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Parameter Optimization for Power Line Communications Considering Operational Status of Electrical Appliances

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Abstract– Power line communication (PLC) is considered as one of communication systems to support a smart grid. Especially, PLC has the advantage that the construction cost is very low, since it can use existing power lines. G3-PLC is an international standard for the low-frequency narrow-band OFDM PLC and it is adopted in Japan. OFDM (orthogonal frequency division multiplexing) is a multi-carrier modulation scheme. Since the transmission-line impedance and noise vary with the operational status of electrical appliances, both the primary modulation and the allocated power for each carrier should be optimized to maximize the transmission capacity.

In this paper, we assume that the transmission-line impedance and noise are obtained by the electrical appliance monitoring system which is incorporated in the smart meter. Under this condition, we formulate the transmission capacity, whose variables are the primary modulation and the allocated power for each carrier. Also, we attempt to optimize these variables to maximize the transmission capacity by PSO (particle swarm optimizer). Finally, the usefulness of our proposed method has been confirmed by numerical experiments.

1. Introduction

A smart grid is a next-generation electrical power grid which can optimize the power balance between supply and demand by using the information communication technology (ICT). Also, since it helps to efficiently use the electric energy and introduce the renewable energy such as solar power, it is regarded as one of measures against global warming.

A smart meter is an electric power meter equipped with communication capabilities. Therefore, it is an important device which combines the consumer with the smart grid. There are two communication routes, called routes A and B, whereby data is directly obtained through the smart meter. Route A links smart meters with electric power companies and route B links smart meters with HEMSs (home energy management systems) [1]. There are plural candidates for communication systems applied to routes A and B. From the viewpoint of the construction cost, PLC (power line communication) [2] has attracted a lot of attention.

In the case of Japan, the communication system for route A is selected from wireless multi-hop system, one-to-many (1:N) wireless system, and PLC system. On the other hand, the communication system for route B is selected from 920MHz wireless system and PLC system. Especially, when PLC system is used for route B, the PLC must keep G3-PLC which is an international standard specification for the low-frequency narrow-band OFDM PLC. OFDM is a multi-carrier modulation scheme.

From these backgrounds, it is clear that PLC is a key technology supporting the smart grid. However, since the transmission-line is the power line, the transmission-line impedance and noise (i.e., characteristics of transmission-line) vary with the operational status of electrical appliances. Therefore, to maximize the transmission capacity of OFDM PLC (e.g., G3-PLC), both the primary modulation and the allocated power for each carrier must be optimized according to the characteristics of transmission-line.

In this paper, to satisfy the above request, we propose the following method. It is assumed that the information about both the transmission-line impedance and noise are obtained by the electrical appliance monitoring system [3] which is incorporated in the smart meter. Under this condition, we formulate the transmission capacity, whose variables are the primary modulation and the allocated power for each carrier, considering the transmission-line impedance and noise. Also, we attempt to optimize these variables to maximize the transmission capacity by PSO (particle swarm optimizer) [4]. Finally, the usefulness of our proposed method has been confirmed by numerical experiments.

2. Model of Power Line Communications

Fig.1 shows a circuit of typical PLC system. For example, if a HEMS (Home Energy Management System)

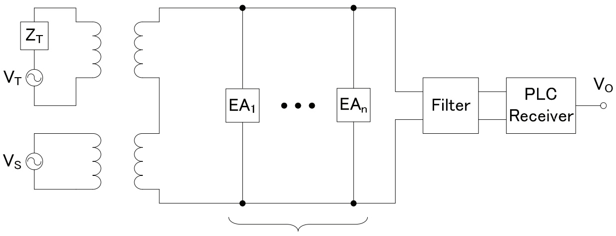

Fig.1 A typical PLC system.

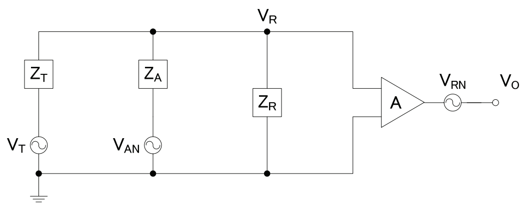

Fig.2 An equivalent circuit of PLC system.

requests data on the electric power consumption to a smart meter, the smart meter is a transmitter and the HEMS is a receiver in route B. In this section, we consider the influence of the transmission-line impedance and noise on PLC.

As shown in Fig.1, when the power supply voltage (e.g., 100VAC, 50/60Hz in Japan) is given by V_S, the transmitting signal voltage (i.e., data) of a carrier, which is restricted within the PLC band (e.g., 10k~450kHz in Japan), is given by V_T, the composite voltage V_C ($=V_S+V_T$) is applied to the power line. Although only the signal corresponding to PLC band can pass through the filter, the received signal voltage V_R is not equal to V_T. Because V_T is changed to V_R by the transmission-line impedance and noise which vary with the operational status of electrical appliances. Considering these facts, we derive the relationship between the output voltage V_O of the receiver and V_T from the equivalent circuit shown in Fig.2. In this figure, Z_T and Z_R are impedances of the transmitter and receiver respectively. Z_A is the combined impedance of electrical appliances in operation. V_{RN} and V_{AN} are the noise generated by the receiver and electrical appliances in operation respectively. Moreover, A is the voltage gain of receiver. Therefore, V_O is given as follows:

$$V_O = \underbrace{A\frac{Z_A // Z_R}{Z_T + Z_A // Z_R}}_{\alpha} V_T + \underbrace{\left(A\frac{Z_T // Z_R}{Z_A + Z_T // Z_R} V_{AN} + V_{RN} \right)}_{\beta} . \quad (1)$$

This equation shows that the carrier to noise ratio (C/N) is given by $C/N=\alpha^2/\beta^2$, if V_T is given by a sinusoidal voltage. Therefore, the BER (bit error rate) of each carrier in the PLC band can be calculated by substituting C/N for the theoretical formula [5].

In this research, we assume that the electrical appliance monitoring system [3] can recall Z_A and V_{AN} for the known operational status of electrical appliances and can evaluate them for the unknown one. Therefore, the larger the operating time of the monitoring system becomes, the more easily α and β in Eq.(1) can be obtained.

3. Parameter Optimization for OFDM PLC

3.1. Cost Function

To maximize the transmission capacity of PLC using OFDM as the secondary modulation (i.e., OFDM PLC), both the primary modulation and the allocated power for each carrier must be optimized according to the characteristics of transmission-line. To satisfy this request, we define the cost function which consists of one objective and two constraint terms.

The objective term f_1 is derived from the transmission capacity R. Here, we assume that the (m, n)-Hamming code (HC(m, n)) is used as the error correcting code (ECC) and the primary modulation for each carrier is selected from M-QAM ($M \in \{4, 16, 64, 256, 1024\}$). If the transmission capacity R is defined as the number of information data bits which are conveyed per unit of time and also demodulated without an error, then R is given by

$$R = \sum_{k=1}^{N_C} \frac{B_k}{T_S} \cdot \frac{n}{m} \cdot \varphi_k , \quad (2)$$

where, k is the carrier index, N_C is the number of carriers, B_k is the number of bits per symbol decided by the primary modulation, T_S is the symbol length, n/m is the coding rate of HC(m, n), and φ_k is the probability that HC(m, n) correctly extracts n bits information data from m bits received data, in other words, the probability that m bits received data is demodulated without an error. If there is only one bit error in m bits received data, HC(m, n) can correct the error. Therefore, φ_k is given as follows:

$$\varphi_k = {}_mC_1 (1-p_k)^{m-1} p_k + (1-p_k)^m = (1-p_k)^{m-1}\{1+(m-1)p_k\}, \quad (3)$$

where, p_k is the BER (bit error rate). In this research, we assume that PLC is under the additive white Gaussian noise (AWGN) channel and Gray code bit mapping is employed. Therefore, the BER of k-th carrier using M-QAM is calculated by substituting C/N_k for the following equations [5]:

$$p_k(a) = \frac{1}{\sqrt{M}} \sum_{i=0}^{(1-2^{-a})\sqrt{M}-1} \left[\begin{array}{l} (-1)^{\left\lfloor \frac{i2^{a-1}}{\sqrt{M}} \right\rfloor} \cdot \left(2^{a-1} - \left\lfloor \frac{i2^{a-1}}{\sqrt{M}} + \frac{1}{2} \right\rfloor \right) \cdot \\ \operatorname{erfc}\left\{ (2i+1) \sqrt{\frac{3 \cdot C/N_k}{2(M-1)}} \right\} \end{array} \right], \quad (4)$$

$$p_k = \frac{1}{\log_2 \sqrt{M}} \sum_{a=1}^{\log_2 \sqrt{M}} p_k(a) . \quad (5)$$

The objective term f_1 is defined by the transmission capacity R and its reference value R_{ref} as follows:

$$f_1 = \ln\left(\frac{R}{R_{\mathrm{ref}}} \right) . \quad (6)$$

If R becomes smaller than R_{ref}, f_1 decreases rapidly.

Next we describe two constraint terms (f_2 and f_3). The first constraint term f_2 is necessary to guarantee that HC(m, n) correctly extracts n bits information data from m bits received data. As mentioned above, if there is only one bit error in m bits received data, HC(m, n) can correct the error. Therefore, if the reference BER p_{ref} is set to $1/m$, the BER of k-th carrier p_k must satisfy $p_k \le p_{\mathrm{ref}}$. To satisfy this condition at all the carriers, the constraint term f_2 is defined as follows:

$$f_2 = \sum_{k=1}^{N_c} \left\{ U(p_k - p_{\mathrm{ref}}) \cdot \ln\left(\frac{p_{\mathrm{ref}}}{p_k} \right) \right\} , \quad (7)$$

where, $U(x)$ is the unit step function. Also, when the k-th carrier is not used, p_k is set to zero. Therefore, even if only one carrier satisfies $p_{\mathrm{ref}} / p_k << 1$, f_2 decreases rapidly. On the other hand, if all the carriers satisfy $p_{\mathrm{ref}} / p_k \geq 1$, f_2 becomes zero.

The second constraint term f_3 is necessary to guarantee that the total power consumption E_T of all the carriers is smaller than or equal to the reference value E_{ref}. To satisfy this condition ($E_T \leq E_{\mathrm{ref}}$), the constraint term f_3 is defined as follows:

$$f_3 = U\left(E_T - E_{\mathrm{ref}}\right) \cdot \ln\left(\frac{E_{\mathrm{ref}}}{E_T}\right). \tag{8}$$

Therefore, if the PLC system consumes the electric power more than E_{ref}, f_3 decreases rapidly. On the other hand, if $E_T \leq E_{\mathrm{ref}}$, f_3 becomes zero.

Using the objective term (f_1) and two constraint terms (f_2 and f_3), the cost function f is defined as follows:

$$f = \gamma f_1 + (1-\gamma)\delta f_2 + (1-\gamma)(1-\delta) f_3, \tag{9}$$

where, γ ($0<\gamma<1$) is a weight coefficient which controls the relationship between the objective term and two constraint ones. Also, δ ($0<\delta<1$) is a weight coefficient which controls the relationship between two constraint terms.

3.2. Parameter Optimization by PSO

In this paper, we attempt to optimize both the primary modulation and the allocated power for each carrier by applying PSO to maximize the cost function in Eq.(9). As mentioned above, B_k is the number of bits per symbol decided by the primary modulation applying to the k-th carrier. The primary modulation is selected from M-QAM ($M \in \{4, 16, 64, 256, 1024\}$). Moreover, we assume the probability that the k-th carrier is not used to convey the data. Therefore, B_k corresponds to one of elements in the set $\{0, 2, 4, 6, 8, 10\}$. Considering these conditions, we define the position vector $\mathbf{x} \in \Re^{2N_c}$ of each particle as follows:

$$\mathbf{x} = \left(\left(b_1, E_1\right), \cdots, \left(b_k, E_k\right), \cdots, \left(b_{N_C}, E_{N_C}\right)\right), \tag{10}$$

where, b_k satisfies $0 \leq b_k \leq 10$ and B_k is an element in the set $\{0, 2, 4, 6, 8, 10\}$ which is the closest to b_k. If B_k is zero, the k-th carrier is not used. On the other hand, if B_k is not zero, the primary modulation is 2^{Bk}-QAM. Also, E_k is the allocated power for k-th carrier and satisfies $0 \leq E_k \leq E_{\mathrm{ref}}$. If B_k is zero, E_k is set to zero forcibly.

The PSO model used in this research is composed of the original PSO developed by J. Kennedy et al. [4] and the reset function. We call it O-PSO-R (O-PSO with resets). In the case of O-PSO, each particle keeps the personal best position $\mathbf{x}_{\mathrm{PB}}$ and its evaluation value f_{PB}, and the swarm keeps the global best position $\mathbf{x}_{\mathrm{GB}}$ and its evaluation value f_{GB}. However, the O-PSO-R eliminates the information about personal/global best at the time of the reset. To avoid the loss of the best solution during the searching process, O-PSO-R stores the best position and its evaluation value at $\mathbf{x}_{\mathrm{TB}}$ and f_{TB} respectively. The subscript "TB" means the trial best. Although the trial best position $\mathbf{x}_{\mathrm{TB}}$ is not used in the update equations in the PSO algorithm, it is used to re-initialize the positon of each particle in the reset process. However, O-PSO-R does not guarantee that $\mathbf{x}_{\mathrm{TB}}$ is a feasible solution. Therefore, if $\mathbf{x}_{\mathrm{TB}}$ is a feasible solution, $\mathbf{x}_{\mathrm{TB}}$ and f_{TB} are copied at $\mathbf{x}_{\mathrm{FS}}$ and f_{FS} as the best feasible solution. Also, O-PSO-R has several special processes in the initialization, the judgement of the reset, the re-initialization, and the end condition as follows.

At the start of the search by O-PSO-R, the position of each particle is initialized based on the feasible solution $\mathbf{x}_{\mathrm{SM}}$ obtained by the simple mapping method shown in Fig.3. Concretely, a particle is set at the position $\mathbf{x}_{\mathrm{SM}}$ and others are set at the positions given by adding the random numbers to $\mathbf{x}_{\mathrm{SM}}$. The random numbers added to b_k-components are given by $r_b \equiv [-0.5, 0.5]$. On the other hand, the random numbers added to E_k-components are given by $r_E \equiv [-E_{\mathrm{ref}}/40,\ E_{\mathrm{ref}}/40]$. Moreover, the velocity of each particle is initialized by randomly choosing the numbers from r_b and r_E.

The purpose of the reset is to improve TB (i.e., $\mathbf{x}_{\mathrm{TB}}$ and f_{TB}). Therefore, if the probability of the improvement of TB is low, the reset should be executed. O-PSO-R has the following four conditions to judge the execution of reset.

a) After the initialization/re-initialization, it is assumed that f_{TB} has not been improved. Also, if the improvement of f_{GB} per iteration is less than 1.0e-6 for 100 successive iterations, the reset is executed.
b) After the initialization/re-initialization, it is assumed that f_{TB} has been improved. Also, if the improvement of f_{GB} per iteration is less than 1.0e-12 for 100 successive iterations, the reset is executed.
c) After the initialization/re-initialization, it is assumed that f_{TB} has not been improved. If the number of iterations achieves 1000, the reset is executed.
d) After the initialization/re-initialization, it is assumed that f_{TB} has been improved. After the improvement of f_{TB}, if the number of iterations achieves 1000, the reset is executed.

At the time of the reset, the position of each particle is re-initialized based on $\mathbf{x}_{\mathrm{TB}}$. All the particles are set at the positions given by adding the random numbers to $\mathbf{x}_{\mathrm{TB}}$ in the same way as the initialization at the start of the search. Also, the velocity of each particle is re-initialized by randomly choosing the numbers from r_b and r_E.

There are two end conditions of a searching trial. The first condition is that the number of resets after the last improvement of f_{TB} achieves 3. The second condition is that the total number of iterations achieves 20000. When one of them is satisfied, O-PSO-R stops searching.

1) The allocated power for each carrier is set to E_{ref}/N_C (i.e., $E_k = E_{\mathrm{ref}}/N_C$). Also, C/N is calculated based on α and β in Eq.(1).
2) If M_D is the largest M detected from the set {4, 16, 64, 256, 1024} under the condition that $p_k \leq p_{\mathrm{ref}}$ (=1/m), the primary modulation for the k-th carrier is M_D-QAM. If M_D is included in this set, $B_k = \log_2 M_D$. Otherwise, B_k=0. Moreover, if B_k=0, then E_k=0 forcibly.
3) From the results of steps 1 and 2, the feasible solution $\mathbf{x}_{\mathrm{SM}}$ is given by $\mathbf{x}_{\mathrm{SM}}=((B_1, E_1), \cdots, (B_{N_C}, E_{N_C}))$. Also, the transmission capacity R_{SM} is calculated by Eq.(2).

Fig.3 A Simple mapping method for PLC.

4. Numerical Experiments

Numerical experiments have been carried out by using the measured data to evaluate our proposed method. As mentioned above, our method can optimize the primary modulation and the allocated power for each carrier to maximize the transmission capacity of OFDM PLC considering both transmission-line impedance and noise. Unfortunately, since we could not obtain the measured data of transmission-line impedance, the following experiments use only the measured data of noise.

The conditions of OFDM PLC are as follows. The band ranges from 11 to 40kHz and the carrier spacing Δf is 1kHz. Therefore, the symbol length T_S is given by $T_S=1/\Delta f$ =1ms and the number of carriers N_C is 30. Also, since HC(7, 4) is used, the coding rate n/m is 4/7 and the reference BER (p_{ref}) is set to 1/7. Moreover, the reference value of power consumption E_{ref} is 1.0e-5 and the value of transmission capacity R_{ref} is set to R_{SM} which is given by the simple mapping shown in Fig.3. The conditions of O-PSO-R are as follows. The weight coefficients of cost function is given by $\gamma=\delta=0.5$. The number of particles is 30. The inertia weight coefficient w and acceleration coefficients c_1, c_2 included in the update equation of PSO are given by $w=0.729$, $c_1=c_2=1.49445$ respectively. The number of searching trials is 20. The other conditions are as mentioned in Sect. 3.

Table 1 shows the performance comparisons between the simple mapping method and our proposed method (i.e., O-PSO-R). From the viewpoint of the maximization of the transmission capacity, it has been confirmed that O-PSO-R is much superior to the simple mapping. Moreover, we show the solutions of the simple mapping and O-PSO-R with the best R in Fig.4 and Fig.5 respectively. From these results, it has been found that our method can change the some primary modulations decided by the simple mapping for better ones by controlling the allocated power.

5. Conclusions

In this paper, we have proposed a PSO-based method to optimize the primary modulation and the allocated power for each carrier to maximize the transmission capacity of OFDM PLC. From numerical experiments, we have confirmed that our O-PSO-R can improve the feasible solution given by the simple mapping method.

In the future, we will have to conduct more experiments using measured data of not only the noise power but also the transmission-line.

Table1 Performance comparisons.

	Transmission capacity (R[bps])	Power consumption (E_T)	Num. of iterations (N_{ITR})	Num. of resets (N_{RST})
Simple mapping	91204.24	0.933333e−5	---	---
O−PSO−R (best R)	94027.69	0.999991e−5	17767	17
O−PSO−R (worst R)	93191.36	1.0e−5	11400	9
O−PSO−R (average)	93726.38	0.999994e−5	11009.45	9.85

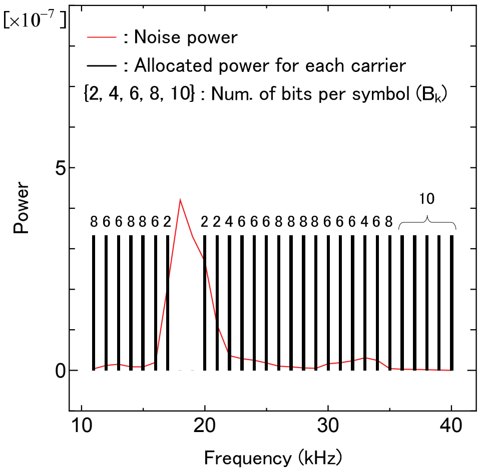

Fig.4 The solution of simple mapping method.

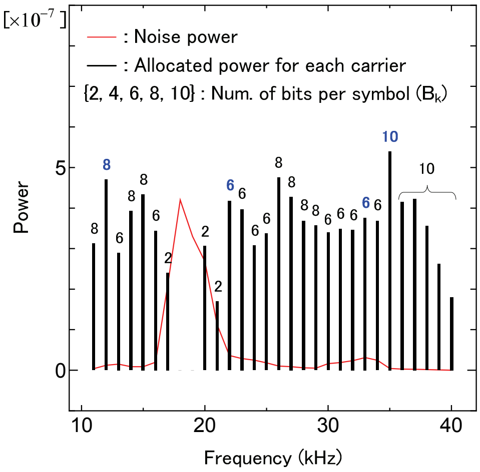

Fig.5 The best solution of O−PSO−R.

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