the signal length, as the signal length varies depending on the communication environment. Furthermore, no methods have been proposed for PLCs to intuitively visualize communication conditions such as eye patterns and constellations in wireless communication. SSP-SC is a new visualization method for those problems, and its effectiveness is confirmed by comparison with conventional methods.**

***Keywords*—PLC, packet capture analysis, visualization of communication status**

I. INTRODUCTION

Power line communications (PLC) is one way to construct a home LAN environment. PLC uses the existing power lines in the house to establish communication links. Therefore, it is possible to easily set up a LAN environment by inserting PLC adapters into the power outlets. PLC is expected to be the same as wireless LAN and wired LAN to configure the home network environment. The majority of high-speed PLC systems deployed in Japan comply with one of three standards: High Definition Power Line Communication (HD-PLC) by HD-PLC Alliance, now evolving into the Nessum Alliance [1], HomePlug AV by HomePlug Alliance [2] and UPA by Universal Powerline Association [3]. Despite these poorly compatible PLC standards, initiatives to enable communication regardless of PLC standards and vendors are in progress [4]. Additionally, the next-generation PLC specifications are shown as IEEE1901a-2019 [5], and it is possible to significantly raise the communication speed to 1 Gbit/s, which is expected to be used for transmitting 4K and 8K videos and to extend the communication distance by reducing the communication speed, which is expected for building management. Undoubtedly, it is an important technology contributing to the Internet of Things.

The communication quality of such PLC systems and other communication methods is evaluated. The communications quality is quantitatively evaluated based on numerical evaluation indicators such as throughput, packet error rate, and even ITU-T recommendations for Internet Protocol communications quality [6]. Along with those indicators, for example, charts such as eye patterns and constellations with many superimposed signals are used together when evaluating the bit error rate of digital wireless communications. These charts are difficult to assess quantitatively, but they are beneficial for understanding the communication status briefly. PLC uses throughput and packet error rates in evaluation time units to quantitatively evaluate communications quality. However, no chart has ever been proposed for PLC, which superimposes several signals and packets and intuitively evaluates the communications status briefly. The conventional method of observing signal waveforms in power lines using an oscilloscope is to evaluate signals in the PLC section. This conventional method makes it difficult to acquire data for a long time if the time resolution is increased, so one packet can be determined with an oscilloscope. Conversely, the time resolution is lowered if priority is given to long-term observation. It becomes difficult to acquire data for each packet.

Furthermore, the signal length varies depending on the quality of the power-line communication environment. Hence, determining the number of burst signal inclusion packets from the signal length is impractical. For these reasons, conventional methods using oscilloscopes make it

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difficult to visualize for an instant the communication status of a PLC from the data obtained.

Therefore, this paper proposes a chart that uses packet capture data to visualize the steady-state communications status. This means that the packet transmission and reception intervals and the throughput are stably fluctuating, i.e., inter-computer communications using HD-PLC systems have no sudden fluctuations. The chart is a system-specific period superimposed chart (hereafter referred to as the "SSP-SC"), which is a two-dimensional plot of the received time of the burst signal, with superimposed time on the horizontal axis and real-time on the vertical axis. Visualization of the steady-state communications status using the SSP-SC is very effective for long-term evaluation of the burst signal reception timing and the number of packets included in the burst signal. In addition, quantitative evaluation indicators based on statistics, such as throughput and packet error rate, show average values over a specific time interval, so it is possible to evaluate the behavior over that interval numerically. However, those quantitative evaluation indicators cannot provide information on the communications status, including important time information, such as how packets were sent and received at a given time. The proposed SSP-SC visualizes such communications conditions that cannot be observed with quantitative evaluation indicators and is useful for evaluating the status of power-line communications, eye patterns, and constellations.

The remainder of the paper is organized as follows: Section II describes the conventional method and packet capture analysis. Section III presents the SSP-SC plotting algorithm. Section IV shows the algorithm for searching the system-specific period required to plot the SSP-SC. Section V shows examples of analysis and the effectiveness of the SSP-SC.

II. Inter-Computer Communications Analysis by Packet Capture

This section describes the conventional method of observing signal waveforms in the power line using an oscilloscope and simple packet capture data analysis. It also examines the periodic existence of intervals longer than the typical burst signal intervals, as demonstrated by packet capture analysis.

A. *Measurement System and Method*

Fig. 1 shows a test bed experiment system free from the influence of extraneous electrical equipment, power-line branches, and distribution boards. In this system, a 100 m Vinyl insulated Vinyl-sheathed Flat-type (VVF) cable was used as the power line for the major transmission medium. The signal reduction from 2 to 28 MHz used in PLC is approximately 7 dB / 10 MHz, and the transmitted signal level at 28 MHz is approximately 21 dB lower than at 2 MHz. A Noise-cut transformer was used to eliminate the influence of other electrical equipment mixed with the commercial power line, and the noise reduction from 2 to 28 MHz averaged 50 dB.

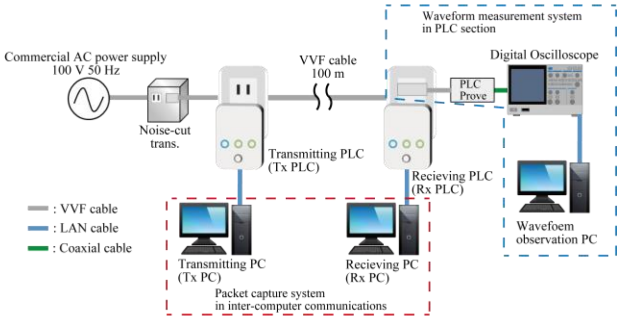

Fig. 1. Measurement system.

UDP (User Datagram Protocol) was used to simplify the evaluation and analysis. Packets were produced by packet generation software iperf [7] and transmitted from the Tx PC to the Rx PC. PLC devices were used in the 2nd generation HD-PLC. The Tx PC and Rx PC captured the packets. Wireshark [8] was used as capture software to measure these packet reception times. The status of the inter-computer communications can be examined in the packet capture by analyzing the area surrounded by the red dotted line. This study is concerned with inter-computer communications, specifically how the Rx PC receives packets sent from the Tx PC; the red dot is the system under study compared to the conventional range of blue dots.

Moreover, the equipment surrounded by the blue dotted line was used to directly evaluate the waveform of the PLC section using an oscilloscope. The PLC probe is a balanced-to-unbalanced converter that uses oscilloscope observation of voltage waveforms transmitted over Power lines are difficult to obtain and must be made by the user. In other words, the conventional method of observing signals in power lines is not versatile or easy. To ensure that the signal type could be identified and that the measurement lasted as long as possible, the oscilloscope's sampling rate was set to 1 MS/s, set to 5 seconds.

TABLE I. Product Names

PLC device	HD-PLC Panasonic BL-PA310 [9]
OS of Tx PC	Ubuntu ver. 13.10 [10]
OS of Rx PC	Ubuntu ver. 14.04LTS [10]
Packet transmission software	perf ver. 2.0.5 [7]
Tx PC packet capture software	Wireshark ver. 1.10.2 [8]
Rx PC packet capture software	Wireshark ver. 1.10.6 [8]
Category of LAN Cable	6A
Wired LAN connection speed	100Base-TX
Noise-cut trans.	UNION MNR-D-9-1010 [11]
Digital Oscilloscope	IWATSU DS-5632 [12]

TABLE II. HD-PLC Specifications

Transmission bandwidth	2 ~ 28 MHz
Modulation method	Wavelet OFDM
Transmission speed (PHY layer)	210 Mbit/s (Maximum)
Access control method	CSMA/CA
Transmission distance	200 m (Maximum)

TABLE III. Communication Specifications

Protocol	User Datagram Protocol (UDP)
Preset UDP transmission speed	30 Mbit/s
Packet size	1512 Bytes
Communication time	180 sec.

Table 1 shows the product names, and Tables 2 and 3 summarize the HD-PLC and communications specifications, respectively.

The communication time in this measurement is 180 seconds. This time was selected to allow packet capture, considering the specifications of the Rx PC used in this study. In practice, continuous measurement over a long time is also possible. For example, increasing the number of Rx PCs and taking turns capturing packets can overlap some of the capture time.

B. PLC Signal Waveform of PLC Section

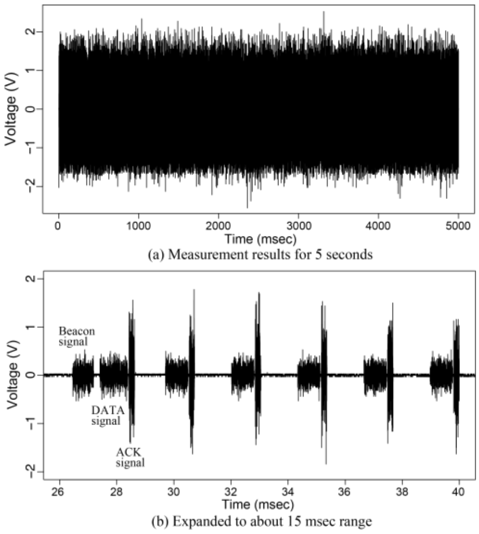

Fig. 2. PLC signal waveform in the power line.

Fig. 2 shows the results of measuring the PLC transmission signal waveform in the power line using the waveform measurement system. Fig. 2 (a) shows an overall view of the 5 seconds of continuous measurement possible in a single measurement. Fig. 2 (b), an expanded Fig. 2 (a), shows the individual waveforms. The signal in the PLC section is measured on the Rx PLC side, so the acknowledgment (ACK) signal, which is the signal sent from the Rx PLC to the Tx PLC, has a relatively high signal level. In contrast, the signal sent from the Tx PLC to the Rx PLC has a relatively low signal level because the 100 m VVF cable reduces it. Therefore, the high-level signal is the ACK signal, and the low-level signal is the DATA signal immediately before that signal. The signal transmitted by the Tx PLC that is not paired with the ACK signal can be identified as a Beacon signal.

In previous studies [13] [14], an oscilloscope analyzed transmission characteristics by directly observing physical signals in power lines. The former uses multi-tones, and the other uses pulse signals to measure the appearance of two different transfer functions synchronized to half the commercial power frequency period when a charger is inserted in the power-line communication path. On the other hand, we are working on inter-computer communications. The signal waveform of this PLC section represents merely a partial observation of the transmission of packets to the Rx PC, and it is unclear whether the Rx PC receives the packets. Therefore, we studied a method for analyzing the communication status of inter-computer communications through packet capture analysis, as shown in the next section.

C. Packet Capture Analysis of Inter-Computer Communications

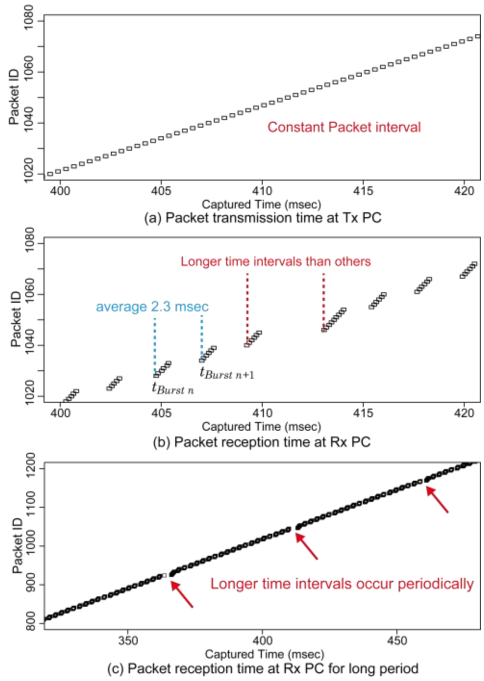

Fig. 3. Relationship between Packet ID and transmitted and received time.

We analyze the inter-computer communications bounded by the red dotted line in Fig. 1 using the packet capture data acquired by the Rx PC. Fig. 3 shows the relationship between the packet identity number (Packet ID) and transmitted and received time. The horizontal axis in each case is the packet capture time, and the vertical axis is the Packet ID attached by Wireshark to the Tx PC or Rx PC. Figs. 3 (a) and (b) show the packet transmission time captured by the Tx PC and the reception time captured by the Rx PC, respectively. Despite the constant packet interval at the Tx PC, the Rx PC captures several packets as burst signals. This is briefly explained in relation to the specifications of the medium access control layer of inter-HD-PLC communications within a power line [15]. The Tx PLC device aggregated several packets and transmitted them in bursts with a single data frame. This indicates that numerous packets are delivered concurrently in the data signal shown in Fig. 2 (b). The Rx PLC device separates them into individual packets. As a result, the Rx PC receives several packets in succession. The preceding study has shown that the burst signal inclusion packets at the preset UDP transmission speed of 30 Mbit/s are, on average, 5 or 6 [16]. When the reception time of the head packet of the burst signal is represented by the burst signal reception time t_{Burst}, the interval between $t_{Burst\ n}$ and $t_{Burst\ n+1}$ in Fig. 3 (b) is 2.3 msec on average. However, the interval was occasionally more than 2.3 msec. Fig. 3 (c) shows the packet reception time at the Rx PC for a long time, including the region shown in Fig. 3 (b). In approximately 47 to 48 msec, a blank indicates no burst signal has been detected. As shown in Fig. 2 (b), beacon signals that control PLC devices are transmitted in that section at regular intervals according to a transmission schedule [15]. The beacon signal controls PLC devices; therefore, it is only visible in the PLC section. Hence, it is not observed in the packet capture analysis of the Rx PC. In addition, immediately before the beacon signal transmission time, the burst signal length, that is, the number of packets to be transmitted, the burst signal transmission, and the ACK transmission from the receiving PLC, is also limited for the transmission of the beacon signal. Thus, the interval becomes longer due to the transmission of the beacon signal and the transmission limitation immediately before the beacon signal is transmitted.

We focus on this blank and propose a two-dimensional superimposed chart of each period's burst signal reception time. As shown in Fig. 3, the packet capture data can only be analyzed locally. The SSP-SC can visualize the steady-state inter-computer communications status briefly and help evaluate the communications status of power-line communications systems.

III. SSP-SC Plotting Algorithm

In two dimensions, the SSP-SC is obtained by plotting the burst signal reception time t_{Burst} at the Rx PC. The time is plotted repeatedly with the blank period observed in Sec.II.C, which is the superimposed period.

Fig. 4 shows the plotting method. The vertical axis represents real-time, while the horizontal axis represents a superimposed time ST. The initial value ST_1 of the superimposed time is arbitrary, and ST_i ($i \geqq 2$) is determined as follows,

$$Int_{Burst\ i-1} = t_{Burst\ i} - t_{Burst\ i-1} \tag{1}$$

$$ST_i = ST_{i-1} + Int_{Burst\ i-1}, \tag{2}$$

$$\text{if } ST_i \geqq P, ST_i = ST_i \bmod P, \tag{3}$$

where Int_{Burst} is the time interval between burst signal reception, and P is the superimposed period. Eq. 3 shows when the superimposed time ST_i equals or exceeds the superimposed period. The green circle on the left side is sequentially arranged based on the reception time of the burst signals. The numbers within the circles indicate the burst signal ID. The lower orange circles indicate the superimposed time. The position of the burst signal ID_1 must first be determined. Since $t_{Burst\ 1}$ in the vertical axis represents the real-time reception time at Rx PC, the position of the first green circle is determined immediately. Then, the superimposed time ID_1 of the horizontal axis is arbitrarily determined within the range of the superimposed period. The black circle ID_1, the intersection of $t_{Burst\ 1}$, and ST_1, is plotted on the SSP-SC. Next, the case in which the burst signal ID_2 is plotted on the chart is described. The second green circle, $t_{Burst\ 2}$, represents the reception time at Rx PC in real-time, therefore this point is determined immediately. Then, the interval $Int_{Burst\ 1}$ between $t_{Burst\ 2}$ and $t_{Burst\ 1}$ is calculated by Eq. 1. Furthermore, the superimposed time ST_2 is obtained by adding ST_1 to $Int_{Burst\ 1}$ using Eq. 2. The black circle ID_2 is plotted at the intersection of $t_{Burst\ 2}$ to ST_2. When these operations are repeated, ST_n may exceed the superimposed period P, for example, when $Int_{Burst\ 4}$ is added to ST_4 in Fig. 4. In this case, Eq. 3 is used to calculate the amount by which ST_5 exceeds the P. As shown in Fig. 4, the plot of ST returns to the origin and extends ST_5 more than the P. Then, ID_5 is plotted at the intersection of $t_{Burst\ 5}$, and ST_5. The SSP-SC that visualizes the packet reception status of inter-computer communications using the HD-PLC system is obtained by repeating this procedure until the communications time is required for analysis.

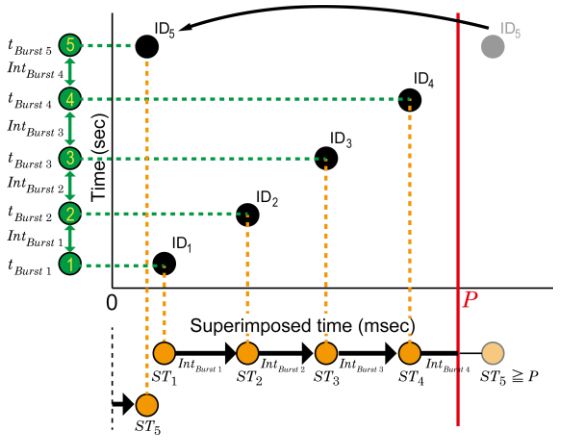

Fig. 4. SSP-SC plotting method.

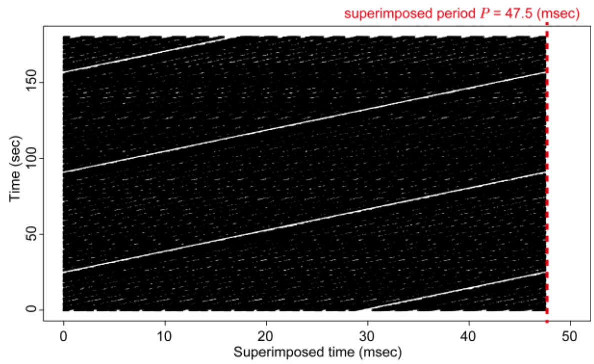

Fig. 5. SSP-SC with no optimum superimposed period.

For example, Fig. 5 shows the SSP-SC plotted by this method using the 180-second packet capture data used in Fig. 3. If we want to observe the whole time of data acquisition, we can plot the whole time. If we focus on a specific time, we can plot the data for 5 seconds, 40 seconds, or any other necessary time. As described in Sect. 2. C, the superimposed period P exists between 47 and 48 msec, so it is set to 47.5 msec, the red dashed line in Fig. 5. In Fig. 5, evaluating the reception of the burst signal is difficult. However, the blanks are lined up diagonally. This is because the superimposed period is not adjusted correctly. Therefore, we propose an algorithm that automatically optimizes the superimposed period using packet capture data. The optimized superimposed period is called the system-specific period. The system-specific period is the superimposed period in which the first burst signal is aligned as vertically as possible immediately after each beacon signal. In other words, if the system-specific period is determined using the first burst signal so that they are aligned vertically, the burst signals that follow it are detected at regular intervals as described in Section II, resulting in the second burst signal sequence also being aligned vertically. For this reason, plotting SSP-SC using the system-specific period has the advantage of superimposing burst signals on each sequence, making it easier to evaluate the communications status.

IV. System-specific Period Search Algorithm

A. *Algorithm Details*

The system-specific period search algorithm consists of 4 steps. First, the 4 steps outline is described. From the packet reception time acquired by the packet capture, the head packet in the burst signal is identified in Step 1, and the first burst signal reception time is specified in Step 2. Step 3 calculates the first burst signal reception time interval, and high-frequency values obtained from its histogram are used as a candidate for the representative value. Step 4 determines the system-specific period by the coarse-to-fine search. Fig. 6 shows the flowchart of the proposed search algorithm. Steps 2-F-1 and 2-F-2 in the flowchart are preliminary steps in case the system-specific period search fails and can be skipped. The process for each step, including the small steps, will be described in detail using actual data.

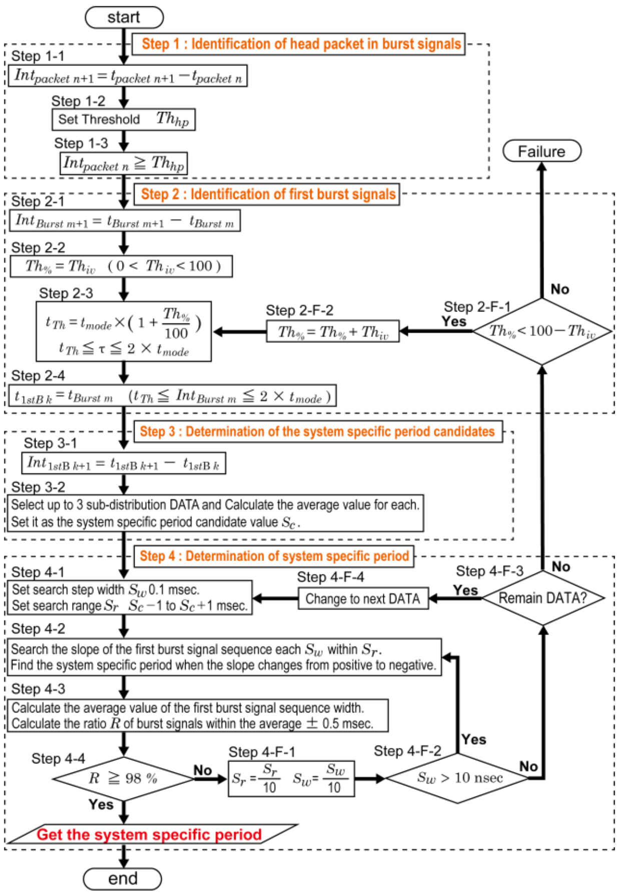

Fig. 6. Flowchart of the system-specific period search algorithm.

Step 1 Identification of head packet in burst signals:
The packet reception time of the packet capture data at the Rx PC is represented as a packet reception time interval histogram. A threshold for determining the head packet in the burst signal is provided on the histogram to identify the head packet in the burst signal.

Step 1-1 Plot of packet reception time interval histogram:
The packet reception time interval Int_{packet} is as follows:

$$Int_{packet\ n+1} = t_{packet\ n+1} - t_{packet\ n}\ , \tag{4}$$

where t_{packet} is the packet reception time, and n is the Packet ID. A packet reception time interval histogram is plotted from the obtained Int_{packet} at Eq. 4. Fig. 7 shows an example of the histogram. The horizontal axis is the packet reception time interval, and the vertical axis is the frequency.

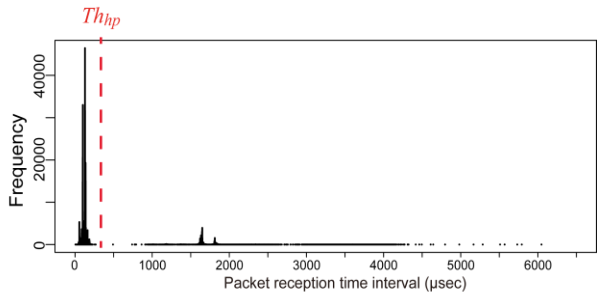

Fig. 7. Packet reception time interval histogram.

Step 1-2 Setting a threshold for determining head packets in burst signals:
The threshold value Th_{hp} for determining the head packet in the burst signal is set concerning the histogram. Th_{hp} is selected considering that the packet reception time interval from the last packet in the burst signal to the first packet in the next one is longer than the packet interval in the burst signal. This can easily be understood by referring to Fig. 3. The red dashed line is an example of the determination threshold Th_{hp}.

Step 1-3 Identification of head packets in burst signals:
Packets that meet the following conditions should be extracted:

$$Int_{packet\ n+1} \geq Th_{hp}. \tag{5}$$

Additionally, these packet reception times t_{packet} is represented as burst signal reception times $t_{Burst\ m}$, where m is a burst signal ID.

Step 2 Identification of first burst signals:

A burst signal reception time interval histogram is plotted using the burst signal reception times $t_{Burst\ m}$. A threshold value is provided in the histogram to identify the first burst signals.

Step 2-1 Plot of burst signal reception time interval histogram:

The burst signal reception time interval Int_{Burst} is as follows:

$$Int_{Burst\ m+1} = t_{Burst\ m+1} - t_{Burst\ m}. \tag{6}$$

A burst signal reception time interval histogram is plotted from the obtained Int_{Burst} at Eq. 6. Fig. 8 shows an example of the histogram. Fig. 8 (a) shows the overall view, and (b) shows the enlarged view of the frequency below 100 in the burst signal reception interval of 2000 to 6000 microseconds. The horizontal axis represents the time interval between burst signal reception, while the vertical axis represents the frequency. Let t_{mode} be the interval of the most frequent value of the histogram and let t_{mode} be the lower limit value of the range determined to be the first burst signal. The burst signal intervals around t_{mode} are the most frequently observed burst signal intervals for this communications condition, as shown in Sec. II.C. When the burst signal with the longer interval is retrieved, it is likely the first one. Furthermore, let $2 \times t_{mode}$ be the upper limit value of that. A reason for a burst signal interval that is more than twice the mode is when a single burst signal is undetected due to a problem in the transmission path or PC. In that case, since the interval before and after the undetected burst signal is the burst signal interval, other burst signals may be extracted instead of the first burst signal to be extracted. The results of observing the packet capture data, as shown in Fig. 3, indicate that for any preset UDP transmission speed, the burst signal reception time interval to be extracted is generally less than twice the most frequent value.

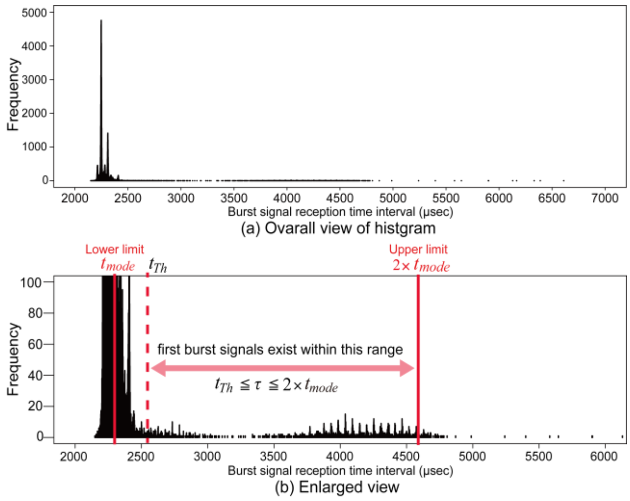

Fig. 8. Burst signal reception time interval histogram.

Step 2-2 Initial value setting for the first burst signal determination threshold:

Since there is still a large amount of the most frequent value of the burst signal interval near the lower limit, the first burst signal is efficiently extracted by reducing the lower limit using the threshold. Let Th_{iv} be an initial value for the first burst signal determination threshold. Th_{iv} is selected from 0 to 100 %,

$$0 < Th_{iv} < 100. \tag{7}$$

Th_{iv} is the initial value of the lower threshold $Th_{\%}$,

$$Th_{\%} = Th_{iv}, \tag{8}$$

which will be used in the next step to extract the first burst signal from the range where the first burst signal is expected to appear. Th_{iv} is also used in **Step 2-F** when the algorithm returns from **Step 4**.

The initial value Th_{iv} is recommended to be 10 %. In the case of 5 %, the amount of extracted burst signals increases, but so does the number of unnecessary burst signals, and in the case of 20 %, the accuracy of the extracted burst signals increases, but the amount of extracted signals decreases. This study set the initial value Th_{iv} to 10 %. If the algorithm fails by the initial value, $Th_{\%}$ is added in **Step 2-F-2** to increase the extraction accuracy.

Step 2-3 Setting the first burst signal determination range:

A ratio corresponding to the threshold value $Th_{\%}$ is added to the lower limit value t_{mode}, and is used as the first burst signal determination threshold value t_{Th}.

$$t_{Th} = t_{mode} \times \left(1 + \frac{Th_{\%}}{100}\right). \tag{9}$$

Let the first burst signal determination range τ be the first burst signal determination threshold value from t_{Th} to the upper limit value $2 \times t_{mode}$,

$$t_{Th} \leqq \tau \leqq 2 \times t_{mode}. \tag{10}$$

Step 2-4 Identification of the first burst signals:

The burst signal reception time $t_{Burst\ m+1}$ having the burst signal reception time interval $Int_{Burst\ m+1}$ within the range τ is set as a first burst signal reception time $t_{1stB\ k}$, where k is a first burst signal ID. The first burst signal reception time $t_{1stB\ k}$ is obtained as follows:

$$t_{1stB\ k} = t_{Burst\ m} \quad (t_{Th} \leqq Int_{Burst\ m} \leqq 2 \times t_{mode}). \tag{11}$$

The process proceeds to **Step 3**.

Step 2-F-1 Failure determination of the system-specific period search algorithm:

If $Th_{\%}$ is less than $100 - Th_{iv}$ go to **Step 2-F-2**. Otherwise, the search algorithm will fail because the first burst signal for searching the system-specific period in the range of Eq. 10 cannot be obtained.

Step 2-F-2 Changing the threshold:

Add threshold initial value Th_{iv} to threshold $Th_{\%}$ and return to **Step 2-3**.

Step 3 Determination of the system-specific period candidates:

The first burst signal reception time histogram is plotted using the first burst signal reception times $t_{1stB\ k}$. Three values with high frequency on the histogram are used as candidates for the system-specific period in **Step 4**.

Step 3-1 Plot of first burst signal reception time interval histogram:

The first burst signal reception time interval $Int_{1stB\ k+1}$ is calculated as follows:

$$Int_{1stB\ k+1} = t_{1stB\ k+1} - t_{1stB\ k}\ . \tag{12}$$

A first burst signal reception time interval histogram is plotted from the obtained Int_{1stB} at Eq. 12. Fig. 9(a) shows an example of the histogram. The horizontal axis is the first burst signal reception time interval, and the vertical axis is the frequency.

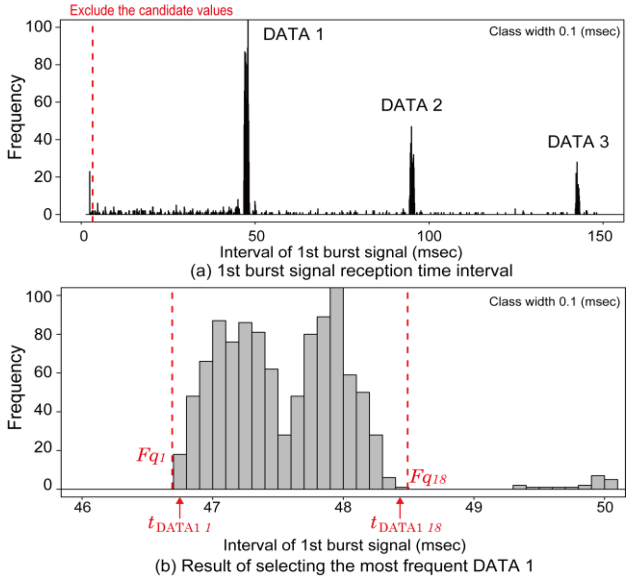

Fig. 9. 1st burst signal reception time interval histogram.

Step 3-2 Selection of system-specific period candidates:

Three high-frequency values are selected as system-specific period candidates $\boldsymbol{S_c}$ from the first burst signal reception interval histogram. Since the frequency around 0 msec is the frequency of the reception time interval between consecutive burst signals that could not be excluded in **Step 2**, these less than 1.5 times t_{mode}, shown to the left of the dotted line in Fig. 9(a) are excluded from the system-specific period candidate values. First, the sub-distribution, including the mode, is extracted and let be DATA 1. Next, from other distributions excluding DATA 1, the sub-distribution, including the mode, is extracted, and let be DATA 2. Similarly, extract up to DATA 3. Since the first burst signal is approximately identified using the burst signal reception time interval in Step 2, the first burst signal interval becomes twice or three times longer when one or two extraction omissions occur from consecutive first burst signals. This can be seen in DATA 2 and DATA 3. Normally, DATA 1 has the shortest first burst signal reception time interval, and there is a high possibility that the system-specific period is included. If the communication environment of the PLC is poor, such as when many electronic devices are connected to the communication channel, the no detection of burst signals, including the first burst signal, will be high. In such a case, even if the burst signals have been properly filtered in the previous steps, it is possible, but very rare, that DATA 2 or DATA 3 will have a higher frequency than DATA 1. For these reasons, three sub-distributions are extracted to prevent the omission of candidate values. When the communications time is short, or the preset UDP transmission speed is low, the amount of data may be small, in which case, the sub-distributions are extracted as far as possible up to DATA 3. A weighted mean value is derived up to 100 µseconds order for each DATA and the value is taken as the system-specific period candidates S_{c1} to S_{c3}. Specifically, Fig. 9(b) shows the actual distribution extracted as DATA 1. It extracts the interval whose frequency is not zero, including the most frequent value surrounded by the red dotted line, and the system-specific period candidate S_{c1} was obtained to be 47.5 msec by the following,

$$S_{c1} = \frac{\sum_{j=1}^{N}(t_{\mathrm{DATA1}\,j} \times Fq_j)}{\sum_{j=1}^{N} Fq_j}, \tag{13}$$

where N is the number of classes in the sub-distribution, $t_{\mathrm{DATA1}\,j}$ is the class value, and Fq_j is the frequency, respectively, as shown in Fig. 9 (b).

Step 4 Determination of system-specific period:

The coarse-to-fine search determines the system-specific period when the first burst signal becomes highly vertical.

Step 4-1 Initial condition of coarse-to-fine search:

An initial search range S_r is set $\pm$ 1 msec of the system-specific period candidate value S_c, and an initial search step width S_w is 0.1 msec. Since the extracted sub-distributions are spread approximately in the plus or minus 1 msec range and the candidate values are obtained up to 100 µsec order, the coarse-to-fine search starts from these initial values to obtain the system-specific period.

Step 4-2 Slope search for the first burst signal sequence:

The slope of the first burst signal sequence is calculated for each step width S_w within the range S_r. Calculate one of the lines in the chart if there are multiple lines. The system-specific period in which the slope changes from positive to negative is obtained.

Step 4-3 Extraction of highly density system-specific period:

The average value of the x-axis values determines the average value of the superimposed time of each plotted point. The ratio R of the first burst signal within the obtained average $\pm$ 0.5 msec is calculated. In other words, the ratio R of all the plotted first burst signals within that range is calculated.

Step 4-4 Judgment of end of coarse-to-fine search:

If the ratio R obtained in the previous step is 98 % or more, the system-specific period search is successful, and this algorithm ends. The 98 % or more value is set to consider outliers because other burst signals may be extracted when the first burst signal is extracted.

Step 4-F-1 Next preparation for coarse-to-fine search:

The search range S_r and the step width S_w are reduced to one-tenth. For example, since the initial value of S_w is 0.1 msec, it is assumed that the optimal value of the system-specific period exists in the width of $\pm$ 0.1 msec after the first search. Therefore, if S_r and S_w are set to one-tenth of their initial values, they will be $\pm$ 0.1 msec and 0.01 msec, respectively, and the search range should be narrowed in consideration of the result of the previous coarse-to-fine search.

Step 4-F-2 Continuation judgment of course-to-fine search:

If the step width S_w is greater than 10 nsec, return to **Step 4-2**. If not, go to **Step 4-F-3**. In other words, the coast-to-fine search is executed up to 100 nsec, which is set to consider the rounding error because the accuracy of the Wireshark timestamp used in this study is 1 µsec.

Step 4-F-3 Confirmation of remaining candidate DATA:

It is checked whether the search for the system-specific period fails in all DATA. If DATA remains, proceed to **Step 4-F-4**. If not, return to **Step 2-F-1**.

Step 4-F-4 Change DATA:

Change from DATA n to DATA $n+1$, and return to **Step 4-1.**

This concludes **Step 4** and this algorithm.

Step 4 will be described in detail concerning Fig. 10. In Step 4-1 since the system-specific period candidates S_{c1} obtained in Step 3-3 was 47.5 msec, the initial search range S_r is 46.5 to 48.5 msec, and the search step width S_w is 0.1 msec. In Step 4-2, the SSP-SCs of only the first burst signal are plotted, and those slopes are calculated for each step. Fig. 10(a) shows the slope value for each step in the 1st coarse-to-fine search. Focusing on 47.5 msec of the slope changes from positive to negative, there should be a system-specific period in which the first burst signal sequence is most vertical. Therefore, in Steps 4-3, the SSP-SC is plotted with a period of 47.5 msec to judge the verticality, and the average value of the superimposed time is obtained. The average value was 26.05 msec. The ratio R of the first burst signal within the average value $\pm$ 0.5 msec is calculated. Fig. 10(b) shows the SSP-SC currently. The red points indicate the region with the average value of $\pm$ 0.5 msec, and the ratio R, that is, the ratio of red points to all the plotted first burst signals, was 2.065 %. In Steps 4-4, if the ratio R is 98 % or more, the algorithm is ended because the verticality is sufficiently guaranteed. However, it is less than that in this case, so the accuracy is increased to one-tenth in Step 4-F-1. As a result, the condition of step width S_w is satisfied in Step 4-F-2, so the coarse-to-fine search is continued. Step 4-F-2 searches with the same data until S_w is 100 nsec. This is the range where the timestamp accuracy of the obtained data would be reliable. In other words, if the verticality is insufficient up to this step, the system-specific period cannot be judged reliably even after further detailed search. This is because the system-specific period candidate S_c may not be correct, or the ratio R may become low because of the outlier of the extracted first burst signal. In such cases, changing the DATA of the system-specific period candidate from Step 4-F-3 and narrowing the extraction range from Step 2-F-1 to increase the accuracy of the first burst signal extraction is applied. However, this is only a preliminary process, and in most cases, the system-specific period is obtained without these loop processes. Figs. 10(c) to (h) show that the verticality of the first burst signal sequence increases as the coast-to-coast search proceeds. In the 4th coarse-to-fine search in Figs. 10(g) and (h), the ratio R of red points exceeded 98 %, so this system-specific period P 47.5342 msec is adopted, and the algorithm succeeds. The end judgment value of 98 % considers outliers incorrectly extracted as the first burst signal even though they were initially the second and third burst signals, as shown in Fig. 10 (h). Although this example is an analysis for 180 seconds, in the case of analysis for a shorter time, for example, 10 seconds, the number of first burst signals is reduced, and the influence of one outlier is significant. Therefore, the value should be set as close to 100 % as possible, but the conditions are too strict, so it was set to 98 %. Fig. 10(h) shows that the verticality is sufficiently guaranteed.

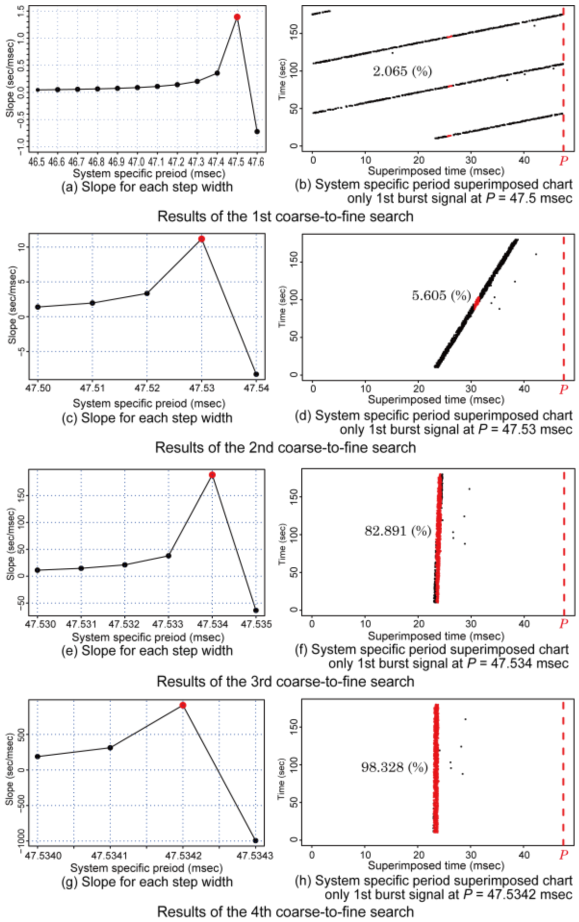

Fig. 10. Coarse-to-fine search.

Fig. 11 shows the SSP-SC using all burst signals when the system-specific period P is 47.5432 msec. The numbers 1 to 21 at the top are the burst signal sequence numbers. As shown in Fig. 5, only white lines were visible before the system-specific period search. Still, after searching for the system-specific period, all burst signal sequences are aligned vertically enough to be identified.

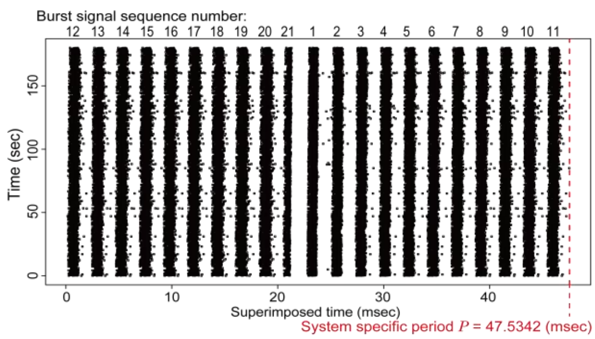

Fig. 11. SSP-SC when ***P*** is 47.5432 msec.

From the above, it is very important to find the system-specific period, the superimposed period vertically aligned using the first burst signal, to identify and visualize the burst signal sequence and evaluate the communications situation after plotting the SSP-SC.

B. Algorithm Application Examples and Validity

We describe the prerequisites for the effectiveness of our proposed algorithm. The algorithm focuses on the interval between the first burst signal and the burst signal immediately before it is longer than the others. Since there are transmission signals between those signals that seem to be control signals of PLC devices, the algorithm is applicable regardless of the communication conditions because the interval between focused burst signal intervals is longer than between other burst signals. Even if the physical characteristics of inter-computer and inter-PLC communications are variable, such as time-varying physical transmission rates, variable packet lengths, and different modulation methods for PLC sections, it is necessary if the burst signal interval at the center of this algorithm is longer than other burst signal intervals. It should be noted that the test bed was used to capture data up to the preset UDP transmission speed of 40 Mbit/s stated below, and the packet error rate was zero. This study used the preset UDP transmission speed of 30 Mbit/s to provide a margin for PLC communications to the range where packet errors do not occur.

Since the proposed algorithm is described using a single case with the preset UDP transmission speed of 30 Mbit/s, we simply show the application and validity of the algorithm for other cases. Fig. 12 shows the distribution selected from the successful completion of the algorithm from the preset UDP transmission speed of 1 to 40 Mbit/s, which shows the distribution selected by Fig. 9 (b) in Steps 3-3 for each speed. The communication time is 180 seconds in both cases. The horizontal axis is the interval of the first burst signal, and the vertical axis is the percentage of each first burst signal interval when the percentage of the extracted sub-distribution is set to 100 %. The interval is between 46.5 and 48.5 msec for all preset UDP transmission speeds.

In some cases, the percentage reaches a maximum of around 47.5 msec; in others, it reaches a bottom. In the bottom case, we assume it is due to data dependency. In such a circumstance, the most frequent value of t_{mode} in Fig. 8 becomes a slightly shorter interval. Some data shows that the distribution of the first burst signal interval is high frequency about 47.5 msec when the threshold $Th_{\%}$ is set to 5 %. Therefore, since the threshold of 10 % is a very significant value, it has been difficult to extract the data of 47.5 msec, which is close to the most frequent value of the first burst signal interval. However, the algorithm can search for the system-specific period in every scenario.

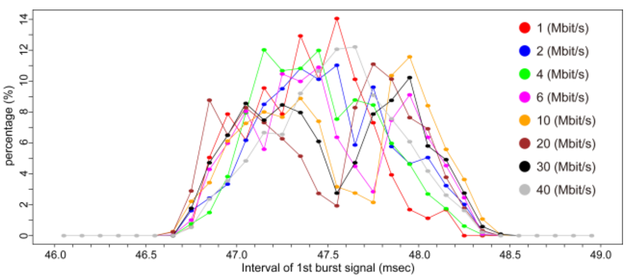

Fig. 12. Distribution of 1st burst signal interval selected for each preset UDP transmission speed.

In all scenarios illustrated here, the system-specific period is 47.5432 msec, and the SSP-SC for each preset UDP transmission speed is shown in our previous study [17]. We are currently working on a detailed analysis.

When the PLC communications system changed, for example, an aggregation tap was placed between the PC and PLC devices from the system configuration in Fig. 1, the system-specific period was 47.5434 msec. The difference of merely 20 nsec worsens the verticality of the burst signal sequence on the SSP-SC, making it difficult to analyze with high accuracy. Therefore, searching for the system-specific period with the highest verticality is important when using the proposed algorithm.

Finally, the application example in the 3rd generation HD-PLC [18] is shown. Figs. 13 (a) and (b) show the SSP-SC with a communication time of 180 seconds when using the 3rd generation HD-PLC. Fig. 13 (a) plots only the first burst signals, and Fig. 13 (b) plots all burst signals. These results reveal curved burst signal sequences in the 3rd generation HD-PLC. Since the period of the curve is generally constant, it is assumed that in the 3rd generation HD-PLC, PLC devices evaluate the communications status by some indicator, and according to the evaluation results, the beacon signal interval may be controlled at a constant period to enable stable communications. Therefore, the current system-specific period search algorithm fails because it judges the verticality of the first burst signal sequence. Still, these statistics are based on the results of previous studies [19] to some extent, and the system-specific period was selected manually. In Figs. 13 (a) and (b), the system-specific period is about 120 msec, which is longer than the 2nd generation. Additionally, we estimate that the system-specific period varies periodically because the slope of the burst signal sequence changes positively or negatively at a certain period.

For this reason, for detailed analysis, extracting the interval of the burst signal sequence's constant slope is important, as searching for the system-specific period by the proposed algorithm using only the packet capture data. Figs.13 (c) and (d) show the results of searching the system-specific period using only the packet capture data of the actual communications time from 127 to 145 seconds, which is the constant slope interval surrounded by the yellow dotted line in Fig. 13 (b). Because of the short communications time of about 20 seconds, the number of captured data is small and the weight of one burst signal is large. However, the verticality of the first burst signal sequence is guaranteed by the ending judgment threshold of 98 % or more, which was set with a margin in Steps 4-4. The verticality also indicates that the system-specific period is constant to some certain value within the interval with a constant slope. As described above, applying the system-specific period search algorithm to the 3rd generation HD-PLC and analyzing the SSP-SC is possible. The search algorithm for the curved system-specific period observed in the 3rd generation HD-PLC and its analysis examples are currently under study and will be reported in the future.

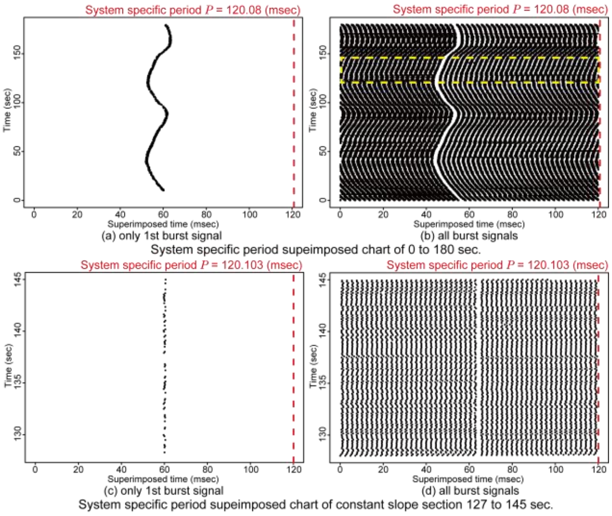

Fig. 13. SSP-SC when using 3rd generation HD-PLC.

In conclusion, the proposed algorithm has been tested in various cases and on HD-PLC systems, and its validity has been demonstrated.

V. Analysis Example of SSP-SC

A. Comparison with Average Beacon Signal Period Superimposed Chart

In the measurement system shown in Fig. 1, it is possible to simultaneously measure the signal waveform of the PLC section using the oscilloscope and the packet capture data on the Rx PC. This section compares the SSP-SC with an average beacon signal period superimposed chart [20], also proposed by the authors (hereafter referred to as beacon superimposed chart). In the Beacon superimposed chart, the receiving time is extracted from the signal waveform of the PLC section as shown in Fig. 2 at the beginning of each beacon and data signal. The receiving time is plotted using the method shown in Fig. 4. The average beacon period is then calculated so that the beacon signal's verticality is highest, which is used as the superimposed period. The oscilloscope was set to the minimum sampling frequency at which beacon and data signals could be distinguished, and the oscilloscope was programmed to automatically measure continuously for as long as possible. As a result, the oscilloscope automatically recorded and saved 5 seconds of data, before acquiring the next data at about 12 seconds. Therefore, the average beacon period for each 5-second data point was calculated and used as the superimposed period.

Fig. 14 (a) and (b) show the Beacon superimposed chart and the SSP-SC for the 25 seconds around 65 seconds extracted from the data continuously measured for 180 seconds. The red points shown in the Beacon superimposed chart Fig. 14 (a) are beacon signals. The most obvious feature of this chart is that there are blank spaces because the continuous measurement is available for only up to 5 seconds. Even if we observe the signals in the power line with the oscilloscope and plot the chart equivalent to the SSP-SC, there are periods when the communication status cannot be evaluated. On the other hand, the SSP-SC in Fig. 14 (b) allows the Rx PC to evaluate the status of inter-computer communications for the entire communication time without interruption.

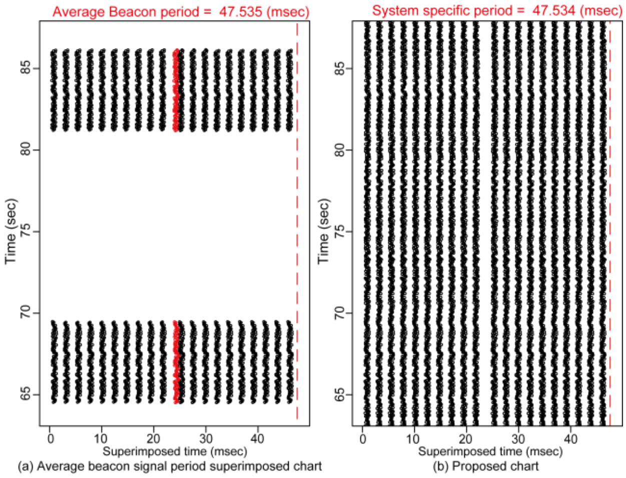

Fig.14. Beacon superimposed chart and SSP-SC.

The next difference is that the average beacon period and the system-specific period differ slightly. This is because the system-specific period is established based on the time received by the Rx PC's NIC after being influenced by numerous devices' transmission and reception timing following the Rx PLC. On the other hand, the average beacon signal period is determined from the beacon signal waveform at the Rx PLC. The system-specific period must be calculated to visualize the communications state of inter-computer communications, which is influenced by many devices in the communications system. However, it was just a little variation in this example.

B. Analysis Examples

Although only the burst signal reception time is plotted in monochrome in Fig. 11 and Fig. 14, the number of burst signal inclusion packets is also stored as the captured data about each burst signal. More extensive analysis becomes possible by reflecting the data in the plotted chart as necessary. Although the number of packets in the burst signal may be determined from the PLC signal waveform, it is difficult to determine instantaneously because the signal length varies depending on the transmission rate.

Fig. 15 shows the SSP-SC in which each point is color-coded based on the number of the burst signal inclusion packets. In the colored legend of Fig. 15, the number of included packets is grouped by 3, and 31 or more are grouped. According to the specification of HD-PLC [15], up to 31 packets are included in one burst signal. First, light blue, having the included packet number of 4 to 6, is dominant. This is because, as shown in Fig. 3 (b), the inclusion packet number is 5 or 6 under this measurement condition at the preset UDP transmission speed of 30 Mbit/s. This number of 5 or 6 burst signal inclusion packets is called the regular state. We will concentrate on the burst signal sequences preceding and following the white clear belt, namely, the 21st and 1st burst signal sequences. The 21st is black, with 1 to 3 packets, and the 1st is further divided into two parts: Blue with 7 to 9 packets in the front near the white clear belt, and light green with 10 to 12 packets at the back.

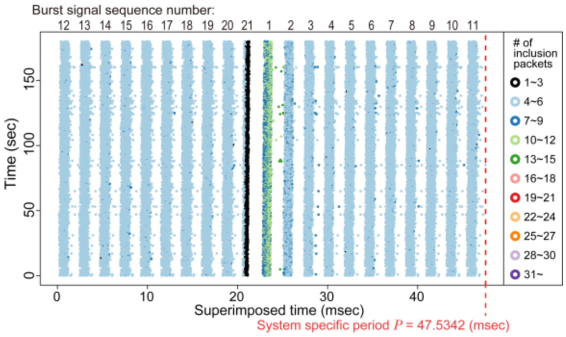

Fig. 15. Color-coded SSP-SC.

To analyze this part in detail, a part of the chart in Fig. 16, the horizontal axis from 18 to 26 msec and the vertical axis from 136.85 to 137.05 sec, was enlarged. The numbers written beneath the plot points represent the number of the burst signal inclusion packets, while the black dotted line represents the duration where the white clear belt exists.

First, in region A, surrounded by a green line, a burst signal with 6 packets in the regular state is detected just before the white clear belt. 6 packets are also detected in the first burst signal just after the white clear belt, indicating a communication situation that can be observed in other burst signal sequences at the preset UDP transmission speed of 30 Mbit/s.

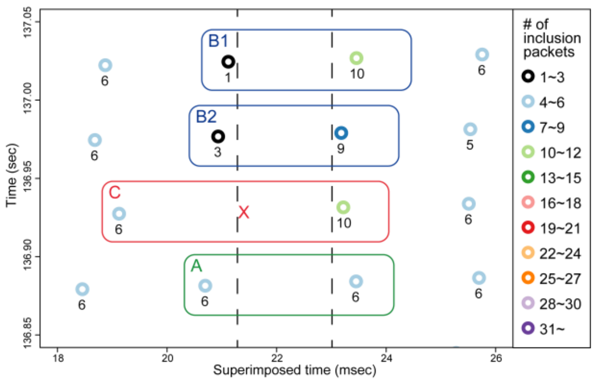

Fig. 16. Enlarged chart of Fig. 15.

Secondly, in regions B1 and B2 surrounded by the blue line, the number of the burst signal inclusion packets detected just before the white clear belt is lower than the regular state 5 or 6 and much lower in B1, which is detected closer to the white clear belt. The number of the first burst signal included packets immediately after the white clear belt is increased by the number of packets added to the scheduled packets. For example, in B1, 5 or 6 packets should have been detected just before the white clear belt. Still, only 1 packet was detected due to the white clear belt, so the first burst signal immediately after the white clear belt detected 10 packets, which is the number of packets added to the normal state 5 or 6 packets, and the undetected 5 or 4 packets. To be added in Fig. 15, light blue in the 21st burst signal sequence is the situation of region A, and black is the situation of region B. In the same way, blue and light green patterns in the first burst signal sequence are also formed because of region B. Although it is difficult to determine because of the overlap, light blue dots also exist due to the situation of region A.

Next, we focus on the burst signal including 6 packets in region C, located around 19 msec on the horizontal axis. The next burst signal, indicated by "X," should be detected about 2.3 msec later in this system. However, that burst signal is not detected because it is in the white clear belt. The first burst signal after the white clear belt was detected as the burst signal included 10 packets, which were added to the 5 or 6 packets that were normally scheduled to be transmitted. The absence of a burst signal in the Rx PC seen in regions B and C is due to the white clear belt serving as the beacon signal transmission control section, as shown in Fig. 2 and Fig. 14 of the oscilloscope-based observation [15]. Packets overlapping that control interval may not be transmitted by the Tx PLC. Using the SSP-SC, the number of burst signal inclusion packets can be clarified, and the Rx PC can examine the behavior of the beacon signal transmission control section. The Beacon superimposed chart in Fig. 14 is plotted from the signal waveform. Although the burst signal length can be used to estimate the number of inclusion packets, the instantaneous determination using the signal length is inferior to the proposed method since the signal length also changes as the transmission rate changes.

Finally, Fig. 17 shows the SSP-SC plotted using packet capture data obtained in a laboratory at Toyo University (hereafter referred to as "under actual environment"). The actual environment uses outlets laid in the wall. Therefore, the power lines branch off in the wall, and various devices are connected and operating outside the outlets used in the experiment. The data acquisition conditions at this time are the same as those in the test bed shown in Table 3. The throughput and packet loss rate, quantitative evaluation indicators of communication quality calculated from the packet capture data of the Tx and Rx PCs, are 30 Mbit/s and 0 %, respectively. This is also the same as the result in the test bed. The difference is obvious when comparing Figs. 15 and 17.

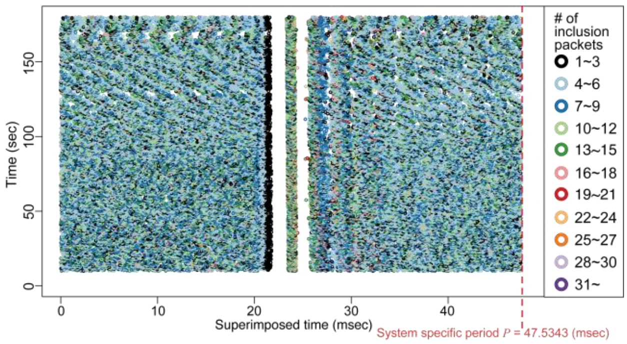

Fig. 17. SSP-SC under actual environment.

In contrast to Fig. 15, where the burst signal sequences were lined up, Fig. 17 makes it difficult to distinguish the second burst signal sequence and the following. The second and following burst signals' irregular transmission and reception timing are visualized as appropriate. Furthermore, focusing on the number of inclusion packets, light blue dominates in Fig. 15. In contrast, a mosaic with a large amount of black appears in Fig. 17. These are because the burst signal transmitted by the Tx PLC device is affected by the actual communications environment. Some of its packets are not received properly by the Rx PLC device (i.e., black is plotted), and those packets are retransmitted (plotted in yellow green, green, and red) with the next packets to be transmitted.

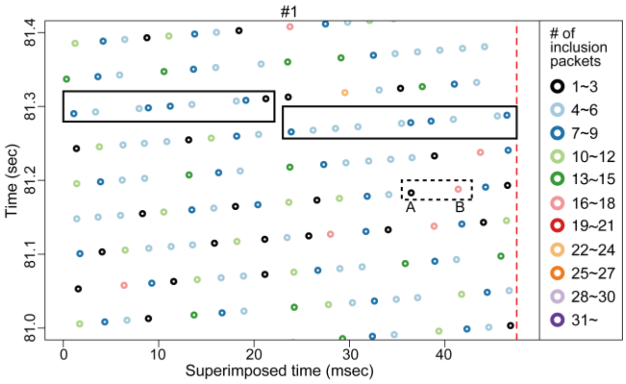

Fig. 18. Enlarged chart of Fig. 17.

Fig. 18 shows an enlarged view of the 81-second area of Fig. 17. The #1 at the top of Fig. 18 indicates the first burst signal sequence. The first burst signal sequence is vertically aligned to some extent, but the second burst signal sequence and beyond are difficult to distinguish. The first burst signal is controlled to be transmitted immediately after the beacon signal. Still, after that, although burst signals are transmitted and received at regular intervals in the PLC section, it can be assumed that there is a slight discrepancy in timing. In addition, there are many cases where burst signals are not detected. For example, in the dotted line in Fig. 18, only about one packet of the A burst signal is detected, and about 16 packets are detected together with the B burst signal. This is the reason why black, yellow green, green, and red are often seen, as explained in Fig. 17. Furthermore, the area surrounded by black squares is a burst signal sent within a certain beacon period. Still, in this period, there are four points where the burst signal is detected continuously with the following burst signal due to a delay in detection. Although the detailed causes of these cases are currently unanalyzed, this figure shows that the communication path conditions were certainly not better during this period. The above is one example, but SSP-SC confirmed the difference between the actual environment and the test bed data.

Thus, visualizing packet transmissions under actual environment using the SSP-SC enabled to confirm the disturbance in the communication. One possible cause of this disturbance is the transmit-receive jitter. The jitter can be assumed to be influenced by a complex combination of factors, such as differences in transmission line lengths under actual environment and processing delay differences due to multiple intervening devices. Although quantitative evaluation indices cannot evaluate the transmit-receive jitter, the eye pattern can evaluate the jitter in wireless communication by the degree of eye-opening. In the same way, for example, the degree of alignment after the second burst signal of SSP-SC could be evaluated to assess the transmit-receive jitter of PLC. For this purpose, it is necessary to construct a simple experimental environment under various conditions, for example, when only a branch of a power line is installed in a test bed or similarly when only electrical equipment is connected, and to examine how these factors are observed in the SSP-SC.

Furthermore, we will clarify the relationship between SSP-SC and throughput and packet loss, which are quantitative evaluation indicators. We expect this will enable us to estimate the communication quality of PLC networks using SSP-SC in a simplified method. Furthermore, we are convinced that SSP-SC can be used for efficient network construction using PLCs, the study of access control methods suitable for PLCs, and other applications.

The SSP-SC can be used to visualize the communication status, which cannot be determined only by quantitative evaluation of communication quality. Since the SSP-SC has the packet reception time, it is possible to evaluate with the time, which is important in communications. Combined with the information on the number of the burst signal inclusion packets, it is possible to evaluate the packet reception status in detail. Furthermore, it is assumed that plotting a Beacon superimposed chart using digital oscilloscope data based on voltage detection may be difficult in a poor communication environment with low C/N and multi-paths. The SSP-SC can evaluate the communication status of a PLC section using packet capture data that is communicated even in a poor environment.

The above examples demonstrate the effectiveness of using the SSP-SC to visualize inter-computer communications in PLC systems.

- Visualization of communications status
- Continuous time analysis without blanks
- Analysis with the passage of time
- The number of the burst signal inclusion packets can also be easily visualized

The above examples show that the SSP-SC visualizes the steady-state communication status, enabling instinctive evaluation of the PLC communication environment.

VI. Conclusion

We proposed the SSP-SC to visualize the steady-state communication status of PLC systems. The system-specific period superimposes the vertically aligned burst signals, allowing the communication status to be understood. The SSP-SC can be visualized for a more extended period than the conventional chart using PLC signal waveforms and can visualize the actual communication that cannot be determined by quantitative communication quality evaluation.

In the future, we will proceed with a detailed analysis of each preset UDP transmission speed utilizing the SSP-SC and an analysis of the variations among HD-PLC generations. An algorithm to plot the same chart using various PLC standards is also being studied. Another important subject is predicting communication quality in an actual environment using the SSP-SC. We also evaluate how the packet transmission status changes depending on the communication path conditions in the SSP-SC and study efficient network construction and access control methods for PLCs. We will continue to analyze the status of PLC communications using packet capture data.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

K. Kita analyzed the data, wrote the manuscript, and processed the Article Processing Charge. W. Abe, J. Aoki, and R. Sato experimented with and analyzed the data. H. Ishikawa reviewed research and revised papers. H. Shinonaga supervised the work. All authors approved the final version.

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