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# Performance Evaluation of CDMA Using Chaotic Spreading Sequences in Indoor Power Line Channels

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**Abstract**—Power line communication is a technology that is used for data transmission on electric power lines. Because impedance mismatching and branched lines cause signal reflections, power line channels possess multi-pass fading characteristics. In this study, the performance of a synchronous code division multiple access (CDMA) using chaotic spreading sequence is estimated in indoor power line channel.

## 1. Introduction

Power line communication (PLC) is considered to be one of the key technologies of smart grids [1]. In a smart grid environment, real-time information of energy consumed by appliances is acquired using highly developed information and communications technologies (ICT). By utilizing this information, only the required amount of electrical energy is intended for delivery to these appliances [2, 3]. These appliances are inevitably connected to power lines. Thus, PLC has attracted much interest for the acquisition of information and the control of appliances. In the context of smart grids, high capacity and high security are both key requirements for ICT.

Conversely, to realize a high-capacity and more secure communication link, a chaos CDMA, to which a real-valued complex chaotic time series with constant power is applied as the spreading sequences, is proposed and evaluated [4, 5]. The high sensitivity to the initial conditions, which is one of the features of the chaos, makes it possible to easily generate various types of spreading sequences. The chaotic sequences possess statistical orthogonality. Simultaneously, the chaotic properties are considered to be usable as the cipher code.

In this study, the performance of synchronous CDMA using the complex chaotic spreading sequences with constant power is investigated in indoor power line channels as a high-capacity and more secure system. Its performance was compared with the system using the Walsh–Hadamard (WH) sequences, which have complete orthogonality in an ideal synchronous system, and which are used in practical CDMA systems. Here, the bit error rates (BERs) are estimated by performing numerical simulations. This paper is organized as follows. In Section 2, the fundamental properties of the complex chaotic spreading sequences are explained. In Section 3, the power line channels used here are explained in detail. In Section 4, the simulated system and parameter settings are explained. The BERs obtained by the numerical simulation are estimated and discussed. Finally, the conclusion is given in Section 5.

## 2. Complex chaotic spreading sequences with constant power

The complex chaotic spreading sequence $\{Z_i\}$ ($i = 0, 1, \cdots N$) used here is composed of In-phase and Quadrature-phase real-valued sequences. The sequences can be obtained by using the Chebyshev polynomials [4]. The quantity $Z_i$ can be represented as $Z_i = X_i + jY_i$, where $j$ indicates an imaginary unit. A part of the sequences, e.g., In-phase $X_i$, is generated by the following relation:

$$X_{q,i+1} = T_q(X_{q,i}), \quad T_q(\cos\theta) = \cos(q\theta), \tag{1}$$

where $T_q(x)$ is the $q$-th order Chebyshev polynomial and $q > 2$, $q \in N$. It is known that the Chebyshev map $T_q(x)$ is ergodic, and it has an ergodic invariant measure given by $\rho(x)dx = dx/(\pi\sqrt{1-x^2})$. It satisfies the relation given by

$$\int_{-1}^{1} T_i(x)T_j(x)\rho(x)dx = \delta_{i,j}\frac{1+\delta_{i,0}}{2}, \tag{2}$$

where $\delta_{i,j}$ is the Kronecker delta function. This relation indicates a statistical orthogonality between the sequences. It is also known that a Lyapunov exponent of the sequence generated by $T_q(x)$ is given by $\log q$. Conversely, another part of the sequence $Y_j$ is generated by

$$Y_{q,i+1} = T'_q(X_{q,i}, Y_{q,i}), \quad T'_q(\cos\theta, \sin\theta) = \sin(q\theta). \tag{3}$$

The invariant measure of $\{Y_i\}$ is the same as that of $\{X_i\}$. It is easy to show that the sequences can realize a constant power as follows:

$$|Z_{q,i}|^2 = X_{q,i}^2 + Y_{q,i}^2 = \cos^2(q\theta) + \sin^2(q\theta) = 1. \tag{4}$$

Finally, the complex chaotic sequence with constant power $\{Z_i\}$ can be generated by the following relation:

$$Z_{q,i+1} = F(Z_{q,i}), \quad F(e^{j\theta}) = e^{jq\theta}. \tag{5}$$

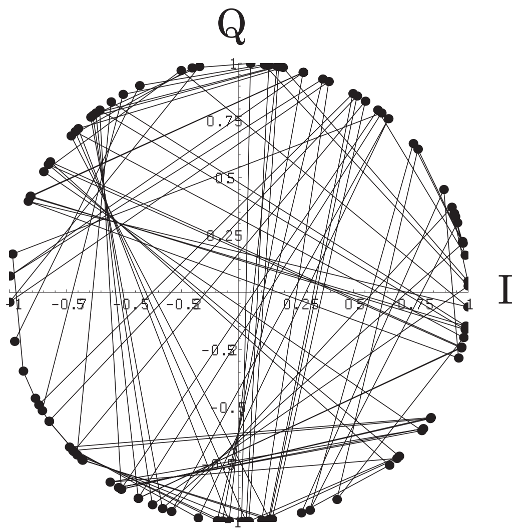


Figure 1: An example of complex chaotic spreading sequence with constant power.

The invariant measure for the transformation $z \rightarrow F(z) = z^q$ is represented by the following uniform measure: $\rho(z)dz = d\theta/(2\pi)$. Fig. 1 shows an example of the complex chaotic spreading sequence with constant power. The sequences applied to each channel or user can be obtained by changing these initial values $X_0$ and $Y_0$ or the order $q$. The performance of complex chip-synchronous CDMA using the above chaotic spreading sequences has been investigated in detail for the system with an additive white Gaussian noise (AWGN) channel [5]. In this study, we apply the sequences $X_{q,j}$ and $Y_{q,j}$ to I (In-phase) and Q (Quadrature-phase) channels, respectively.

## 3. Power line channel

Here, we use a power line channel model proposed by Tsuzuki *et al.* [6]. The power line is a VVF (Vinyl insulation, Vinyl sheath, Flat) electrical cable with two wires of $\phi$1.6 mm, which is widely used in Japan for indoor power lines. One of the configurations of the channels is shown in Fig. 2. The signal transmitter and receiver are set at points A and D, respectively. There are two branches at points B and C, while the appliances can be connected at points E and F. Impedance mismatching causes signal reflection, which results in a frequency selective fading response in the power line channel. A practical model of the transfer function is developed for VVF cable by adopting the measured parameters. Here, we assume that the impedances are matched along the cable, transmitter, and receiver. In this branched configuration, open-ended branches with no appliances are assumed. Fig. 3 shows the transfer function as a function of the frequency for the power line channel used here. From the figure, it is observed that the gain decreases non-monotonically and drops sharply around a particular frequency. At the same time, nonlinear phase characteristics are shown. From these results, it is confirmed that this power line channel has a frequency-selective fading response.

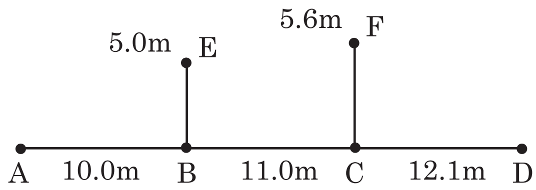


Figure 2: Transmission line composed of VVF cables.

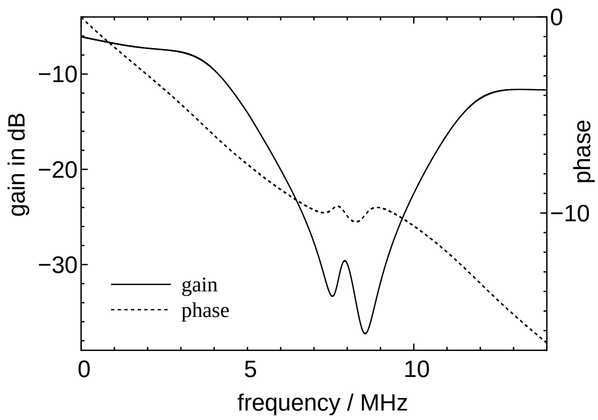


Figure 3: Transfer function for the power line channel used here.

## 4. Bit error rate obtained by numerical simulation

In this study, the performance of a synchronous CDMA using the chaotic spreading sequences with constant power is evaluated for the power line channels explained in the previous section. The performance is compared with that of the one using the WH sequences, which is well known to possess complete orthogonality in an ideal synchronous system. Fig. 4 shows a schematic diagram of the investigated communication system, which focuses on one user. Here, $b$ and $C$ indicate the transmitted bit ±1 and spreading sequences, respectively. In the multi-user case, all users' signals are combined in one transmitted signal, and the signal is inputted to the channel $H(f)$. Each user uses both I and Q channels, and raised cosine filters are set. The bandwidth is set to $(1 + \alpha)/T_c$, where the chip rate $1/T_c$ is 5 Mcps (chip per second) and the roll-off factor $\alpha$ is 0.5. The channel $H(f)$ is the power line channel shown in Fig. **??**. The quantity $\varphi$ is a phase delay caused by this channel. The white Gaussian noise is added to the signal after passing through $H(f)$. The carrier frequency $\omega_c$ was set to 2 MHz since frequencies between 2 and 30 MHz are used for high-speed power line communication. The number of users was set to two and the spreading factor $N$ was set to 128. In the case where $N = 128$, the number of obtainable

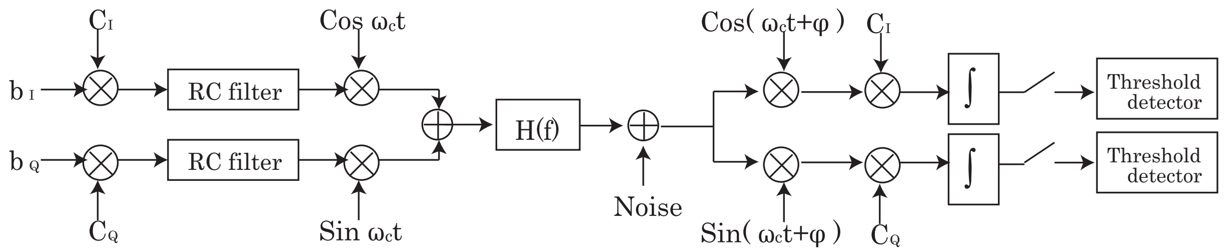


Figure 4: Schematic diagram of the communication system investigated here.

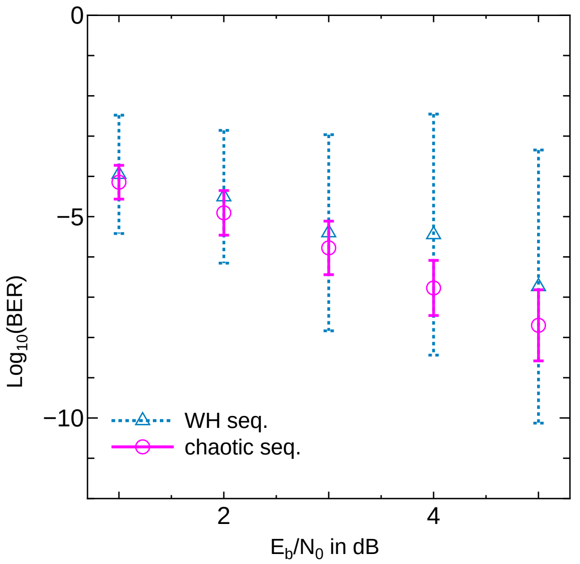


Figure 5: BER in synchronous CDMA as a function of bit energy at transmitter over noise power $E_b/N_0$ in the power line channel.

WH sequences is 128. For every set of simulations, four different sequences were randomly extracted from these 128 sequences. In the case where the chaotic spreading sequences are used, the initial values $X_0$ and $Y_0$ were randomly set for every set. These four randomly-selected sequences were applied to each of the I/Q channels for two users. For one set of simulations, 40 bits for each channel were transmitted, i.e., a total of $40 \times 4$ bits (two users and two I/Q channels) were transmitted. The bits were randomly set to $\pm 1$. We obtained a distribution of sampled correlator output data before the input to a threshold detector. The BERs for each set were estimated numerically by applying the standard Gaussian approximation to the distribution. Finally, 40 sets of simulations were executed.

Fig. 5 shows the BER as a function of bit energy at a transmitter per noise power $E_b/N_0$. Each point indicates the mean value for 40 sets. The error bars indicate the standard deviations, which are obtained after applying a common logarithm to each of these 40 BERs. From this figure, it is found that the mean BERs of the system with the chaotic spreading sequences are lower than the ones with the WH sequences. In addition, with regards to the standard deviation, there is a large difference between the chaotic and the WH sequence. While there is a large deviation for the WH sequences, the deviation for the chaotic sequences was found to be much narrower. This result implies that the performance for the chaotic spreading sequences does not depend on the choice of these sequences, such as the choice of the initial values for the chaotic sequences $X_0$ and $Y_0$. On the contrary, the choice from the limited number of the WH sequences (which is 128 sequences in this study), significantly affects the BER. This is because the chaotic spreading sequences possess a much smaller difference each other in the power spectral distribution when compared with the WH sequences. Finally, on the basis of these results, it was found that the system with the chaotic spreading sequences has a BER with much narrow error bars, which does not depend on the selection of these sequences. Conversely, for the WH sequences, it was necessary to select the sequences that are appropriate to the channel response. The WH sequences appropriate to the channel realize a significantly low BER; however, it would be more difficult to select the matched sequences as the number of users increase.

## 5. Conclusion

In this study, the performance of synchronous CDMA using the complex chaotic spreading sequences with constant power was estimated in the power line channel which has the frequency-selective fading response. The performance of the system with the chaotic sequences was compared with that of the one with the WH sequences. It was found that the system with the chaotic spreading sequences has lower mean BERs and much narrower standard deviation of BERs than the system with the WH sequences in the power line channel. This result implies that, as the number of users increase, the system with the chaotic spreading sequences has a significantly better performance when compared with the system with the WH sequences. As for future topics, it would be interested if the performance for the power line channels of a synchronous CDMA systems with the use of chaotic spreading sequences is investigated and compared with the use of the Gold sequences. The CDMA system using the complex chaotic spreading sequence is highly expected to realize a more secure system with higher capacity.


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