NOLTA, IEICE

Paper

Power packet dispatching with features on safety

Yanzi Zhou [1a], *Ryo Takahashi* [1b], *and Takashi Hikihara* [1c]

[1] *Department of Electrical Engineering, Kyoto University Katsura, Kyoto 615-8510, Japan*

[a] *y-zhou@dove.kuee.kyoto-u.ac.jp*
[b] *takahashi.ryo.2n@kyoto-u.ac.jp*
[c] *hikihara.takashi.2n@kyoto-u.ac.jp*

Received July 24, 2015; Revised October 26, 2015; Published April 1, 2016

Abstract: This paper investigates and proposes one advantageous function of a power packet dispatching system, which has been proposed by authors' group with being apart from the conventional power distribution system. Here is focused on the feature on safety of power packet dispatching which covers two aspects: information safety (protect the information of packet from attackers) and power safety (keep loads safe regarding supplied power from packet). For the purpose of achieving the information safety and the power safety, we introduce simple modulations of power packets before sending them. In particular, in order to protect the information of packets, partial packet modulation is proposed first, i.e., modulating partial information tags of packets. Modulation scheme based on chaotic signal is one possibility for this purpose and we adopt the differential chaos shift keying (DCSK) scheme in this paper. Next, the power safety can be achieved by applying pulse width modulation (PWM) to the payload of packets. Meanwhile, considering the effect of the noise on the packet dispatching, further modulation of the payload using the DCSK scheme is proposed, which can spread the spectrum of the noise. Consequently, we introduce the concept of whole packet modulation, in which PWM is applied to the payload of packets first, and then modulation using the DCSK scheme is applied throughout the whole packet. In this manner, both the information safety and the power safety can be achieved and the spectrum of noise is spread as well. Additionally, it is worth mentioning that the rigorous examination of the modulation method is not the target in this moment.

Key Words: power packet dispatching, safety, power packet modulation, pulse width modulation

1. Introduction

In the context of the growth of renewable power sources in electricity generation and power delivery on demand, a power packet dispatching system has been proposed for the purpose of managing low DC power sources, including renewable power sources, together with commercial power sources for adjusting to demands [1–4]. The basic configuration of the power packet dispatching system is

  DOI: 10.1587/nolta.7.250

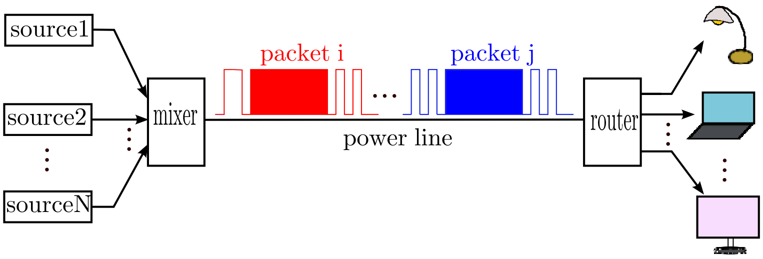


Fig. 1. Basic configuration of power packet dispatching system.

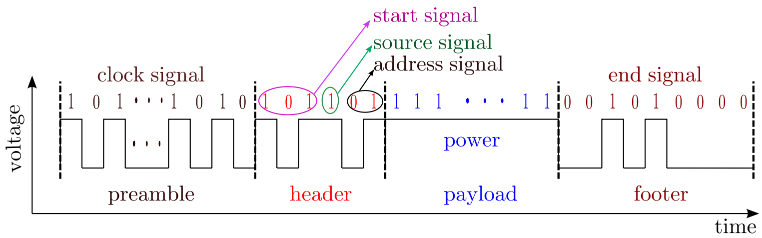


Fig. 2. A setting of a power packet in this paper. The preamble is added in front of each packet to achieve the clock synchronization. The preamble, the header, the payload, and the footer have 12 bits, 6 bits, 85 bits and 9 bits of signal, respectively.

illustrated in Fig. 1, which consists of DC power sources, a mixer, power line, a router, and loads. The mixer produces power packets by switching the selected power source on and off based on its clock frequency. The power packets are then transmitted from the mixer to the router through a power line in Time-Division Multiplexing (TDM) fashion. Figure 2 presents a setting of a power packet adopted in this paper which includes the header, the payload, and the footer. The start signal and the footer indicate the beginning and the end of the power packet. The source signal and the address signal in the header contain information on power source and power destination, respectively. The payload carries electric power with current. The packet dispatching is determined by the attached information of the packet [5–10]. In addition, it should be pointed out that the recognition of packet signal as '1' or '0' in the router depends on the voltage of power packets [5, 7]. For example, in [7], if the voltage of power packets is greater than 2.4V, the packet signal is recognized as '1'. Otherwise, the packet signal is identified as '0'. As the basic function of the power packet dispatching system, the packet dispatching were studied in [5–10]. Synchronous packet dispatching using an external clock line was realized in [5, 7]. Besides that, the preamble is added in front of each packet as shown in Fig. 2 so that asynchronous packet dispatching can be realized based on autonomous clock synchronization [10].

In this paper, we propose a concept of safety of power packet dispatching which covers information safety and power safety. The concept has not been figured out before for dispatching electric energy, until the power packet dispatching was introduced. The information safety refers to protecting the information of packets from attackers while the power safety is considered from the perspective of keeping the loads safe regarding power. At first, for the system in Fig. 1, when an attacker existing between the mixer and the router receives a power packet, he or she may deduce the packet signal and accordingly obtain some important information. For instance, by recognizing the address signal, the attacker may learn the time and the amount of power consumption of the corresponding load. In this sense, the safety of information with power packet is very weak. We can easily imagine that the attacker may even change the packet signal purposely, send the tampered packet to the router, and give rise to wrong power distribution. In this way, the attacker may lead to damage to the running system [10]. Considering the consumers' privacy and the system stability, the information needs to be protected from attackers and modulating information tags of power packets before sending them is a possible solution. Next, on the loads side the supplied power should be lower than their rated power. For this reason, the rescaling of the transferred power of packets is desired, which can be realized by modulation of payload since the payload carries the power of packets. In other words, modulation of payload in packets can keep the loads safe regarding power.

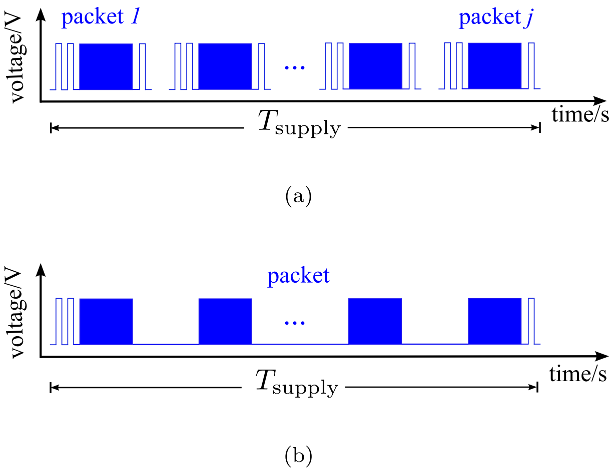
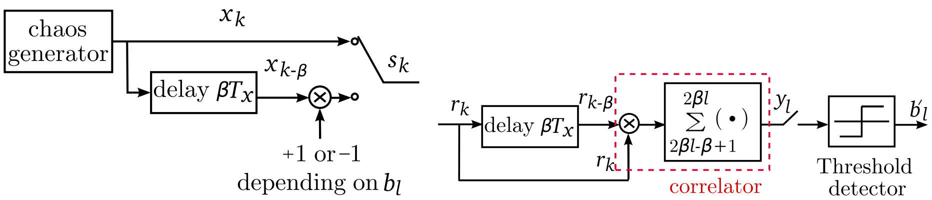


Fig. 3. Adjusting the amount of transferred power by (a) pulse density modulation of a train of power packets; (b) pulse width modulation of the payload in an equivalent big packet. T_{supply} is the determined time duration when the power packets are transferred.

The similarity between a power packet dispatching system and a communication system has been mentioned in [4, 10]. Therefore, we can refer to the modulation schemes used in communication systems for protecting the information of packets. Moreover, in the power packet dispatching system, power packets are generated in digital form and thus digital modulation schemes are required. The use of chaos in communication systems is appealing due to several intrinsic properties of chaotic signals, such as aperiodic and broadband. Hence, many chaos-based communication systems have been proposed and analyzed in [11–23], among which the chaos shift keying (CSK) scheme with coherent detection was firstly proposed in [12, 14] to encode digital symbols with chaotic signals. However, the sensitive dependence of chaotic signals upon initial condition makes it very difficult to replica signal in the receiver [18], i.e., non-coherent detection of received signal has advantage over coherent detection. The differential chaos shift keying (DCSK) scheme is a typical non-coherent chaos-based communication scheme [16], which also solves the problem of threshold shift in non-coherent CSK system [18]. In addition, the DCSK scheme is much easier compared to some advanced schemes such as the code division multiple access (CDMA) scheme [24]. As a result, in order to achieve the information safety, we modulate part of the information tags using the DCSK scheme.

With respect to power, a train of power packets are generated in a determined time duration T_{supply} so that power can be supplied to loads as illustrated in Fig. 3(a). In the case that the packets are exactly the same, we can manage the total transferred power by applying pulse density modulation (PDM) to the train of packets. In this sense, the power safety can be achieved through the pulse density modulation. Furthermore, given the fact that the information tags do not carry power, the pulse density modulation of the train of packets is equivalent to applying pulse width modulation (PWM) to the payload of a big packet as shown in Fig. 3(b). Here, we refer to the modulation of the payload using PWM as premodulation and the resulting packet as premodulated packet. From now on, we take the equivalent big packet as the packet we discuss. As previously mentioned, the power packet is produced by switching on and off the selected source in the mixer and noise may arise in the packet signal due to the switching operation. It is clear that more switching operation will be performed when the premodulation is introduced. Consequently, more noise may arise in packet signal during the payload. In order to reduce the possible effect of the noise on the packet dispatching during the payload, we further modulate the payload of the premodulated packet using the DCSK scheme because the chaos-based modulation can spread the spectrum of noise [18, 25, 26]. Here, it should be stressed that there is no need to recognize the signal in the payload. Therefore, the type of noise generated by the premodulation process and the potential effect of the noise on demodulation during the payload is not discussed in detail in this paper. Based on the above discussion, we finally propose the whole packet modulation, in which premodulation of a packet is carried out first for



(a) (b)

Fig. 4. Block diagram of a non-coherent single-user DCSK system. (a) modulator; x_k is the chaotic signal sample generated in the chaos generator. b_l is the bit to be transmitted and s_k is the modulator output. (b) demodulator. r_k is the received signal and b_l' is the recovered l-th bit.

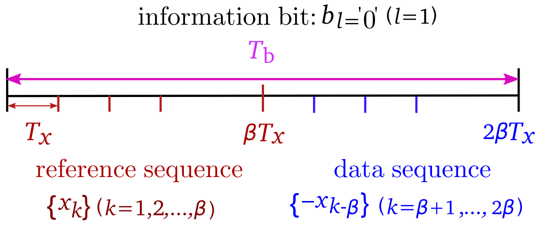


Fig. 5. Representation of one bit b_1 (b_1 = ‘0’) in the DCSK scheme.

achieving the power safety. Next, in order to achieve the information safety and reduce the effect of the noise, the whole premodulated packet is modulated using the DCSK scheme.

The paper is organized as follows. In Section 2, the operating principles of the DCSK scheme is summarized according to references [16, 18]. Section 3 presents the detail of partial packet modulation using the DCSK scheme. In Section 4, the DCSK scheme is modified in the whole packet modulation for achieving both the information safety and the power safety. The final section is devoted for the conclusions.

2. Differential chaos shift keying

The operating principles of the differential chaos shift keying (DCSK) scheme were reported in [16, 18]. The block diagram of a DCSK system is presented in Fig. 4 which includes a DCSK modulator and a DCSK demodulator. In the DCSK modulator, every bit period (T_b) is divided into two equal time slots so that every information bit b_l ($l \in \mathbb{N}_1$ denotes the serial number of bits) is represented by two consecutive chaotic signal samples: reference sample and data sample. As an example, Fig. 5 shows the representation of one bit b_1 = ‘0’ using the DCSK scheme. As seen from the plot, $T_\mathrm{b} = 2 \times \beta T_x$, where T_x is the time interval between two consecutive points of the chaotic sample, and 2β ($\beta \in \mathbb{N}_1$) is defined as the spreading factor. In the first time slot (0 to βT_x), the reference sample ($\{x_k\}$, $k \in \mathbb{N}_1$ indicates the serial number of sample points) is transmitted and in the second time slot (βT_x to $2\beta T_x$), the data sample ($\{-x_{k-\beta}\}$) is sent. Here, we can see that for bit ‘0’, the data sample is inverted to the half bit period delayed reference sample. Whereas, in the case of b_l = ‘1’, the data sample will be identical to the delayed reference sample. In this manner, the data sample carries information in the DCSK scheme. In the DCSK demodulator, r_k is the received signal and y_l stands for the correlation of r_k and $r_{k-\beta}$ at the end of the l-th bit duration. Comparing y_l with the threshold value in the threshold detector, the transmitted bit can be recovered as b_l'. It is worth noting that according to the principle of the DCSK demodulator [18], the spreading factor (2β) is essential to recover the transmitted bit correctly.

3. Partial packet modulation

In order to protect the information of power packets from attackers, we propose to modulate the preamble and the header in packets, namely, partial packet modulation. As introduced in [10], the preamble is designed to achieve the clock synchronization for power packet dispatching. It is thus important to modulate the preamble during packet transmission so that the clock information can be

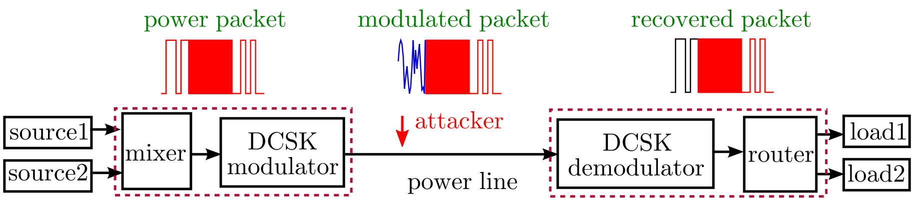


Fig. 6. Block diagram of the power packet dispatching system with partial packet modulation.

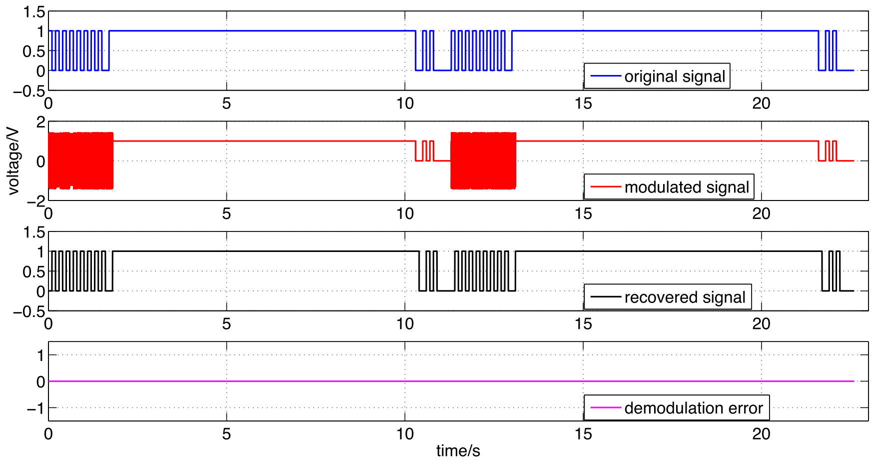


Fig. 7. Partial packet modulation in simulation with correct key in the demodulator.

protected. The header should also be modulated because it includes some useful information. In this sense, the information safety is possibly established, provided that the preamble and the header are protected.

The block diagram of a power packet dispatching system with partial packet modulation is illustrated in Fig. 6, where a DCSK modulator and demodulator are embedded in the mixer and the router, respectively. As illustrated in Fig. 6, the power packet generated in the mixer is partially modulated by the DCSK modulator. Subsequently, the modulated packet signal is recovered through the DCSK demodulator. As such, the whole packet can be recovered in the partial packet modulation, not only because the recovered preamble and header suffice to determine the packet dispatching, but also because no modulation of the payload keeps the power of packet unchanged. Additionally, we define the spreading factor (2β) as the key in the partial packet modulation since 2β is critical for correct signal recovery in the DCSK demodulator.

For the purpose of demonstrating the effect of the key on the signal recovery, we build the DCSK modulator and demodulator in Simulink and perform simulation of partial packet modulation. Noise performances of the DCSK schemes over additive white Gaussian noise (AWGN) channels have been discussed in [22, 23, 27, 28]. Whereas, at present we assume the channel between the modulator and the demodulator is ideal i.e., no noise is considered during the packet transmission in simulation. Moreover, in real applications, the limitation of spectrum suitable for communication may be caused by the components of power grid, e.g. the power transformers. This kind of limitation is beyond the scope of discussion because our aim here is to confirm potential ways of protecting the information of packet. Power packets with the composition as in Fig. 2 are adopted in simulation. As mentioned, there are 112 bits of signal in one packet duration including 12 bits of preamble and six bits of header. We also set one bit of '0' as the guard interval between two consecutive packets. To the settings, the parameters of the DCSK scheme are given as $T_\mathrm{b} = 0.1$ s and $T_x = 0.001$ s, i.e., $2\beta = 100$.

Given the above assumptions, simulations are performed for the partial packet modulation with different keys in the demodulator. Figure 7 shows the modulation and demodulation of the partial packet modulation, assuming that the key is given correctly in the demodulator. First, we can see that only the preamble and the header (18 bits of packet signal in total) in one packet are modulated.

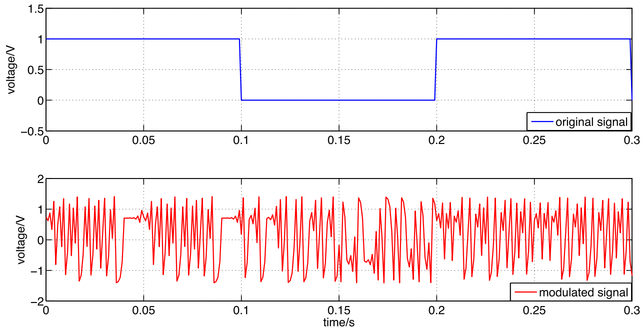


Fig. 8. Detailed DCSK modulation in partial packet modulation in simulation. Each bit period ($T_b = 0.1$ s) is divided into two equal time slots (0.05 s). The data sample (chaotic signal sample in the second time slot) is identical or inverted to the reference sample (chaotic signal sample in the first time slot) depending on the bit '1' or '0'.

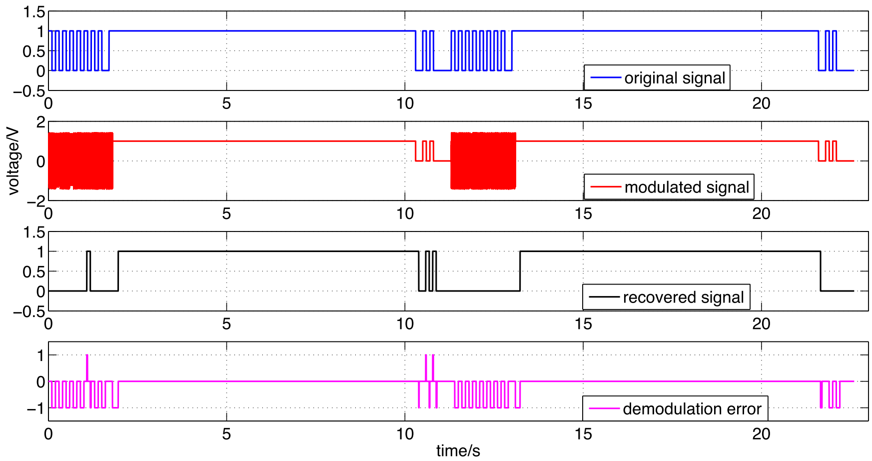


Fig. 9. Partial packet modulation in simulation with wrong key in the demodulator.

Then, Fig. 8 shows the detail about the modulation, based on which it is confirmed that the data sample is inverted to the reference sample for bit '0' and is identical to the reference sample for bit '1'. Moreover, from Fig. 7, it can be observed that the modulated packet signal is recovered without error. Whereas, as seen from Fig. 9, error appears in the demodulation due to the incorrect key (98) given in the demodulator. According to the above results, one may conclude that if the attacker receives a modulated packet, he cannot deduce the packet signal correctly without the key. That is the information safety is achieved by modulating the preamble and the header using the DCSK scheme.

4. Whole packet modulation

After achieving the information safety in the partial packet modulation, we continue to discuss about the power safety. In particular, we aim to achieve the information safety and the power safety simultaneously. To begin with, the payload of packets is modulated using PWM in order to adjust the amount of transferred power and it is defined as the premodulation of packets. Then, we modulate the whole premodulated packet using the DCSK scheme so as to protect the information of packets and to reduce the effect of noise on packet dispatching. Accordingly, Fig. 10 shows the block diagram of the power packet dispatching system with whole packet modulation.

4.1 Information safety

In the whole packet modulation, we still try to achieve the information safety by modulating the information tags of the premodulated packet using the DCSK scheme. In addition, the payload of the premodulated packet is also modulated using the DCSK scheme for reducing the influence caused by

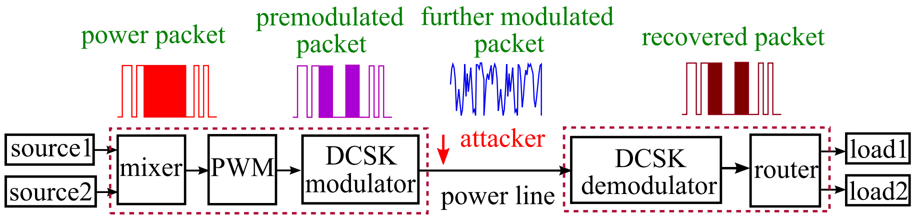


Fig. 10. Block diagram of the power packet dispatching system with whole packet modulation.

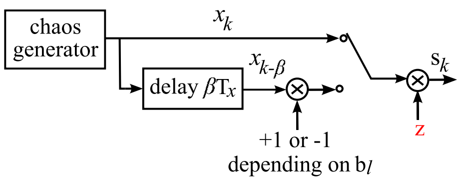
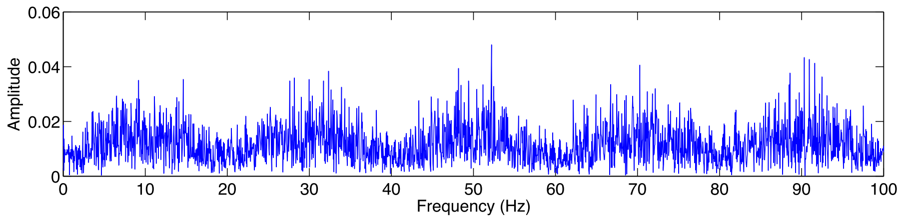


Fig. 11. Block diagram of modified DCSK modulator in whole packet modulation.

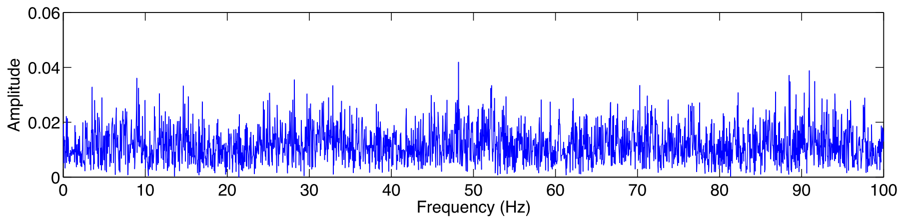
noise. Thus, it is necessary to check whether the modulation of payload using the DCSK scheme works on the information safety first. Special attention should be paid to the signal in payload duration because the payload carries electric power as physical quantity. Therefore, the DCSK modulator needs to be modified for transferring power in whole packet modulation as in Fig. 11. In the modified DCSK modulator, after the conventional DCSK modulation the modulated signal is multiplied by the absolute voltage amplitude of the power packet. Here, we assume the voltage of the packet signal is '$+z$' or '$-z$' in volts. The packet signal of amplitude $+z$V or $-z$V are recognized as bit '1' or '0', respectively.

Based on the modified DCSK modulator, we carry out a simulation of whole packet modulation to discuss about the information safety. The parameters in simulation are set as $T_{\mathrm{b}} = 0.1$ s, $T_{\mathrm{sam}} = T_x = 0.001$ s, $N_{\mathrm{b}} = 200$, and $2\beta = 100$. T_{sam} is the system sampling period and N_{b} represents the bit number of the payload. We also define the duty ratio of PWM in the premodulation as D ($D \in [0, 1]$). Given the above parameters, the amplitude spectrums of the DCSK modulator output signal (s_k) with different values of D in premodulation are plotted in Fig. 12. For some values of D, especially for those which are far away from 0.5, rough repetition can be observed in the shape (envelope) of the amplitude spectrum. It is well known that in the field of sampling theory [29], sampling in the time domain gives rise to repetition in the associated frequency domain, where sampling interval T_{sint} corresponds to a repetition with period of $f_{\mathrm{period}} = 1/T_{\mathrm{sint}}$. We can consider the whole packet modulation as a special sampling process: the premodulated packet signal is sampled first with $T_{\mathrm{sint}} = \beta T_x$ and then each signal sample is represented by β points of chaotic sample. Given $T_x = 0.001$ s and $\beta = 50$, it can be deduced that a repetition for every $f_{\mathrm{period}} = 1/\beta T_x = 20$ Hz exists in the frequency domain. In Figs. 12(a) or 12(e), the repeated structure of the amplitude is found in frequency domain; the amplitude drops at every about 20 increase. As for Figs. 12(b), 12(c) and 12(d), this structure blurs. It shows that the blurring depends on the duty ratio D. It should be noted that the repeated structure may be a clue to obtain the key 2β for estimating the decoded information as is mentioned in [30]. However, it can be considered that the blurring by D of PWM has a potential to be one of the methods to hide the structure. This is one of the future topics of this study.

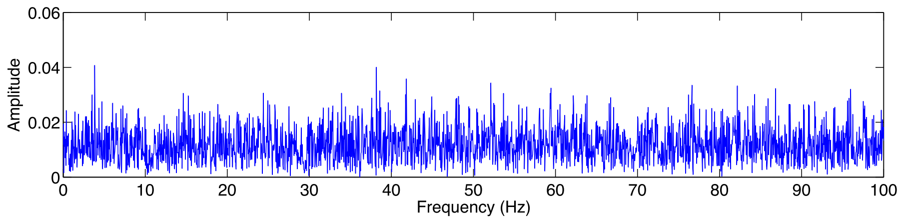
According to above analysis, the repetition in frequency domain should be hidden. Referring to the sampling theorem, we can overlap the adjacent envelopes by changing the sampling interval T_{sint}. Correspondingly, the DCSK scheme needs to be modified. By contrast with the conventional DCSK scheme in which the transmitted bits are mapped to two chaotic samples with equal length, each bit in the modified DCSK scheme is mapped to two chaotic samples with different lengths. The spreading factor 2β remains to denote the number of points of chaotic sample representing one bit. Also, a new parameter is defined as partial spreading factor α ($\alpha \in \mathbb{N}_1$ and $\alpha < 2\beta$) which indicates the first part of each bit is represented by α points of chaotic sample. In addition, given the relationship between



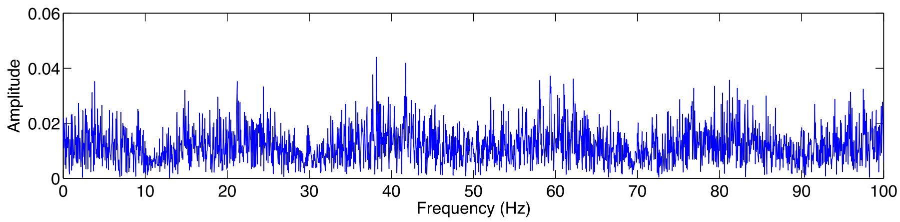
(a)



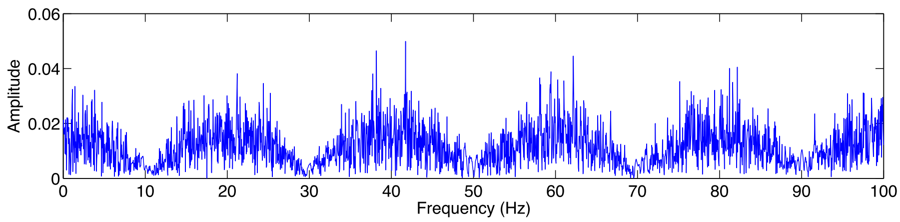
(b)



(c)



(d)



(e)

Fig. 12. Amplitude spectrum of the modulated signal in the whole packet modulation with different values of D in premodulation. (a) $D = 0.2$; (b) $D = 0.4$; (c) $D = 0.6$; (d) $D = 0.8$; (e) $D = 1$.

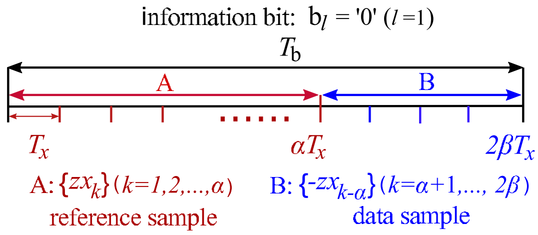


Fig. 13. Representation of one bit b_1 (b_1 = '0') using the modified DCSK scheme with $\alpha > \beta$.

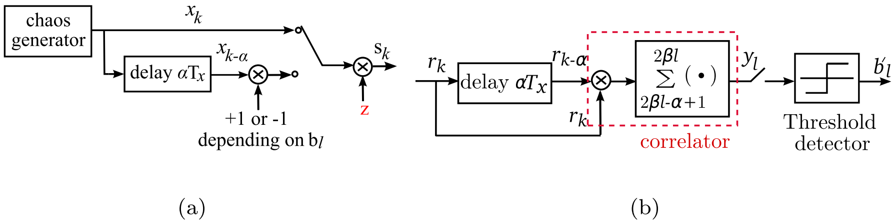


Fig. 14. Block diagram of the modified DCSK system. (a) modulator; (b) demodulator.

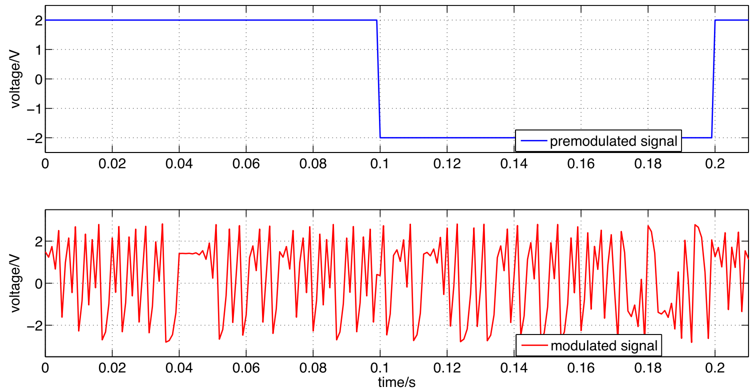


Fig. 15. Modified whole packet modulation in simulation with $\alpha = 70$.

α and β, the DCSK scheme can be modified in two ways.

In the beginning, we set $\alpha > \beta$ and take the $2\beta - \alpha$ points of chaotic sample in the second time slot as the data sample. The representation of one bit (b_1 = '0') in this modified DCSK scheme is exemplified in Fig. 13. We can see that the data sample is inverted to the first $2\beta - \alpha$ points of the reference sample because of b_1 = '0'. More generally, the modulator output signal s_k can be described as in Eqs. (1) and (2). It should be noted that b_l here represents the l-th bit of the premodulated packet signal. The DCSK demodulator needs to be modified correspondingly as in Fig. 14(b).

For b_l = '1',

$$s_k = \begin{cases} zx_k, & (l-1)2\beta + 1 \le k \le (l-1)2\beta + \alpha, \\ zx_{k-\alpha}, & (l-1)2\beta + \alpha + 1 \le k \le (l-1)2\beta + 2\beta. \end{cases} \quad (1)$$

For b_l = '0',

$$s_k = \begin{cases} zx_k, & (l-1)2\beta + 1 \le k \le (l-1)\beta + \alpha, \\ -zx_{k-\alpha}, & (l-1)2\beta + \alpha + 1 \le k \le (l-1)\beta + 2\beta. \end{cases} \quad (2)$$

A simulation of whole packet modulation using the modified DCSK scheme with $\alpha = 70$ is performed. At first, the detailed modulation is shown in Fig. 15. From the figure, we can confirm that the data sample in each bit period, i.e., the last 30 points ($2\beta - \alpha = 30$), is identical to or inverted to part of the reference sample (the first $2\beta - \alpha = 30$ points in each bit period) depending on the transmitted bit. Figure 16 illustrates the modulation and demodulation of the whole premodulated

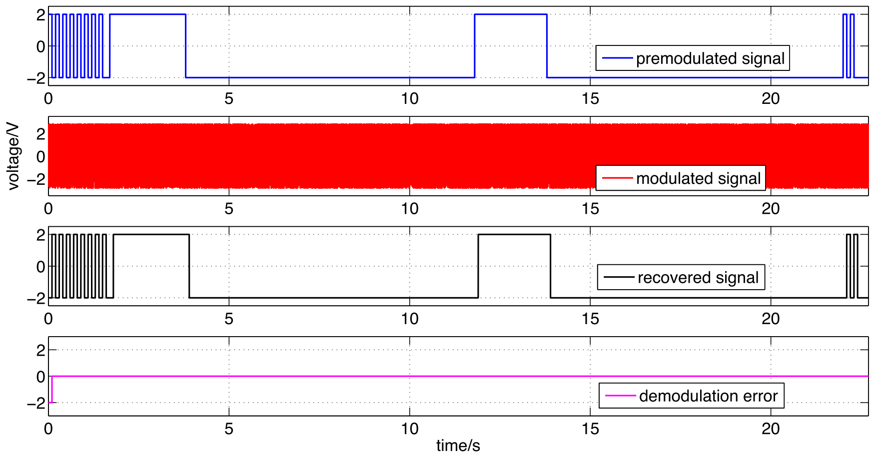
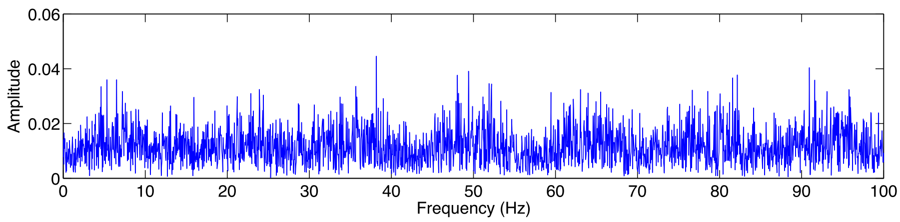
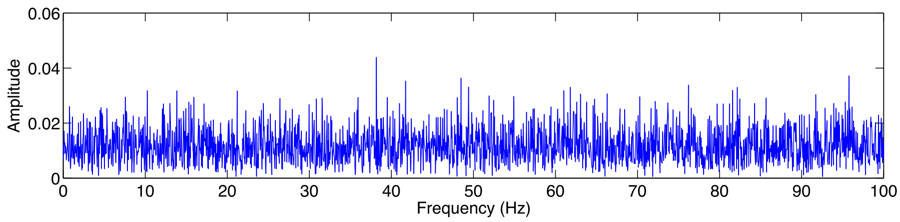


Fig. 16. Modulation and demodulation of whole packet in simulation with correct keys in the demodulator. The power packet is recovered without error. $T_{\rm b} = 0.1$s, $T_x = 0.001$s, $2\beta = 100$, and $\alpha = 70$.



(a)

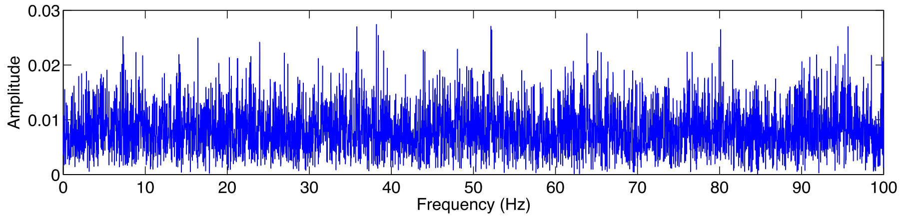


(b)

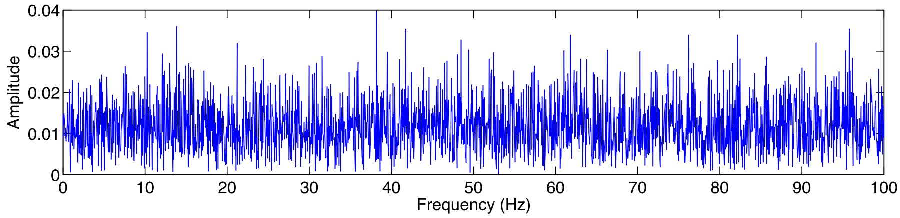
Fig. 17. Amplitude spectrum of the DCSK modulator output signal s_k in one packet duration with $\alpha > \beta$. (a) $\alpha = 70$; (b) $\alpha = 90$.

packet, where D is fixed at 0.2 in the premodulation. It can be seen in Fig. 16 that the premodulated packet signal is recovered correctly when both α and 2β are known in advance in the demodulator. We refer to α and 2β as two keys in the whole packet modulation. Next, the information safety based on the modified DCSK scheme is considered. Part of the amplitude spectrum of s_k with different α are plotted in Fig. 17 so as to analyze the effect of α on the information safety. Comparing Figs. 17(a) and 17(b) to Fig. 12(a), it can be found that within the range of $\beta < \alpha < 2\beta$, the greater the α, the more overlapped the envelopes of the amplitude spectrum. This result further implies that it gains the benefit of difficulty to derive the period of the DCSK signal. Besides, the amplitude spectrum of s_k for $D = 0.4$ with different α are exhibited in Fig. 18. Still, no obvious repetition is observed in the spectra. As a result, one may conclude that, adopting the modified DCSK scheme, the information safety is achieved in the whole packet modulation for different values of D in premodulation.

In the case of $\alpha < \beta$, the representation of one bit is exemplified in Fig. 19. As shown in the plot, the second part of each bit (B) is represented by α points of chaotic sample and it is the opposite of the reference sample 1 (A1) for $b_1 =$ '0'. Hence, B is treated as the data sample. The remaining $2\beta - 2\alpha$ points are defined as reference sample 2 (A2). As a result, s_k during the l-th bit period can



(a)



(b)

Fig. 18. Amplitude spectrum of the DCSK modulator output signal s_k in one packet duration for $D = 0.4$. (a) $\alpha = 10$; (b) $\alpha = 90$.

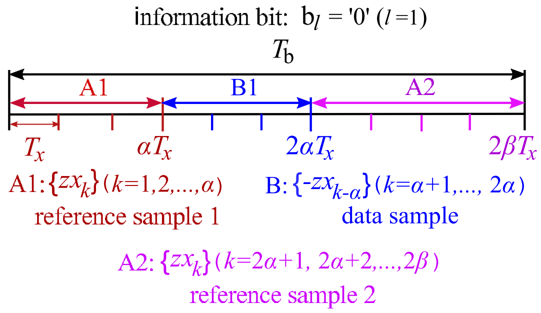


Fig. 19. Representation of one information bit b_1 (b_1 = '0') using modified DCSK scheme with $\alpha < \beta$.

be described as follows.

For b_l = '1',

$$s_k = \begin{cases} zx_k, & (l-1)2\beta + 1 \leq k \leq (l-1)2\beta + \alpha, \\ zx_{k-\alpha}, & (l-1)2\beta + \alpha + 1 \leq k \leq (l-1)2\beta + 2\alpha, \\ zx_k, & (l-1)2\beta + 2\alpha + 1 \leq k \leq (l-1)2\beta + 2\beta. \end{cases} \quad (3)$$

For b_l = '0',

$$s_k = \begin{cases} zx_k, & (l-1)2\beta + 1 \leq k \leq (l-1)2\beta + \alpha, \\ -zx_{k-\alpha}, & (l-1)2\beta + \alpha + 1 \leq k \leq (l-1)2\beta + 2\alpha, \\ zx_k, & (l-1)2\beta + 2\alpha + 1 \leq k \leq (l-1)2\beta + 2\beta. \end{cases} \quad (4)$$

Figure 20 presents the simulation results of the whole packet modulation in the case of $\alpha = 30$. The other parameters are set the same as those for $\alpha > \beta$. It can be seen that the data sample (31th to 60th points in each bit period) is identical to or inverted to the reference sample 1 (the first 30 points in each bit period). Particularly, it should be pointed out that the DCSK demodulators for $\alpha > \beta$ and $\alpha < \beta$ are different due to the difference between the modulations. Shown in Fig. 21 is the modified demodulator for $\alpha < \beta$. Furthermore, the amplitude spectrum of s_k with different α

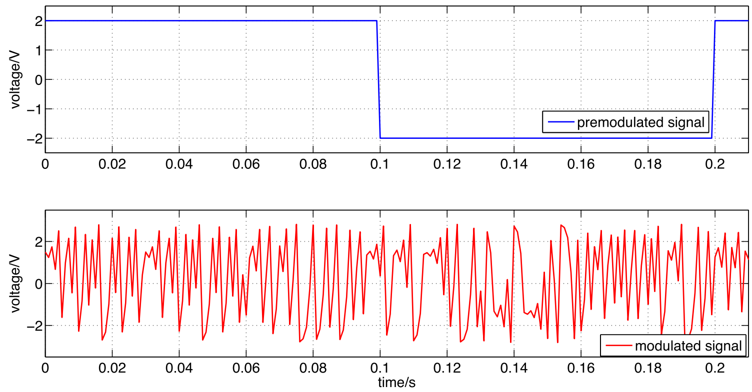


Fig. 20. Modified whole packet modulation in simulation with $\alpha = 30$.

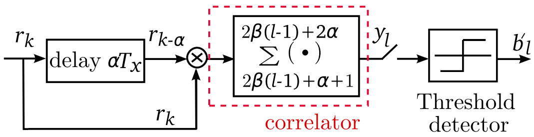
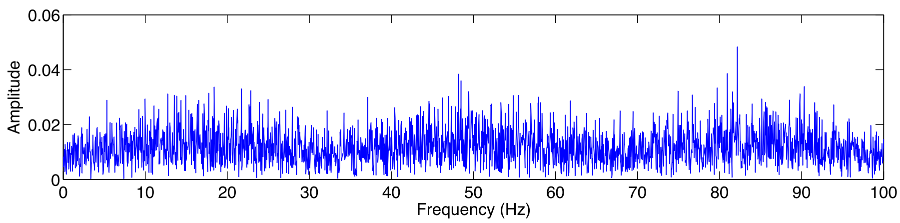
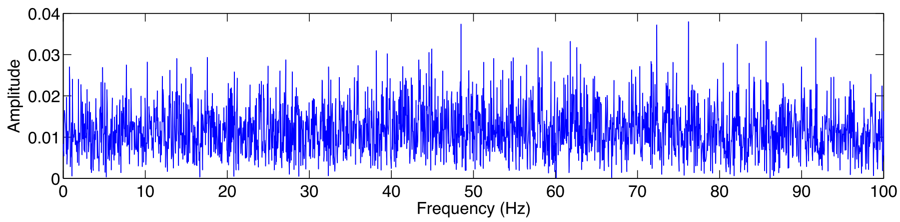


Fig. 21. Block diagram of the demodulator in the modified DCSK system for $\alpha < \beta$.



(a)



(b)

Fig. 22. Amplitude spectrum of the DCSK modulator output signal s_k in one packet duration with $\alpha < \beta$. (a) $\alpha = 30$; (b) $\alpha = 10$.

($\alpha < \beta$) are plotted in Fig. 22. Comparing Figs. 22(a) and 22(b) to Fig. 12(a), it is obvious that the smaller the α, the more overlapped the envelopes of the amplitude spectrum.

Based on the above discussion, one may conclude that the two keys (2β and α) in the modified DCSK scheme facilitate keeping the information safety in the whole packet modulation. Moreover, the farther the α is away from β, the more difficult for attackers to estimate keys directly from the amplitude spectrum of the modulated packet signal.

4.2 Power transfer in whole packet modulation

The power transferred after whole packet modulation is analyzed in this section. Since the power of packet is carried by the payload, we focus on the average output power of the modulator in payload duration named as P_{modout}. Also, we assume that the chaotic signal generated from the chaos generator carries power for modulation. In other words, it is assumed that the power to generate the

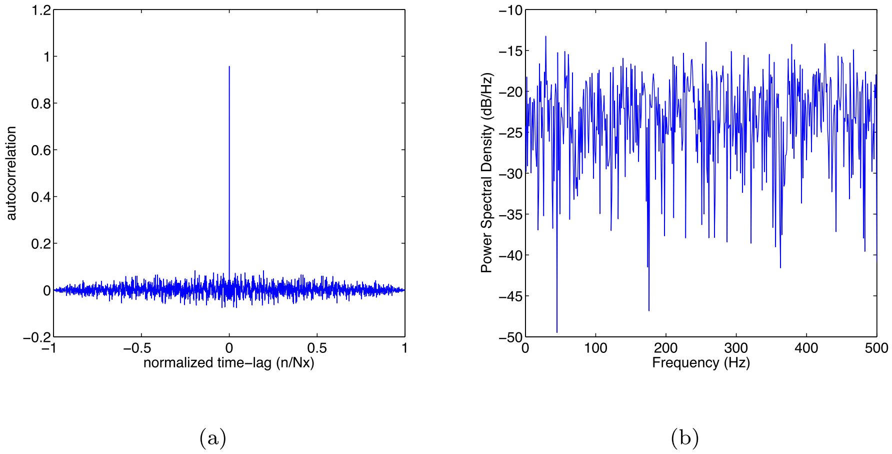


Fig. 23. Characteristics of the chaotic sample in simulation. (a) Normalized approximated auto-correlation; (b) Approximated power spectral density.

chaotic signal and to modulate the power packet is not from the power sources in the power packet dispatching system. Then referring to Eqs. (3) and (4), P_{modout} in the case of $\beta < \alpha < 2\beta$ can be calculated by Eq. (5), where P_{modout} is in watts (W) and x_{lm} denotes the m-th point of chaotic sample in the l-th bit period. Likewise, P_{modout} for $0 < \alpha < \beta$ can be calculated from Eq. (6).

$$P_{\mathrm{modout}} = \frac{D\sum_{l=1}^{N_{\mathrm{b}}}(\sum_{m=1}^{\alpha} z^2x_{lm}^2T_x + \sum_{m=1}^{2\beta-\alpha} z^2x_{lm}^2T_x)}{N_{\mathrm{b}}T_b}. \tag{5}$$

$$P_{\mathrm{modout}} = \frac{D\sum_{l=1}^{N_{\mathrm{b}}}(\sum_{m=1}^{\alpha} z^2x_{lm}^2T_x + \sum_{m=1}^{\alpha} z^2x_{lm}^2T_x + \sum_{m=2\alpha+1}^{2\beta} z^2x_{lm}^2T_x)}{N_{\mathrm{b}}T_b}. \tag{6}$$

Consequently, the chaotic sample needs to be determined first to obtain P_{modout}. Without loss of generality, we generate chaotic sample x_k in simulation by the normalized improved logistic map [18] as in Eq. (7). The initial value is set at $x_1 = 0.75$. x_k is thus limited in the range of $[-1.4142, +1.4142]$.

$$x_{k+1} = \sqrt{2}(1 - x_k^2). \tag{7}$$

In addition, the time interval between two points of chaotic sample is $T_{\mathrm{x}} = 0.001\,\mathrm{s}$ and the generated sample is of finite length 1000 ($N_{\mathrm{x}} = 1000$). Accordingly, the numerical approximation of auto-correlation function of x_k is shown in Fig. 23(a). We can see that $R(x, x) \approx \delta[n]$, which demonstrates that x_k is random-like. Meanwhile, the power spectral density of x_k is exhibited in Fig. 23(b), from which the wide-band property of x_k is confirmed. According to the above characteristics of x_k, Eqs. (5) and (6) can be approximately simplified as Eqs. (8) and (9), respectively. The equations suggest that the power of the modulated packet is eventually determined by the duty ratio of premodulation (D), the characteristic chaotic sample ($E[x_k^2]$) and the voltage of the original power packet (z). For example, under the settings of $T_x = T_{\mathrm{sam}} = 0.001$ s, $T_b = 0.1$ s, and $2\beta = 100$, the mean values of x_k and x_k^2 in the payload duration (200 bits) can be obtained as $E[x_k] = -0.0012$ and $E[x_k^2] = 1.0007$. Thus the transferred power is determined by D and z^2 approximately in the whole packet modulation.

$$\begin{aligned} P_{\mathrm{modout}} &\approx \frac{Dz^2T_x}{T_b}\{\alpha E[x_k^2] + (2\beta - \alpha)E[x_k^2]\} \\ &= DE[x_k^2]z^2. \end{aligned} \tag{8}$$

$$\begin{aligned} P_{\mathrm{modout}} &\approx \frac{Dz^2T_x}{T_b}\{\alpha E[x_k^2] + \alpha E[x_k^2] + (2\beta - 2\alpha)E[x_k^2]\} \\ &= DE[x_k^2]z^2. \end{aligned} \tag{9}$$

Next, we will consider how to transfer the power of the modulated packet correctly. In the fundamental power packet dispatching system, once the header is recognized in the router, the inside switches will be turned on and the power of packet is transferred. This is based on the fact that electric current appears when the positive voltage of the packet signal is applied to loads. As explained in [10], loads are restricted to be resistors in the system currently. However, using the DCSK scheme, the modulated signal is of both positive and negative voltages. It should be noticed that no power is transferred when the voltage of the modulated signal is negative. For this reason, it is necessary to shift the voltage of the modulated signal to be positive for transferring full power of the modulated packet. On the other hand, the preamble and the header do not carry power and they are supposed to be recovered for determining the packet dispatching through the DCSK demodulator. According to the principles of the DCSK demodulator, the positive and negative voltages of the modulated signal are essential for the correct demodulation. As a result, we first shift the voltage of the modulated signal in the whole modulated packet at the output of the modulator for transferring power. Then, the voltage of the modulated signal in preamble and header duration is shifted back to the original values in the demodulator before demodulation starts. It is worth stressing again that the power of concern is only transferred in the payload duration. As for the preamble and the header, we only care about the information carried by the signal. Not any current or power is contained in the preamble and the header. Moreover, the aim of this paper is to propose a possible method to transfer power with safety feature. Therefore, the power loss generated by shifting of voltage is not considered at present. In this manner, the information contained in the preamble and the header can be obtained correctly and the power of modulated packet is transferred completely to the designated load.

5. Remarks

In this paper, we proposed a method to modulate power packets before sending them in a power packet dispatching system for the purpose of protecting the information from attackers and keeping the loads safe regarding the power. At first, we summarized the principles of the DCSK scheme referring to other researchers' work. Then partial packet modulation using the DCSK scheme was proposed, through which the information safety was achieved. After that, we proposed to modulate the whole power packet, in which premodulation using PWM is applied first for adjusting the amount of transferred power. Then, the whole premodulated packet is modulated using the modified DCSK scheme which has two advantages: one is to keep the information safety and the other is to spread the spectrum of noise. Here, the noise is caused by the switching operation in the mixer and it is at the lower frequency than signals. The rescaling of power by premodulation in the whole packet modulation might be a potential advantage from the viewpoint of expanding the range of power sources to meet the demand of loads. Additionally, it should be pointed out that the power packet modulation method is very preliminary and is proposed primarily to suggest a possible way to improve the function of power packet dispatching.

Acknowledgments

This work was supported by Council for Science, Technology and Innovation (CSTI), Cross-ministerial Strategic Innovation Promotion Program (SIP), "Next-generation power electronics" (funding agency: NEDO). The authors also acknowledge to Prof. Ken Umeno and Prof. Yasuo Okabe for fruitful discussions. The author (R.T.) was partially supported by the JSPS, Grant-in-Aid for Young Scientist (B), 26820144.

References

[1] T. Hikihara, "Power router and packetization project for home electric energy management," *Proc. Santa Barbara Summit on Energy Efficiency*, Santa Barbara, CA, USA, pp. 12–13, 2010.

[2] T. Takuno, M. Koyama, and T. Hikihara, "In-home power distribution systems by circuit switching and power packet dispatching," *Proc. First IEEE International Conference on SmartGridComm*, IEEE, pp. 427–430, 2010.

[3] T. Takuno, Y. Kitamori, R. Takahashi, and T. Hikihara, "AC power routing system in home based on demand and supply utilizing distributed power sources," *Energies*, vol. 4, no. 5, pp. 717–726, 2011.

[4] R. Takahashi, T. Takuno, and T. Hikihara, "Estimation of power packet transfer properties on indoor power line channel," *Energies*, vol. 5, no. 7, pp. 2141–2149, 2012.
[5] K. Tashiro, R. Takahashi, and T. Hikihara, "Feasibility of power packet dispatching at in-home dc distribution network," *Proc. Third IEEE International Conference on SmartGridComm*, IEEE, pp. 401–405, 2012.
[6] S. Nawata, N. Fujii, Y.Z. Zhou, R. Takahashi, and T. Hikihara, "A theoretical examination of an unexpected transfer of power packets by synchronization failure," *Proc. NOLTA*, IEICE, pp. 60–63, 2014.
[7] N. Fujii, R. Takahashi, and T. Hikihara, "Networked power packet dispatching system for multi-path routing," *Proc. IEEE/SICE International Symposium on System Integration*, IEEE, pp. 357–362, 2014.
[8] Y.Z. Zhou, R. Takahashi, and T. Hikihara, "Realization of autonomous clock synchronization for power packet dispatching," *IEICE Trans. Fundamentals*, vol. E98-A, no. 2, pp. 749–753, 2015.
[9] R. Takahashi, K. Tashiro, and T. Hikihara, "Router for power packet distribution network: Design and experimental verification," *IEEE Trans. Smart Grid*, vol. 6, no. 2, pp. 618–626, 2015.
[10] Y.Z. Zhou, R. Takahashi, and T. Hikihara, "Power packet dispatching with second-order clock synchronization," *International Journal of Circuit Theory and Applications*, in press, 2015.
[11] R. Takahashi and K. Umeno, "Performance evaluation of CDMA using chaotic spreading sequence with constant power in indoor power line fading channels," *IEICE Trans. Fundamentals*, vol. E97-A, no. 7, pp. 1619–1622, 2014.
[12] U. Parlitz, L.O. Chua, L. Kocarev, K.S. Halle, and A. Shang, "Transmission of digital signals by chaotic synchronization," *International Journal of Bifurcation and Chaos*, vol. 2, no. 4, pp. 973–977, 1992.
[13] K.M. Cuomo and A.V. Oppenheim, "Circuit implementation of synchronized chaos with applications to communications," *Phys. Rev. Lett.*, vol. 71, no. 1, pp. 65–68, 1993.
[14] H. Dedieu, M. Kennedy, P. Michael, and M. Hasler, "Chaos shift keying: modulation and demodulation of a chaotic carrier using self-synchronizing Chua's circuits," *IEEE Trans. Circuits Syst. II*, vol. 40, no. 10, pp. 634–642, 1993.
[15] T. Kohda and A. Tsuneda, "Pseudonoise sequences by chaotic non-linear maps and their correlation properties," *IEICE Trans. Commun.*, vol. E76-B, no. 8, pp. 855–862, August 1993.
[16] G. Kolumban, "Differential chaos shift keying: A robust coding for chaotic communication," *Proc. 4th Int. Workshop on NDES*, pp. 87–92, 1996.
[17] G. Kolumban, M.P. Kennedy, Z. Jako, and G. Kis, "Chaotic communications with correlator receivers: theory and performance limits," *Proc. IEEE*, vol. 90, no. 5, pp. 711–732, May 2002.
[18] F.C.M. Lau and C.K. Tse, "Performance analysis methods for non-coherent differential chaos-shift-keying systems," in *Chaos-Based Digital Communication Systems*, pp. 63–96, Springer Berlin Heidelberg, 2003.
[19] Y. Tao, "A survey of chaotic secure communication systems," *International Journal of Computational Cognition*, vol. 2, no. 2, pp. 81–130, 2004.
[20] H. Chen, J. Feng, and C.K. Tse, "A general noncoherent chaos-shift-keying communication system and its performance analysis," *Proc. ISCAS 2007.*, IEEE, pp. 2466–2469, 2007.
[21] R. Takahashi and K. Umeno, "Performance analysis of complex CDMA using complex chaotic spreading sequence with constant power," *IEICE Trans. Fundamentals*, vol. E92-A, no. 12, pp. 3394–3397, December 2009.
[22] G. Kaddoum, F. Gagnon, P. Charge, and D. Roviras, "A generalized BER prediction method for differential chaos shift keying system through different communication channels," *Wireless Personal Communications*, vol. 64, no. 2, pp. 425–437, 2012.
[23] G. Kaddoum, J. Olivain, G. Beaufort Samson, P. Giard, and F. Gagnon, "Implementation of a differential chaos shift keying communication system in gnu radio," *Proc. ISWCS, 2012*, IEEE, pp. 934–938, 2012.

[24] Y. Nathan, J.P.M. Linnartz, and G. Fettweis, "Multi-carrier CDMA in indoor wireless radio networks," *IEICE Trans. Commun*, vol. 77, no. 7, pp. 900–904, 1994.

[25] G. Mazzini, R. Rovatti, and G. Setti, "Chaos-based asynchronous DS-CDMA systems and enhanced rake receivers: Measuring the improvements," *Circuits and Systems I: Fundamental Theory and Applications, IEEE Transactions on*, vol. 48, no. 12, IEEE, pp. 1445–1453, 2001.

[26] A. Kordonis and T. Hikihara, "Harmonic reduction and chaotic operation towards application of AC/AC converter with feedback control," *IEICE Transactions on Fundamentals of Electronics, Communications and Computer Sciences*, vol. 97, no. 3, pp. 840–847, 2014.

[27] Zhenchao Wang and Shibing Zhang, "An improved scheme for noise reduction to DCSK based on its retransmission characteristic," *Proc. ICCSE '09. 4th International Conference on*, pp. 366–370, July 2009.

[28] YiPing, Chen, Ying Shi, and Dianlun Zhang, "Performance of differential chaos-shift-keying digital communication systems over several common channels," *Proc. Future Computer and Communication (ICFCC), 2010 2nd International Conference on*, vol. 2, pp. 755–759, 2010.

[29] A.I. Zayed, "Advances in Shannon's sampling theory," CRC press, 1993.

[30] Francis, Lau, Kai Cheong, and Chi K Tse, "Permutation-based DCSK and multiple-access DCSK systems," *Circuits and Systems I: Fundamental Theory and Applications, IEEE Transactions on*, vol. 50, no. 6, pp. 733–742, 2003.