PAPER

On the Influence of Transmission Line on Communication System Using Chaos Synchronization

Junji KAWATA†, Yoshifumi NISHIO††, *Members*, Hervé DEDIEU†††, *Nonmember*, *and* Akio USHIDA††, *Member*

SUMMARY In this paper some new results for analog hardware realization of secure communication system using chaos synchronization have been presented. In particular the effect of the use of transmission line as channel has been considered assuming practical implementation. The influence of the loss of transmission line and mismatching on synchronization has been investigated in chaotic systems based on the Pecora-Carroll concept. It has been shown that desynchronization due to loss can be checked by using an amplifier with appropriate gain. Moreover the bit error rate (BER) has been evaluated in a digital communication system based on the principle of chaotic masking.

key words: *chaotic communication, transmission line, line loss, impedance mismatching, compensation, bit error rate*

1. Introduction

Chaos synchronization has recently received a great deal of attention since its discovery by Pecora and Carroll [1]. Particular attention has been paid to the field of communications in which some classes of chaotic systems have been proposed as basic building blocks for modulation and demodulation of chaotic carriers [2]–[4]. In general these chaotic systems will offer two advantages: spreading the spectrum of an information signal and some level of security. For realization of such communication systems it is of primary importance to assess the system performance in presence of channel noise, channel power loss, etc. Surprisingly enough, in most of the studies developed so far, the transmitter and the receiver have been supposed to be interconnected with a perfect channel, i.e. coupled through voltage buffer [2], [3]. Only a few preliminary studies have been carried out with imperfect transmission lines as in [4] in which the authors have developed a digital communication and considered the influence of noise and gain distortion caused by an analog transmission line. In [5] the authors have regarded communication channel as a kind of filter and investigated the effect of filtering on chaotic communication system. In [6] the effect of coupling a transmitter and receiver by using a coaxial cable has been investigated by simulation for the cases in which the coaxial cable is adapted with its characteristic impedance or not. In [7] synchronization of optical chaotic systems coupled with an optical fiber cable has been confirmed experimentally. In [8] an adaptive controller has been proposed for a chaotic switching system in order to equalize a time-varying channel.

However more detailed research will have to be done to investigate the effect of non-ideal transmission channel on communication systems using chaos synchronization. In this paper we present some new results for analog hardware implementation of chaos communication systems. We pay particular attention to the use of a transmission line as channel. In the first part of this paper the influence of the transmission line loss and mismatching on synchronization is investigated in a transmitter-receiver system based on the Pecora and Carroll drive-response concept. Further we propose a simple compensation technique in order to avoid an undesirable effect due to loss. In the second part we consider the case in which a digital information signal is added to a chaotic carrier (chaotic masking modulation). In particular the bit error rate (BER) is evaluated for different operation modes.

In order to model the transmission line, we use the method of characteristics [9] which has been proposed for the transient simulation of transmission lines. For uniformly constant *RLCG* transmission lines, a brute-force approach [10] is used, where the *RLCG* transmission line is modeled by several cascaded cells which consist of lumped resistors and a lossless line. Further the lossless line is replaced by its characteristic model.

This paper is organized as follows. Section 2 describes the emitter circuit model and its synchronization when the transmission line is lossless. Section 3 examines the influence of loss on chaos synchronization for a lossy transmission line. Also a compensation technique using an amplifier is proposed. In Sect. 5 we evaluate the BER for a system in which a digital signal has been modulated and demodulated using the chaotic masking principle. Concluding remarks are given in Sect. 6.

Manuscript received January 16, 1998.
Manuscript revised May 24, 1998.

†The author is with the Department of Information Science and Systems Engineering, Tokushima Bunri University, Kagawa-ken, 769–2193 Japan.
††The authors are with the Department of Electrical and Electronic Engineering, Tokushima University, Tokushima-shi, 770–8506 Japan.
†††The author is with the Department of Electrical Engineering, Swiss Federal Institute of Technology, Lausanne, CH-1015 Switzerland.

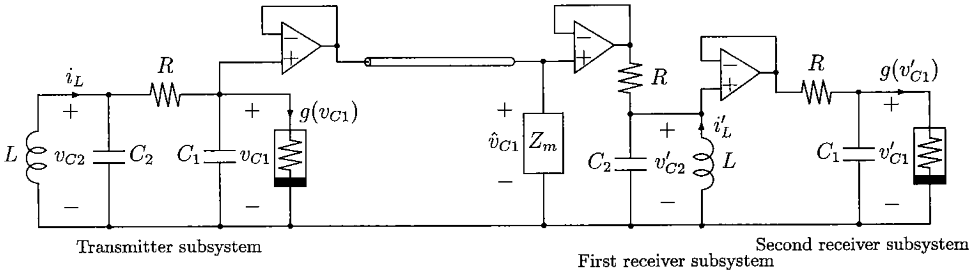


Fig. 1 Transmitter-receiver system using Chua's circuit.

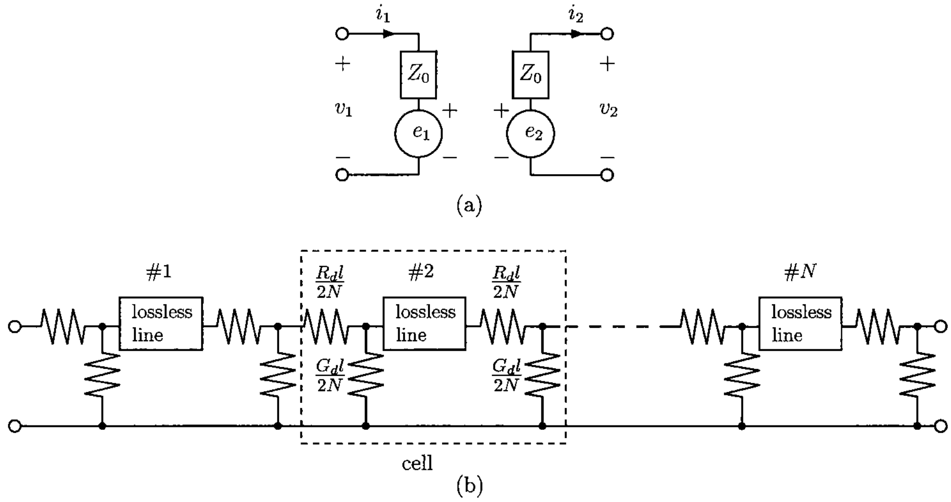


Fig. 2 (a) The characteristic model of lossless transmission line and (b) modeling of lossy transmission line.

2. Circuit Model and Synchronization

Figure 1 shows a transmitter-receiver system based on the Pecora and Carroll drive-response concept. Each subsystem is based on Chua's circuit which chaotic behavior has been widely studied (see Ref. [12]). The transmitter and receiver are interconnected with a transmission line. The transmission line is connected to a resistor, the impedance of which matches the characteristic impedance of the line in order to avoid signal distortion due to reflection. A transmission line is usually matched at both ends by its characteristic impedance to avoid the reflection. However, it can be expected that a transmission line fairly matched only at the receiving end does not so cause the multiple reflection if the transmission line has loss. Therefore a matching impedance at the transmitting end is eliminated in this paper.

The system operates as follows. The chaotic signal v_{C1} is transmitted to the receiver through the transmission line. After some time delay τ, the transmitted signal reaches the receiving terminal. If the transmission line is lossless and if its characteristic impedance is completely matched to the matching impedance the voltage $\hat{v}_{C1}(t)$ at the termination is equal to $v_{C1}(t-\tau)$. Therefore the first receiver subsystem produces the signal $v'_{C2}(t)$ which will synchronize to $v_{C2}(t-\tau)$ if the components of the subsystem are exactly identical to those of the transmitter subsystem. The signal $v'_{C1}(t)$ is then produced by the second receiver subsystem, the components of which are also equal to those of the transmitter. In these conditions $v'_{C1}(t)$ will synchronize to $v_{C1}(t-\tau)$. The different conditions for synchronization are given in [8].

In order to deal with a tractable analysis of the transmission system, the transmission line is replaced with a convenient model. A lossless transmission line can be modeled using the so-called characteristic model [9] as shown in Fig. 2 (a). Using such a model yields to the following system of equations for the transmission system:

$$C_1\frac{dv_{C1}}{dt} = G(v_{C2}-v_{C1}) - g(v_{C1}), \tag{1}$$

$$C_2\frac{dv_{C2}}{dt} = G(v_{C1}-v_{C2}) + i_L, \tag{2}$$

$$L\frac{di_L}{dt} = -v_{C2}, \tag{3}$$

$$\hat{v}_{C1} = e_2(t-\tau)\cdot Z_m/(Z_0+Z_m), \tag{4}$$

$$e_1(t) = 2\hat{v}_{C1} - e_2(t-\tau), \tag{5}$$

$$e_2(t) = 2v_{C1} - e_1(t-\tau), \tag{6}$$

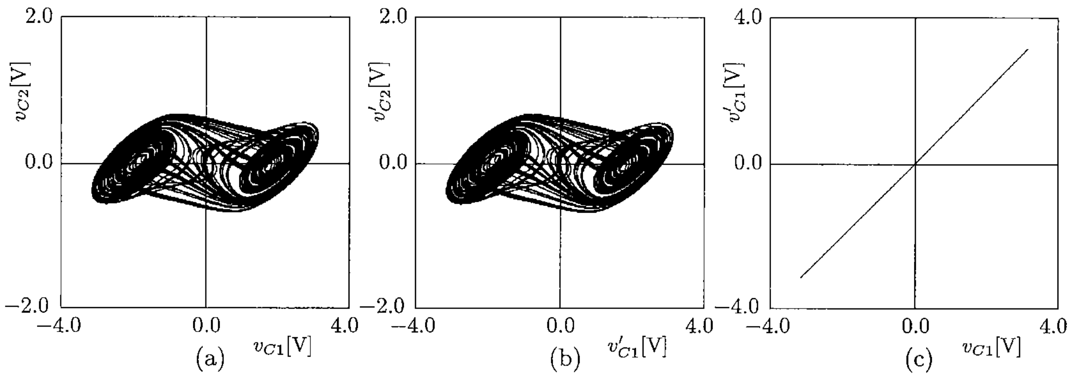


Fig. 3 Synchronization of the system for lossless transmission line with complete matching: Phase portrait in (a) v_{C1}–v_{C2} plane, (b) v'_{C1}–v'_{C2} plane, (c) v_{C1}–v'_{C1} plane, respectively.

$$C_2 \frac{dv'_{C2}}{dt} = G(\hat{v}_{C1} - v'_{C2}) + i'_L, \tag{7}$$

$$L \frac{di'_L}{dt} = -v'_{C2}, \tag{8}$$

$$C_1 \frac{dv'_{C1}}{dt} = G(v'_{C2} - v'_{C1}) - g(v'_{C1}), \tag{9}$$

where $g(\cdot)$ is a piecewise linear function defined by:

$$g(v) = m_1 v + \frac{1}{2}(m_0 - m_1)[|v + B_p| - |v - B_p|]. \tag{10}$$

Equations (1)–(3), (7), (8) and (9) describe the dynamics of the transmitter, the first receiver, and the second receiver subsystem, respectively, while Eqs. (4)–(6) are derived from the characteristic model [9], where Z_0 and τ are the characteristic impedance and the time delay, respectively.

An *RLCG* lossy transmission line is approximately modeled by several cascaded cells as shown in Fig. 2 (b) [10]. Each cell consists of lumped resistors and a lossless line which is replaced with its characteristic model. In [11] a theoretic justification for this approach as well as an error analysis in the frequency domain have been reported. Based on this model we can decide on the number of cells we need for a prescribed modeling error. This number is adjusted according to both magnitude of the loss and frequency of signal. Consequently Eqs. (4)–(6) must be replaced by the corresponding state equations.

To investigate the synchronization in the transmitter-receiver system, let us fix the parameters of the transmitter so that it exhibits a chaotic attractor. From Chua's circuit, the double scroll attractor can be observed for the following parameters:

$$R = 1/G = 1700\,[\Omega], \quad C_1 = 10\,[\text{nF}],$$
$$C_2 = 100\,[\text{nF}], \;\; L = 18\,[\text{mH}], \;\; m_0 = -0.75\,[\text{mS}],$$
$$m_1 = -0.41\,[\text{mS}], \quad B_p = 1\,[\text{V}].$$

These values are fixed throughout the following discussion.

We suppose here that the parameters of both transmitter and receiver subsystems are completely identical. First, let's examine the system for the case in which the transmission line is lossless and has the following parameters:

$$Z_0 = 50\,[\Omega], \quad \tau = 0.5\,[\text{msec}].$$

Using the classical method of characteristics [9], the computer simulation is carried out using a 4th order Runge-Kutta method (stepsize is 0.00001 [msec]). Figure 3 shows the results for the case of $Z_m = Z_0$. In the figure, it should be noted that the horizontal axis in (b) and the vertical axis in (c) are the time-delayed voltage v'_{C1}, and the vertical axis in (b) is the time-delayed voltage v'_{C2}. As we had expected, the transmitted signal v_{C1} and the reproduced signal v'_{C1} synchronized completely. For arbitrary values of Z_0, τ different from the above example, they also synchronized completely.

3. Influence of Loss and Mismatching

In order to investigate what happens for a real transmission line such as a coaxial cable, we investigate the system for the case of lossy transmission lines. In this case the time-delayed signal $\hat{v}_{C1}$ at the receiving end is different from the transmitted signal v_{C1} because of attenuation. In the simulation we used the following set of parameters:

$$R_d = 20\,[\Omega/\text{km}], \quad L_d = 0.25\,[\text{mH/km}],$$
$$C_d = 100\,[\text{nF/km}], \quad G_d = 0\,[\text{S/km}].$$

The per-unit-length parameters of a real coaxial cable is of the same magnitude order. In the transient analysis the number of cells N is 1. From the error analysis [11], the modeling error, in this case, is within 0.1% in the frequency range of 100 times the natural frequency of chaotic signal transmitted. We calculated the value of matching impedance by the following equation:

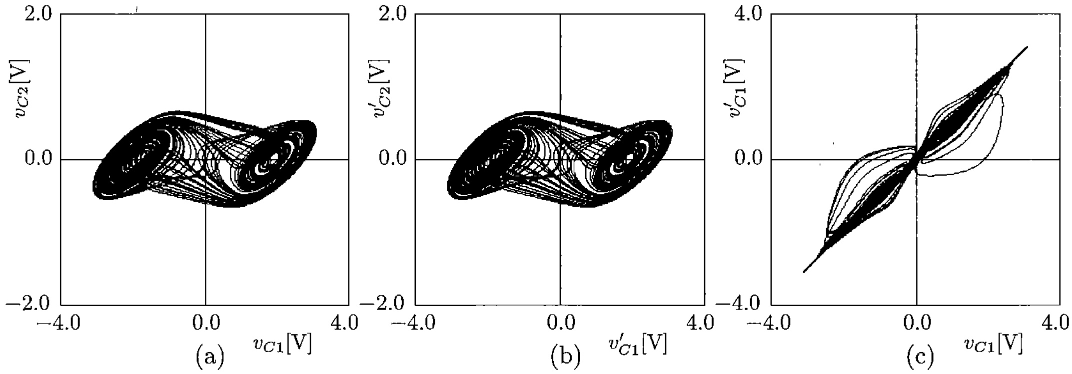


Fig. 4 Synchronization of the system for 0.01 [km] lossy transmission line with complete matching: Phase portrait in (a) v_{C1}–v_{C2} plane, (b) v'_{C1}–v'_{C2} plane, (c) v_{C1}–v'_{C1} plane, respectively.

$$Z_m = |Z_0(j\omega_c)| = \left| \sqrt{\frac{R_d + j\omega_c L_d}{G_d + j\omega_c C_d}} \right|,$$

where ω_c is the natural angular frequency of Chua's circuit decided by L and C_2. See Fig. 4. Roughly speaking, the subsystems synchronize yet. Further we examine the system for larger loss. To investigate the effect of loss, we fix the per-unit-length parameters and then simulate the system by varying the line length. In this case the total loss of transmission line increases with the length. For larger loss, the subsystems did not synchronize unfortunately, and obvious differences in the phase plain were not found. In order to investigate the effect of increasing loss fully, thus, we examined the time variation of synchronization error $v_{C1} - v'_{C1}$ for various length. Some results are shown in Fig. 5, where we chose N 5, 25 and 50 which correspond to the length 0.1 [km], 0.5 [km] and 1.0 [km], respectively. In these case the modeling error is also within 0.1% in above mentioned frequency range. As we had expected, it seems that synchronization breaks more frequently as loss increases.

Here we will investigate the effect of mismatching on synchronization, i.e., the mismatch between Z_m and Z_0. Adding an error factor to the matching impedance, the influence of matching error is examined. In this case the reflection due to mismatching takes place at the receiving end and consequently the transmitted signal is affected by the distortion. The synchronization error is plotted in Fig. 6 for the case of 5% mismatch. For lossless transmission line, synchronization largely breaks at times, while the remarkable difference by matching error is not observed for lossy transmission line (compare Figs. 5 (a) and (b) with Figs. 6 (b) and (c)). This reason will be that the attenuation due to loss affects synchronization than mismatching for the chosen line parameters; that is, the reflection waveforms induced by mismatching is also attenuated because of loss. If we had chosen a low loss, the mismatching will prevent synchronization similar to the case of lossless transmission line.

4. Compensation Using Amplifier

It seems impossible to realize practical communication system as it is, because desynchronization occurs more frequently with increasing length (loss) as confirmed in Sect. 3. Here, therefore, we propose a simple way to compensate the effect of loss. The method are summarized as follows:

Step 0: Replace the voltage buffer between the transmission line and the first receiver by the amplifier.

Step 1: Find the natural angular frequency ω_c of the transmitter subsystem.

Step 2: Decide the initial gain of the amplifier.

Step 3: Trim the gain by sending a test signal, i.e., decide a correction value K_c.

We will mention here the detail. Assume that a lossy transmission line is matched perfectly and frequency-independent. In this case, the attenuation constant is a function of the frequency, line parameters and length, and it is defined as follows:

$$\begin{aligned}\alpha &= \mathrm{Re}[\theta(j\omega_c)] \\ &= \mathrm{Re}\left[\sqrt{(R_d + j\omega_c L_d)(G_d + j\omega_c C_d)}\ l\right].\end{aligned}$$

Then the attenuation factor is given by $e^{-\alpha}$. Thus amplifying the received signal by the reciprocal of the attenuation factor e^{α} with the use of an amplifier, it can be expected that the received signal will be of the same magnitude as that of the transmitted signal. Therefore we have to find first ω_c and then α to decide the gain.

One may be afraid that the above mentioned procedure can not compensate the effect of attenuation completely because chaotic signals contain a variety of high-frequency components. That is true, however it is found

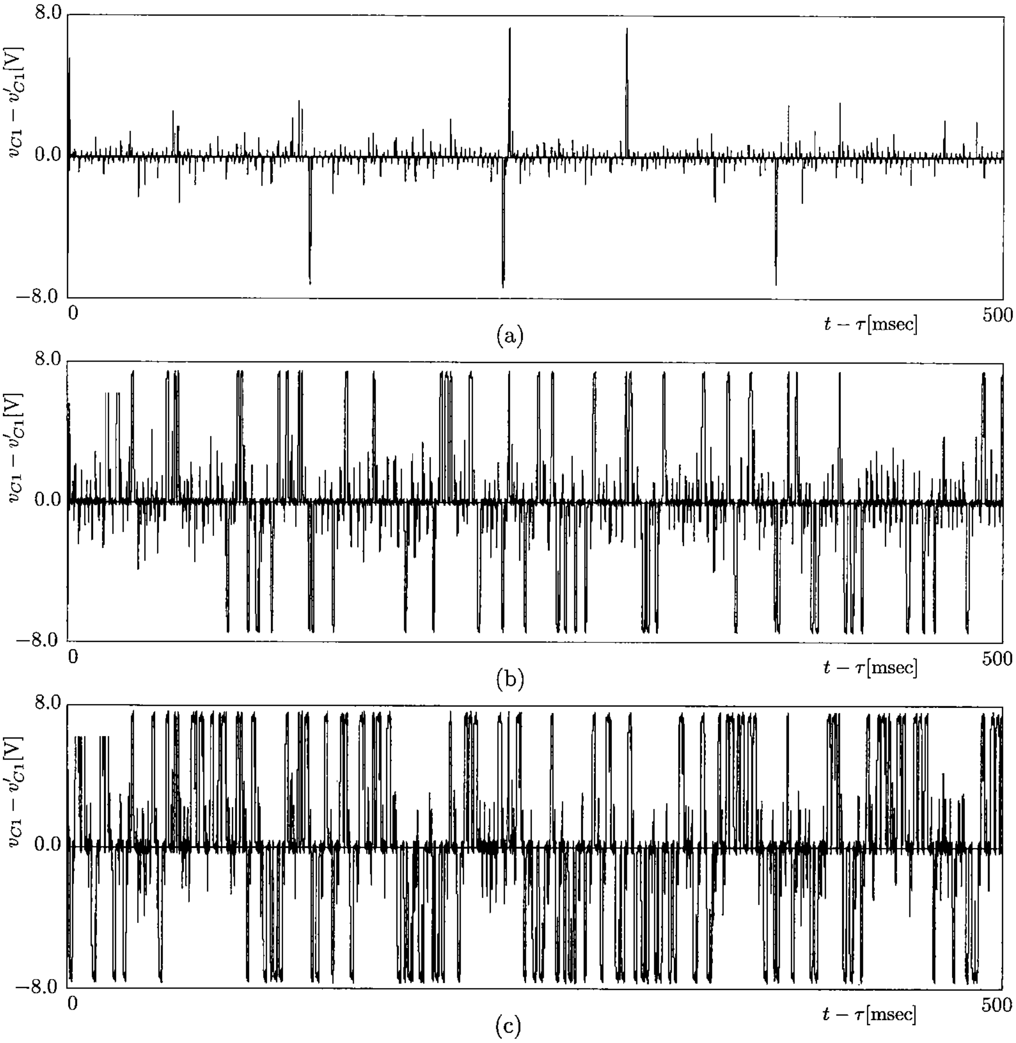


Fig. 5 Time evolution of $v_{C1}-v'_{C1}$ with the variation of loss with length, under complete matching. (a) 0.1 [km], (b) 0.5 [km], (c) 1 [km].

from our numerical experiments that by multiplying a constant number K_c the system almost synchronizes. This implies that by trimming the gain initially decided in *Step 2* synchronization will be achieved. The numerical confirmation of our method are shown in Fig. 7 where the values of K_c are 1.008 and 1.035 which correspond to the length 0.1 [km] and 0.5 [km], respectively.

Note that it is relatively easy to trim the gain with the use of a variable resistor and that the manual tuning is required only once when a circuit configuration is implemented; that is, chaotic circuits, line parameters and line length are decided.

As an example using an another compensation method we tried to use an adaptive controller [8]:

$$\dot{K}(t) = -k_1(K(t)|\hat{v}_{C1}| - |v'_{C1}|).$$

The simulation results are shown in Fig. 8 where $k_1 = 1$. Desynchronization almost disappears. The use of such an adaptive controller will be also very useful to cancel the effect of mismatching as well as loss. However this method probably becomes complicated the circuit implementation and it is difficult to apply this method to chaotic masking or chaotic modulation communication systems as yet.

5. Transmission of Digital Signal and Evaluation of BER

In this section, we consider the problem of masking a digital information signal using chaotic carrier. The block diagram of the system based on chaotic masking is shown in Fig. 9. In the system, each subcircuit is identical to that used in Fig. 1, and the voltage buffer between the transmission line and first receiver subsystem is replaced by an amplifier with gain K. We assume again the ideal conditions that the parameters of both transmitter and receiver are matched and that the transmission line is noiseless. The component values of each

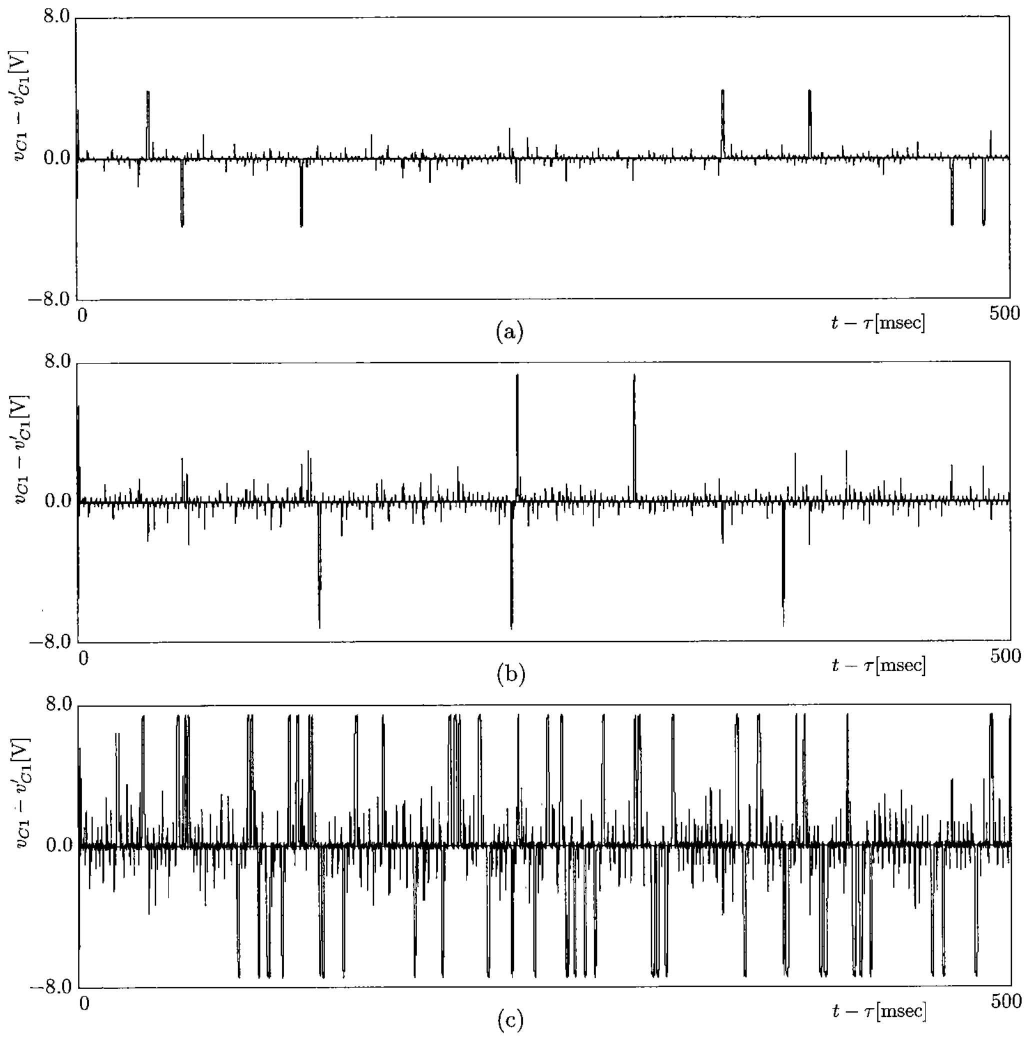


Fig. 6 The influence of matching error 5% for (a) lossless line, and lossy line with length (b) 0.1 [km], (c) 0.5 [km].

subsystem and line parameters (incl. Z_m) are those used in Sects. 2 and 3, respectively.

We consider first the ideal case in which the transmission line is lossless and when there is perfect matching between Z_m and Z_0. A random data sequence of bit $(+1, -1)$ is masked by chaotic signal and then transmitted. The bit error rate (BER) is then evaluated by computer simulation for various amplitudes and bit rate of a random 10,000 bits sequence. Before computing BER, let us examine the voltage waveform of each signal in the system, where $K = 1$ because of lossless transmission line. The waveforms for the amplitude 0.1 [V] and bit rate 10^3 [bps] are shown in Fig. 10. As found from the figure, the recovered signal $s'(t)$ contains high frequency components due to the transient behavior at the rising and falling edges of the bit string. This effect makes the BER to be worse beyond expectation. To overcome this, we introduce a simple RC low-pass filter (LPF) as shown in most right part of Fig. 9. Let $s''(t)$ be the output of LPF and it is used to evaluate BER by detecting the sign of the bit at just before of the bit switching. From simulations, 25%–40% of bit interval seemed to be appropriate as the time constant of the LPF. So we fix the time constant to 30% of the bit interval throughout the evaluation of BER including Fig. 10, where the resistor of LPF is fixed to 1 [kΩ] and the capacitor is chosen according to the bit interval. BER's versus amplitude and bit rate are shown in Fig. 11. It is found from the figure that BER becomes better as bit rate or amplitude decreases. For larger amplitude the transmitted signal (or its initial value) is largely changed at each instant of bit switching, consequently it takes relatively long time until the transient settle down. For this reason the BER becomes worse as amplitude increases. The larger the bit interval is and the better is the synchronization since a message signal with larger bit interval is not so affected by temporal desynchronization.

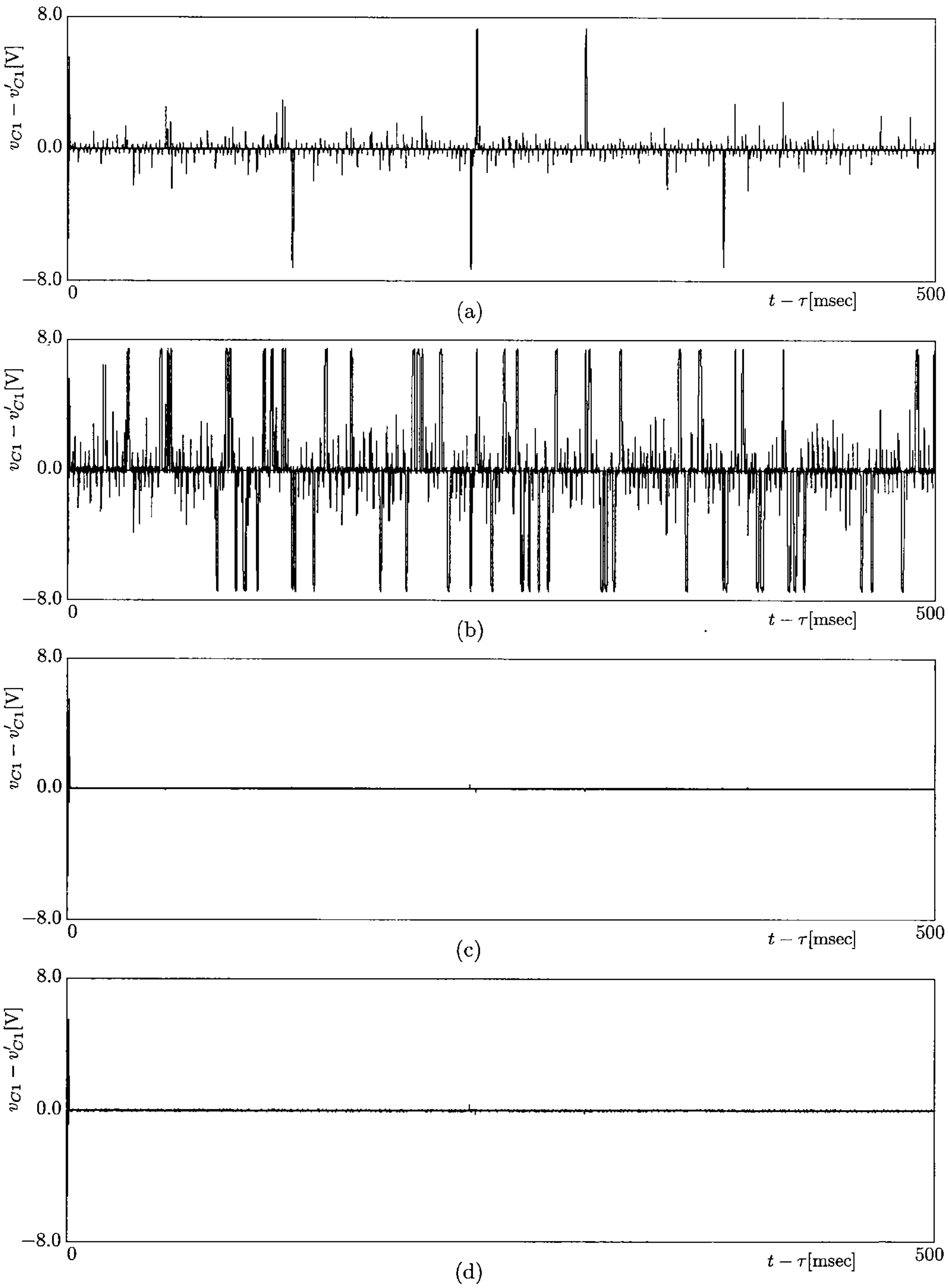


Fig. 7 Compensation using the amplifier, under complete matching: (a) 0.1 [km] and e^{α} (resp. line length and gain), (b) 0.5 [km] and e^{α}, (c) 0.1 [km] and $K_c e^{\alpha}$, (d) 0.5 [km] and $K_c e^{\alpha}$.

Next, the influence of mismatching on BER is investigated. For lossless transmission line, the reflection waveforms caused by mismatching go back and forth over the line without attenuation, consequently they pollute the received signal $s'(t)$. However it can be expected that the output $s''(t)$ of LPF does not so receive damage compared with $s'(t)$. The time waveforms for 5% matching error, amplitude 0.3 [V] and bit rate 10^3 [bps] are shown in Fig. 12. It is found from the figure that the reflection waveforms due to mismatching pollute the recovered signal $s'(t)$. However the output $s''(t)$ of LPF does not receive damage compared with $s'(t)$, thus the LPF is also effective to check the effect of mismatching. Figure 13 indicates BER versus matching

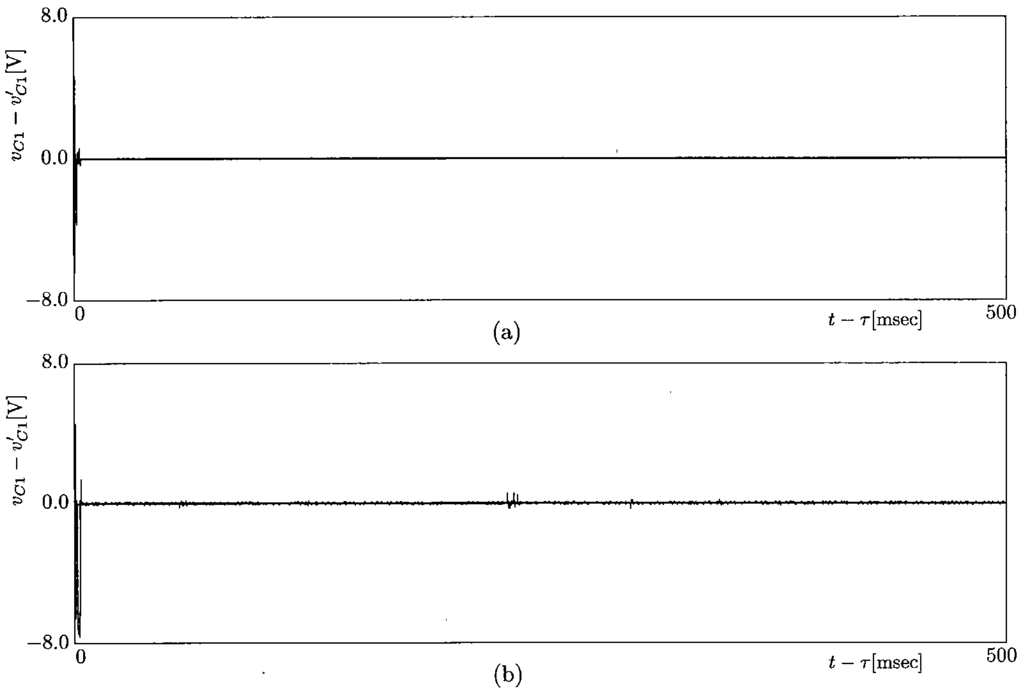


Fig. 8 Compensation using the adaptive controller, under complete matching: (a) 0.1 [km], (b) 0.5 [km].

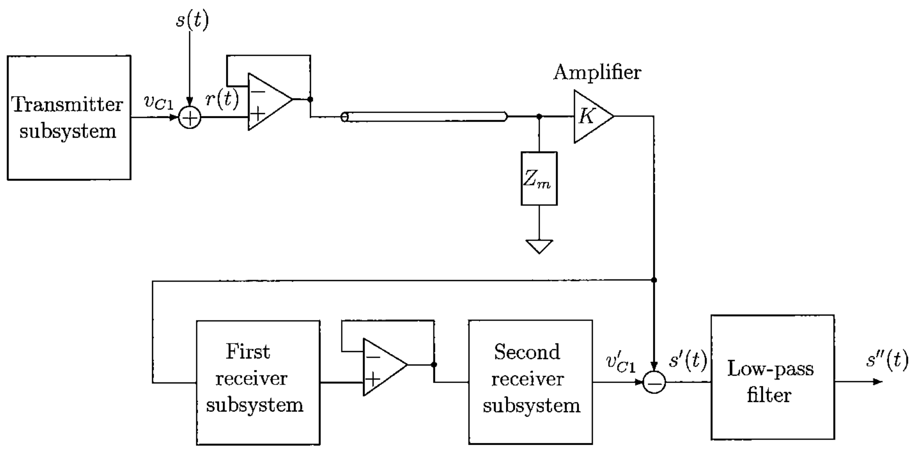


Fig. 9 Block diagram of digital communication system based on chaotic masking.

error. BER becomes worse as matching error increases, as expected. In this case bit data with smaller amplitude is more affected by mismatching, so that BER gets worse as amplitude decreases in contrast to the ideal case. The BER will not be improved unless the amplitude of chaotic signal v_{C1} is made small, because the amplitude of the reflected signal depends on that of the transmitting signal and matching error.

From now, we investigate the effect of loss under the condition that matching is perfect. The amplitude and bit rate are hereafter fixed as 0.1 [V] and 10^3 [bps], respectively. Since the adaptive controller [8] can not be used for chaotic masking scheme, the cases in which the attenuated (received) signal is not amplified (i.e., $K = 1$) and in which it is amplified by the amplifier with gain $K = e^{\alpha}$ and $K = K_c e^{\alpha}$, are examined for different line length (loss). Where K_c is introduced to achieve the smallest possible desynchronization as before, and the values of N and K_c are (5, 1.008), (25, 1.035) and (50, 1.06) which correspond to the length 0.1, 0.5 and 1.0 [km], respectively. BER's for these cases versus line length are given in Fig. 14. For the case of non-amplification, the BER is pretty bad, while amplification according to transmission length improves BER. In particular, when amplification is optimal BER is little changed independently of length. Finally the influ-

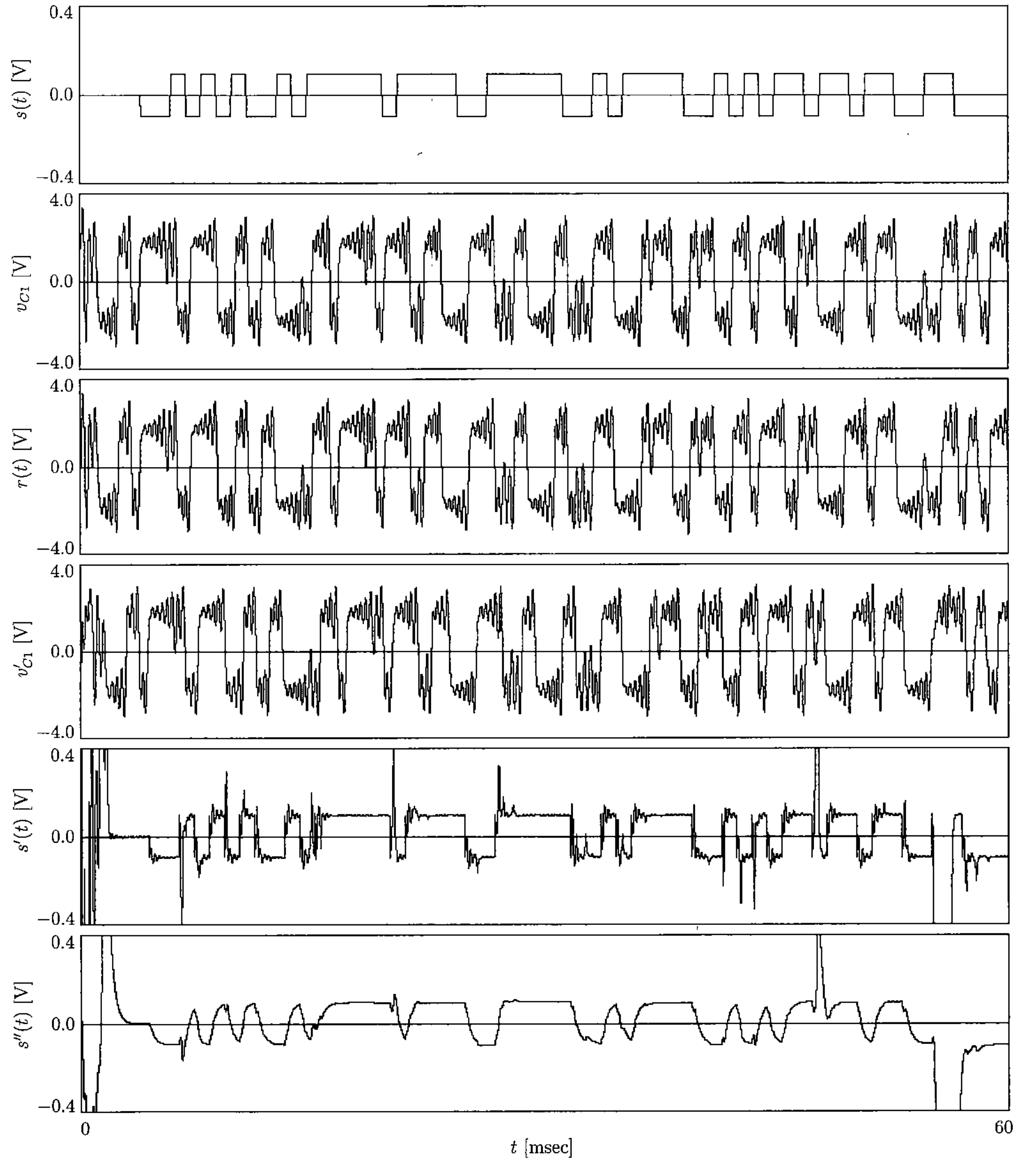


Fig. 10 Time waveform of each signal in the digital communication system with ideal (or completely matched lossless) transmission line. amplitude = 0.1 [V] and bit rate = 1000 [bps].

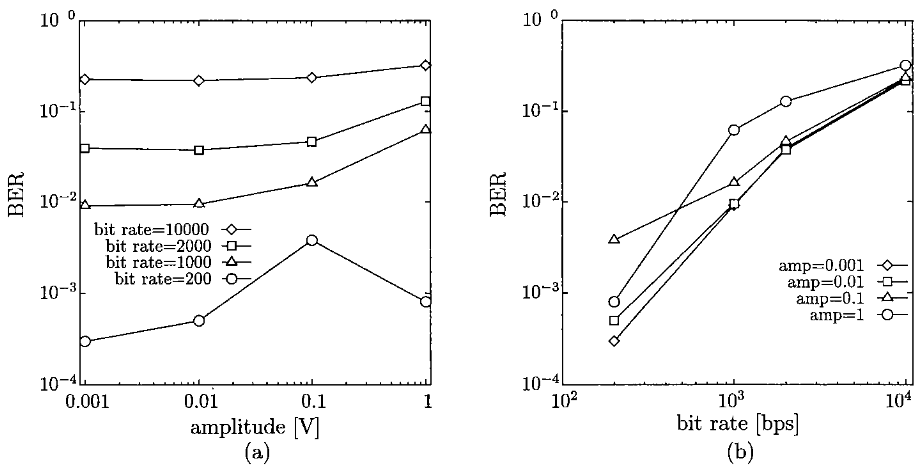


Fig. 11 BER versus (a) amplitude and (b) bit rate for ideal transmission line.

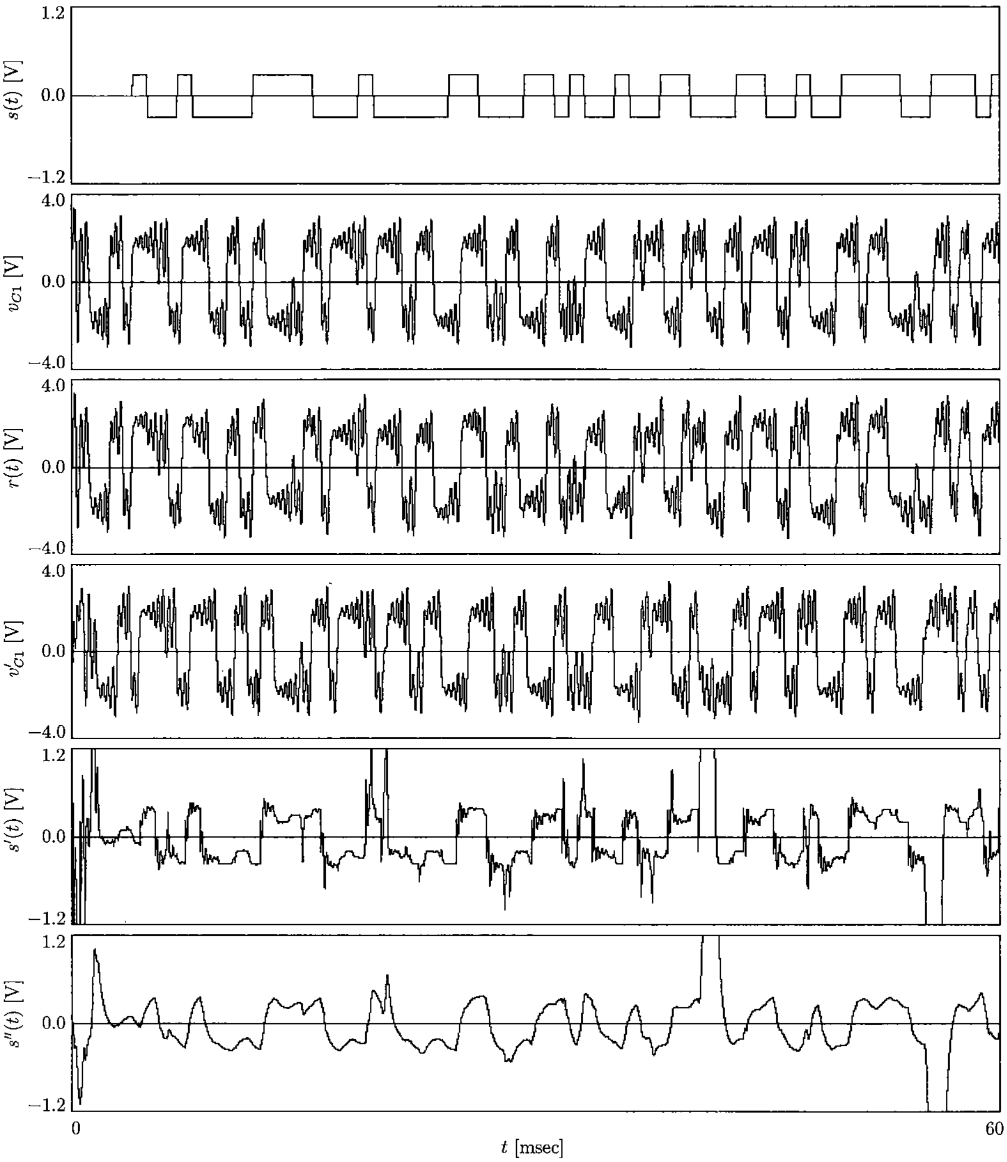


Fig. 12 Time waveform of each signal for lossless line and matching error 5%. amplitude $= 0.3$ [V] and bit rate $= 1000$ [bps].

ence of mismatching is considered again. BER versus mismatching for the case of gain $K = K_c e^{\alpha}$ is shown in Fig. 15. Compared with the case of lossless line, BER does not become so worse. However, even for lossy transmission line, the effect of mismatching is serious. This will be overcome to some extent by inserting an additional matching impedance at the transmitting side of the transmission line.

In summary, bit rate of bit string must be small to get good BER in our system. Bit data with smaller amplitude is more affected by loss and mismatching, although it is suitable for security. Thus amplitude will have to be determined by the trade-off between BER and security. In real digital communication system, also, bit rate required is greater than 10^4 [bps], however in our system increasing bit rate will not be proper from the point of BER. In order to increase bit rate without affecting BER, thus, it will be needed to increase the natural frequency of Chua's circuit about 2 order. Further, as BER required for practical communication is at least less than 10^{-4}, an error-correcting code will have to be introduced for practical application of this system.

6. Conclusion

In this paper we have presented some new results for analog hardware implementation of chaotic communication system. In particular our attention has been devoted to the use of transmission line as channel. The influence of the loss of transmission line and mis-

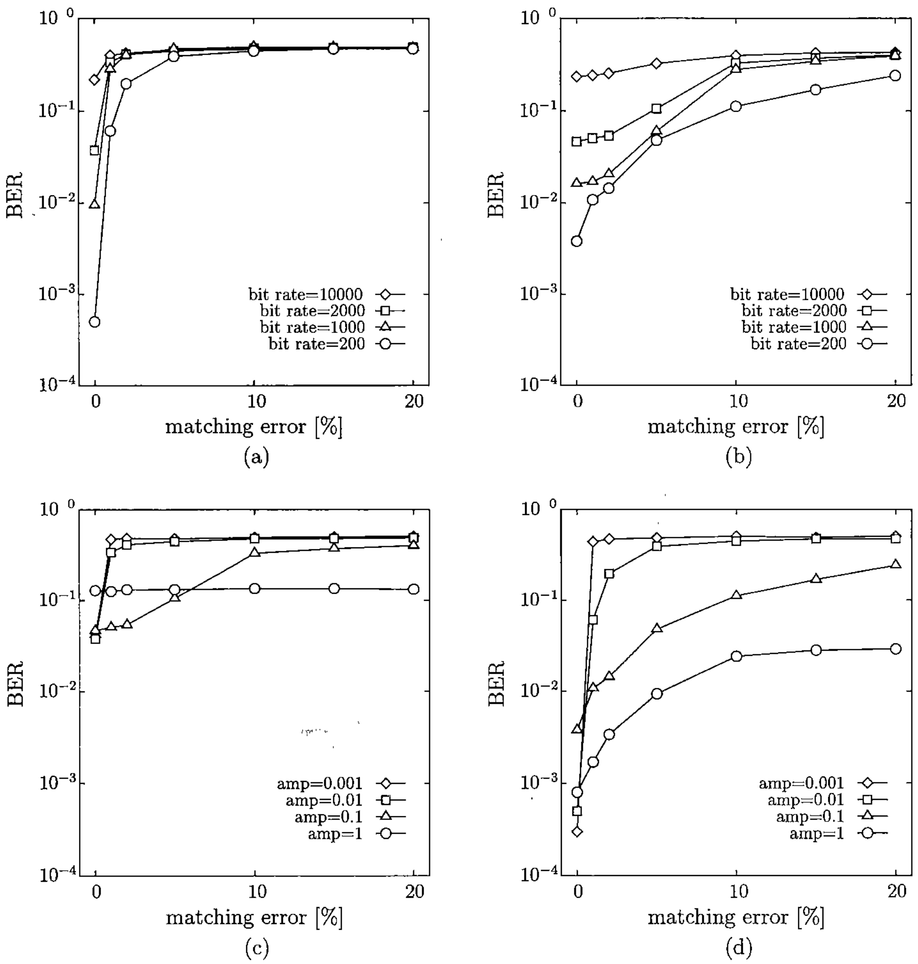


Fig. 13 BER versus mismatching for lossless transmission line. (a) amplitude = 0.01 [V], (b) amplitude = 0.1 [V], (c) bit rate = 2000 [bps], (d) bit rate = 200 [bps].

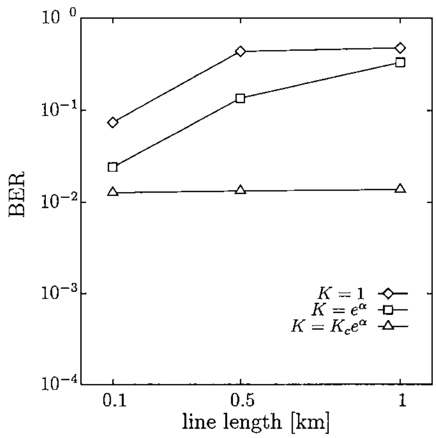


Fig. 14 BER versus line length l for lossy transmission line with complete matching.

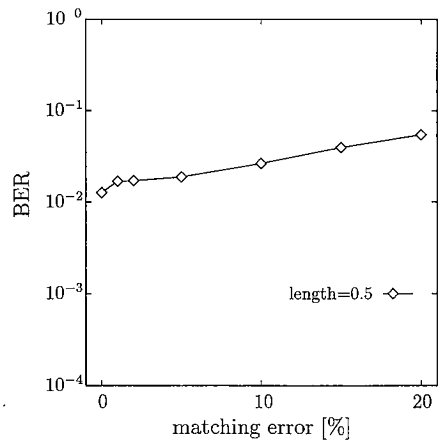


Fig. 15 BER versus mismatching for 0.5 [km] lossy transmission line.

matching on synchronization has been investigated in a transmitter-receiver system using chaos synchronization. It has been shown that desynchronization due to loss can be compensated by the use of an amplifier with suitable gain. This will hold true for other chaotic communication systems using transmission line. Also the bit error rate (BER) to various conditions has been evaluated in a digital communication system based on chaotic masking. Further we have discussed on the conditions of bit data transmitted for practical implementation of our system.

We will have to investigate the influence of noise and parameter mismatching of transmitter and receiver, and consider a mean to adjust the gain of amplifier automatically (or an adaptive controller) for chaotic masking systems. Also we want to examine BER for the other chaotic communication systems.

References

[1] L.M. Pecora and T.L. Carroll, "Synchronization in chaotic systems," Phys. Rev. Lett., vol.64, no.4, pp.821–824, Feb. 1990.

[2] L. Kocarev, K.S. Halle, K. Eckert, and L.O. Chua, "Experimental demonstration of secure communication via chaotic synchronization," Int. J. Bifurcation & Chaos, vol.2, no.3, pp.709–713, Sept. 1992.

[3] H. Dedieu, M.P. Kennedy, and M. Hasler, "Chaos shift keying: Modulation and demodulation of a chaotic character using self-synchronizing Chua's circuits," IEEE Trans. Circuits & Syst. II, vol.40, no.10, pp.634–642, Oct. 1993.

[4] H. Kamata, T. Endo, and Y. Ishida, "Secure communication system using chaos via DSP implementation," Proc. of IEEE ISCAS'96, vol.3, pp.112–115, May 1996.

[5] T.L. Carroll and L.M. Pecora, "The effect of filtering on communication using synchronized chaotic circuits," Proc. of IEEE ISCAS'96, vol.3, pp.174–177, May 1996.

[6] R. Caponetto, L. Fortuna, M. Lavorgna, G. Manganaro, and L. Occhipinti, "Experimental study on chaos synchronization with non-ideal transmission channel," Proc. of IEEE GLOBECOM'96, pp.2083–2087, 1996.

[7] P. Celka, "Synchronization of chaotic optical dynamical systems through 700 m of single mode fiber," IEEE Trans. Circuits & Syst., vol.43, no.10, pp.869–872, Oct. 1996.

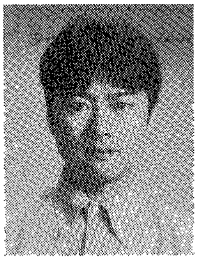
[8] L.O. Chua, T. Yang, G. Zhong, and C.W. Wu, "Synchronization of Chua's circuits with time-varying channels and parameters," IEEE Trans. Circuits & Syst., vol.43, no.10, pp.862–868, Oct. 1996.

[9] F.H. Branin, Jr., "Transient analysis of lossless transmission line," Proc. IEEE, vol.55, pp.2012–2013, 1967.

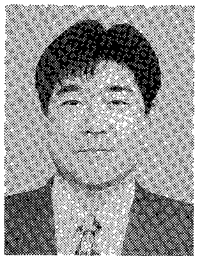
[10] H.W. Dommel, "Digital computer solution of electromagnetic transients in a single or multiphase networks," IEEE Trans. Power App. & Syst., vol.PAS-88, pp.388–399, 1969.

[11] R. Gupta and L.T. Pileggi, "Modeling lossy transmission lines using the method of characteristics," IEEE Trans. Circuits & Syst., vol.43, no.7, pp.580–582, July 1996.

[12] L.O. Chua, "Chua's circuit: Ten years later," IEICE Trans. Fundamentals, vol.E77-A, no.11, pp.1811–1821, Nov. 1994.

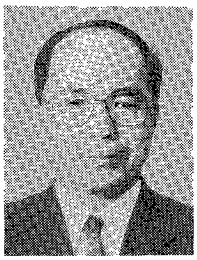


Junji Kawata was born in Kagawa, Japan, on 1967. He received the B.E. and M.E. degrees form Tokushima University, Tokushima, Japan, in 1990, 1992, respectively. He is currently working towards the Ph.D. degree. His research interests is in circuit simulation and chaotic communication. Mr. Kawata is a member of the IEEE.



Yoshifumi Nishio received the B.E., M.E., and Ph.D. degrees in electrical engineering from Keio University, Yokohama Japan, in 1988, 1990, and 1993, respectively. In 1993, he joined the Department of Electrical and Electronic Engineering at Tokushima University, Tokushima Japan, where he is currently an Associate Professor. His research interests are in chaos and synchronization phenomena in nonlinear circuits. Dr. Nishio is a member of the IEEE.

Hervé Dedieu received his Ph.D. degree from the Institute National Polytechnique de Toulouse, France, in 1988. From 1984 to 1988 he worked with the Signal Processing Laboratory of the Ecole Nationale Superieure d'Electronique, d'Electrotechnique et d'Hydraulique de Toulouse where his research was concentrated on adaptive filtering. During the same period he worked also as a contractual engineer for the French Spatial Agency (CNES). In 1989 he joined the Circuits and Systems group of the Swiss Federal Institute of Technology in Lausanne where his research interests include identification of nonlinear systems, applications of nonlinear dynamics in signal processing and speech recognition. He co-authored two books "Electrical Filters" with C. Dehollain, M. Hasler and J. Neirynck and "Nonlinear Effects in Digital Filters" with R. Boite and M. Hasler (in French, Ed. Presses Polytechniques Romandes). He is currently lecturer at the Swiss Federal Institute of Technology of Lausanne.



Akio Ushida received the B.E. and M.E. degrees in electrical engineering from Tokushima University in 1961 and 1966, respectively, and the Ph.D. degree in electrical engineering from University of Osaka Prefecture in 1974. He was an associate professor from 1973 to 1980 at Tokushima University. Since 1980 he has been a Professor in the Department of Electrical Engineering at the university. From 1974 to 1975 he spent one year as a visiting scholar at the Department of Electrical Engineering and Computer Sciences at the University of California, Berkeley. His current research interests include numerical methods and computer-aided analysis of nonlinear system. Dr. Ushida is a member of the IEEE.