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Development of Digital Power Line Carrier System

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Abstract- Development of digital power line carrier systems is strongly demanded for more stable operation of power systems along with a rapid advancement of IP technology and digital communication devices. In power line carrier systems, high voltage power transmission lines are used as a communication channel. We developed a novel digital power line carrier system and verified its performance by a field experiment.

Keywords-Digital power line carrier, Adaptive equalizer, Carrier frequency offset, Field experiment

1. Introduction: A power line carrier system which uses high-voltage (66-154kV) transmission lines has a long history as a communication technique for the stable operation of power systems. To provide high reliability in cases of a disaster, the power line carrier system can be deployed at electric stations in mountainous areas where metal cables are difficult to deploy. Along with a rapid growth of IP technology and digital of communication devices, development of a digital power line carrier (DPLC) system is strongly demanded.

We have a DPLC system having bandwidth of 50 kHz in the frequency band of 100-450 kHz$^{(1)\text{-}(3)}$. We developed a DPLC system using 64 Quadrature Amplitude Modulation (64QAM) adopting a Least Mean Square (LMS) adaptive linear equalization scheme and a Carrier Frequency Offset (CFO) estimation and compensation scheme. We conducted a field experiment to verify its performance.

In this paper, we describe the adaptive linear equalization scheme and CFO estimation scheme that were implemented in our developed DPLC system. Then we present the field experiment results, which demonstrated that our developed DPLC system is feasible in actual use.

2. Field experiment setup using DPLC system: The field experiment setup using developed DPLC system is illustrated in Fig. 1. DPLC system is a communication system using a frequency band of 100-450 kHz. LT is connected to a power transmission line for prevention of high frequency inflow to a power station and substations. The DPLC system is connected to the power transmission line through CC and CF. A line trap is inserted at one of the branching points of the power transmission line used in the field experiment. For this reason, the reflection from branching point causes a large time delay paths. Furthermore, the noise encountered in the transmission line is characterized by a superposition of the impulse noise and the Gaussian noise.

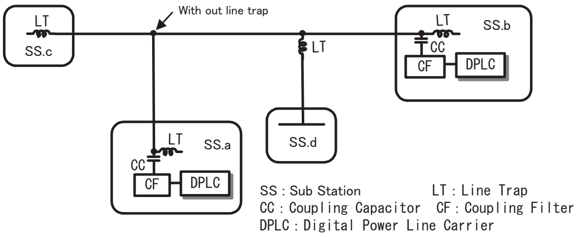

Fig. 1. Field experiment setup using developed DPLC system.

3. Applied technology for DPLC

3.1 Linear adaptive equalizer using the LMS algorithm: The reflection of the transmitted signal from the power transmission line branch points and electric station terminators produces severely delayed signals. The presence of severely delayed signals produces the inter-symbol interference and degrades the Bit Error Rate (BER) performance of the DPLC system. To improve the BER performance, a linear adaptive equalizer using the LMS algorithm was implemented in the our developed DPLC system. The adaptive LMS equalizer implemented in the DPLC system is shown in Fig. 2.

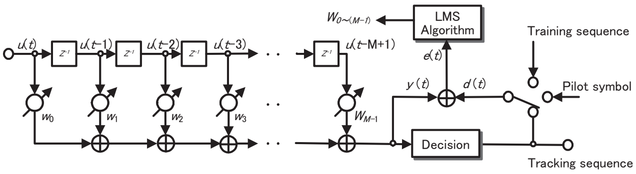

Fig. 2. Adaptive LMS equalizer implemented in the system.

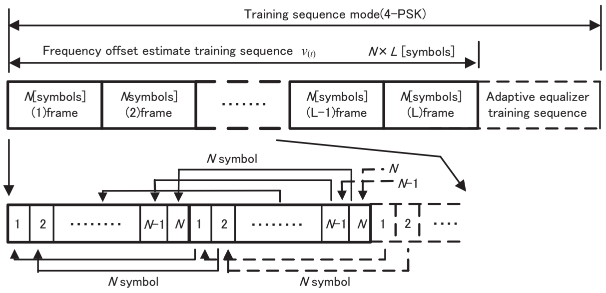

Fig.3. Frame structure of CFO estimate training sequence.

The equalizer output $y(t)$, which is the desired response $d(t)$ at time t. is given as

$$y(t)=\mathbf{w}^{\mathrm{H}}(t)\mathbf{u}(t), \tag{1}$$

where $\mathbf{u}(t)=[u(t),u(t\text{-}1),\ldots,u(t\text{-}M\text{+}1)]^T$ represents the tap input vector of the transversal filter with superscript T and M denoting the transposition operation and the number of taps, respectively, and $\mathbf{w}(t)=[w_0(t),w_1(t),\ldots,w_{M\text{-}1}(t)]^T$ represents the tap weight vector. The estimation error $e(t)$ is defined as

$$e(t)=d(t)-y(t)=d(t)-\mathbf{w}^H(t)\ \mathbf{u}(t), \tag{2}$$

where superscript H denotes Hermitian transposition and d (t) is the known symbol in the training sequence (note: that in the tracking mode, the received symbol after the decision is used) The tap weight vector update is done as

$$\mathbf{w}(t\text{+}1)=\mathbf{w}(t)+\mu\mathbf{u}(t)\ e^*(t), \tag{3}$$

where the asterisk and μ denote the complex conjugation and the step-size parameter, respectively.

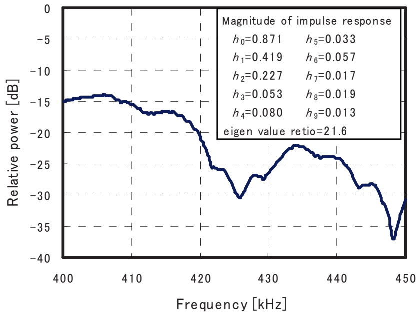

Fig.4 Frequency characteristics of real field.

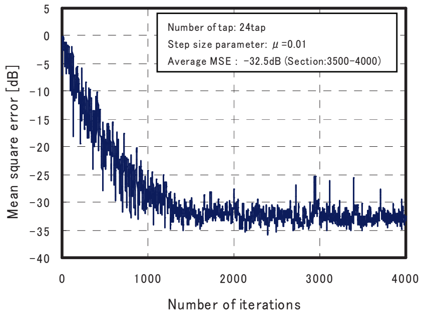

Fig.5 MSE convergence performance.

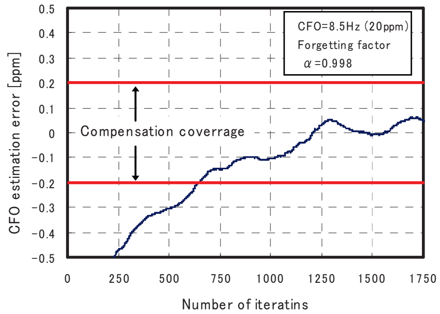

Fig.6 CFO estimation performance.

3.2 CFO estimation scheme: The presence of CFO between of the local crystal oscillators in the transmitter and receiver degrades the BER performance after equalization. We developed a digital Auto Frequency Control (AFC), which can performance accurate CFO estimation and compensation even in the presence of severely delayed signals. Four Phase Shift Keying (4PSK) is training sequence generated by a PN sequence is used. The CFO estimated by autocorrelation measurement of the received training sequence.

The frame structure of the training sequence for CFO estimation is illustrated in Fig. 3. The training sequence consists of L frames, each frame consisting of N 4PSK symbols. The number of symbol N at one frame and the time interval N(symbol) of autocorrelation are the same. For the simplicity purpose, the zero-mean white noise is assumed below. Denoting the received signal and transmit symbol at the time t by $r(t)$ and $s(t)$, respectively, the autocorrelation, $R(N) = E[r(t)r^*(t-N)]$, of $r(t)$ is given as

$$R(N) = \left[\left(\sum_{i=0}^{\infty} s(t-i)h(i)\right) \times \left(\sum_{i=0}^{\infty} s^*(t-i-N)h^*(i)\right)\right] \times e^{jN\Delta\phi} \tag{4}$$

where $\Delta\varphi$ is the phase rotation during one 4PSK symbol period caused by CFO and $\{h(i);\ i=0\sim N-1\}$, is the impulse response of the power line channel. The 4PSK symbol spaced signal representation is used. The training sequence is a periodic sequence with a period of N 4PSK symbols. Therefore, $s(t-i)=s(t-i-N)$ when integer multiple of N in Eq. (4). Furthermore the impulse response length is shorter than N 4PSK symbol, i.e. $h(i)=0$ if $i>N$. Therefore. we have

$$R_{(N)} = E\left[|r(t)|^2\right] \times e^{jN\Delta\phi} \tag{5}$$

Using the above equation, the amount of phase rotation $\Delta\varphi$ due to CFO can be obtained from.

$$\Delta\phi = \frac{1}{N}\ln\left(\frac{R(N)}{E[|r(t)|^2]}\right) \tag{6}$$

4. Field experiment results: The channel frequency response measured by field experiment is shown in Fig. 4. The measurement was done over a frequency range of 400 kHz to 450 kHz. It can be seen that the channel frequency response fluctuates due to the presence of multiple delayed paths in the transmission line. Also the channel delay profile, i.e., $\{(|h(0)|^2, |h(1)|^2, \ldots, |h(9)|^2)\}$ measured by using the 4PSK training sequence and the measured eigenvalues ratio of the autocorrelation matrix of $\mathbf{u}(t)$ are also shown in Fig.4.

4.1 Convergence performance: The Mean Square Error (MSE) convergence performance obtained by averaging the results of 10 trials is in Fig. 5. 4PSK training sequence was used. It can be seen that the tap weight vector is converged after about 2000 times updating. The average MSE after the convergence is -32.5 dB.

An average MSE is about -32.5dB, which is higher than the theoretically predicted one (-39 dB for the measured channel impulse response at the thermal noise power of -42 dBm), is observed. This degraded MSE may be due to sampling timing error at the receiver and the excess MSE(2).

4.2 CFO estimation performance: CFO was set to 20 ppm in the experiment. Averaging of the autocorrelation $R(N)$ was used a forgetting factor α by first-stage IIR filter. And the average CFO estimation error characteristic in 10 trials is presented in Fig. 6. 4PSK training sequence was used. It can be seen that the CFO estimation error becomes within +/- 0.2 ppm (which is required for CFO compensation) even in the presence of severely delayed propagation paths if a 4PSK training sequence of 750 symbols is used. If the training sequence length of longer than 1250 symbols is used , the CFO estimation error can be within +/- 0.1 ppm.

4.3 BER measurement: BER measurement was conducted during one hour period using our developed DPLC having parameters shown in Table 1. In this case, DPLC transmission distance was 16.6 km. CFO was 20 ppm. The received SNR was 32.5 dB. It was confirmed that error-free transmission was achieved.

Table 1. Parameters of the developed system

TA modulation	64QAM (Symbol rate=34.3 kbps)
Tx power	20 dBm
Filter	Root nyquist filter (Roll-off factor=0.4)
Error correcting	Read-Solomon code RS (255,239)
Interleaving	Block interleaver (256 byte×3 byte)
Bit rate	205.8 kbps

5. Conclusion: In this paper, we presented the real field experiment results our developed DPLC system. Field experiment demonstrated that our DPLC system can be useful in the real field.

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