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EXPERIMENTS ON RF BAND COMMUNICATIONS USING CHAOS

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This paper presents experimental results of wire-line and wireless analog information transmission in RF band via chaos using standard signal formation and reception methods.

1. Introduction

A number of approaches to the design of communications systems with chaos have recently been proposed [Kocarev *et al.*, 1992; Belsky & Dmitriev, 1993; Cuomo *et al.*, 1993; Dedieu *et al.*, 1993; Halle *et al.*, 1993; Volkovskii & Rul'kov, 1993]. Low-frequency physical experiments demonstrating a principle possibility of such system realization have also been made [Kocarev *et al.*, 1992; Bohme *et al.*, 1994; Dmitriev *et al.*, 1994, 1995; Delgado-Restituto *et al.*, 1995].

The main element of the mentioned systems is a chaotic module devoted to form the chaotic signal and to introduce information into the transmitter signal, and at the same time, to retrieve the information in the receiver. One of the most important operation requirements to the majority of the known systems is the equality of the chaotic module parameters in the transmitter and receiver [Belsky & Dmitriev, 1995]. This is associated with the necessity to obtain in the receiver an exact copy of the signal formed in the transmitter (synchronous response) [Pecora & Carroll, 1990]. A question then arises: Can the synchronous response, hence, information retrieval, be achieved in real conditions, i.e. by using developed chaotic modules in RF-band communications systems? The problem is that in such systems the signal undergoes a number of additional manipulations (modulation, heterodyning, detection, amplification, etc.) which can lead to distortions, regarding the complex structure of the formed signal and essentially nonlinear characteristics of system functional elements.

This paper describes the experiments on speech signal transmission in RF band on example of a chaotic module with nonlinear information mixing [Dmitriev *et al.*, 1994, 1995].

The structure of the paper is as follows. First we describe the structure of a communications system employing dynamic chaos. Then we derive a mathematical model of the communications system and analyze computer modeling results. The last section is devoted to experiments on communications in the RF band.

2. Communications System Structure

The structure that we have chosen for the communications systems was close to the classical one (Fig. 1).

In the transmitter, low-frequency information signal from the microphone is fed to the chaotic

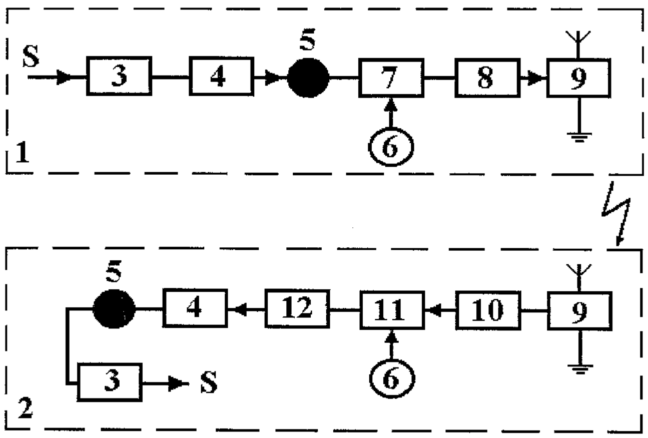


Fig. 1. The structure of the communication system. It includes transmitter 1, receiver 2, microphone 3, low-frequency amplifier 4, chaotic module 5, RF carrier oscillations generator 6, modulator 7, power amplifier 8, antenna 9, selective amplifier 10, demodulator 11, low-frequency filter 12, information signal S.

model input. In the chaotic module, the information signal is nonlinearly mixed to the chaotic signal. The module output signal, a mixture of chaotic and information signals, modulates the amplitude of RF-band oscillations. The oscillations are then amplified and transmitted.

In the receiver, the radio signal received by antenna is selectively amplified, demodulated and passed through a low-pass filter. By filtering, the signal is cleaned of the components lying outside the chaotic module frequency band. The receiver chaotic module extracts the information signal from the mixture.

Thus the communications system structure differs from the classical one only by the presence of additional elements, i.e. chaotic modules in the transmitter and receiver. This fact allows us to extensively use standard radioengineering devices in the experiments.

Formally, in a chaotic AM communications system, if one will transmit a mixture of information signal with low-frequency chaotic signals instead of the information signal using, e.g. a chaotic transmission module [Dmitriev *et al.*, 1994, 1995], then in the receiver one can extract the information component by means of the synchronous response of the chaotic receiving module. In practice however, there are difficulties. As is known, in communications systems based on synchronous response in the receiver (an example of such a system is the system with nonlinear mixing of information that we discuss in this paper), tough conditions should be fulfilled on the equality of chaotic module parameters in the receiver and transmitter.

In low-frequency experiments, this problem is solved by careful selection and tuning of circuits elements. However, when signals are carried up to the RF band and back, they undergo a set of additional manipulations (amplification, modulation, filtering, demodulation, etc.). Each of these manipulations leads to additional distortions, and inhibits formation in the receiver of an exact copy of the signal formed in the transmitter.

Hence, transmission of speech signals imposes tougher restrictions on the accuracy of to and back manipulations, then in a low-frequency system. Practically, total signal distortion along the entire manipulation path should not exceed 1–2%.

Another distorting factor is the presence of additive noises in the channel.

In the next section we discuss the model of the communications system and estimate the effect of various perturbing factors on its characteristics.

3. Mathematical Model and Computer Simulation

There are two frequency scales in the discussed communications system: Low frequencies (to several kilohertz) characteristic of information signals and chaotic module oscillations, and high frequencies (tens of MHz) of RF oscillations. Low-frequency signals modulate high-frequency oscillations. By analysis of dynamic properties of standard radio systems, "slow variables" describing the high-frequency signal envelope are introduced, and corresponding differential equations are investigated.

In our case, we consider a low-frequency model as a mathematical model of the communications system, i.e. a model describing the dynamics of transmitting and receiving chaotic modules both in the absence and presence of the information signal. Such a model allows us to analyze the main dynamic characteristics of the communications system depending on the chaotic module properties. At the same time, it does not account for the effect of various signal manipulations on the system dynamics, that are made outside the chaotic modules in the transmitter and receiver. In order to estimate the potential results of these effects on the system operation, we model the manipulation and communications channel tolerances by introducing special perturbations: signal filtering, nonlinear distortions, and additive noises.

3.1. *Chaotic modules*

The communications system employs nonlinear mixing of information and chaotic signals in the transmitter chaotic module with subsequent information restored in the receiver by means of synchronous response formation. The basic element of the chaotic module in the chaos generator obtained by decomposition of Chua's circuit [Madan, 1993] into two subsystems (RLC and $\mathrm{RCN_R}$) [Figs. 2(b)

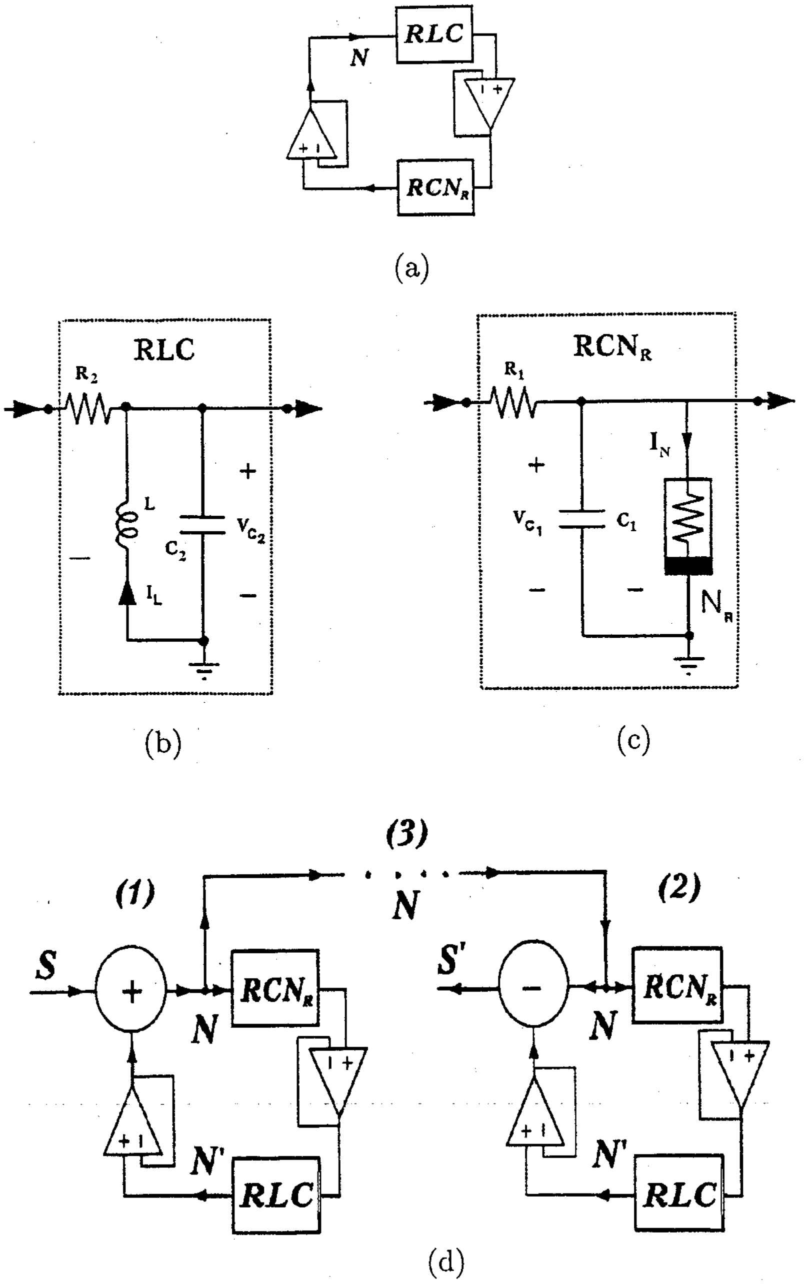


Fig. 2. (a) Block-diagram of the chaotic generator. It includes subsystem RLC and subsystem $\mathrm{RCN_R}$. The triangular symbols are voltage buffers (op amp). (b) RLC subsystem. The values of the parameters (in the experiments) are: $L = 40$ mH, $C_2 = 100$ nF, $R_2 = 1.9$ kΩ. (c) $\mathrm{RCN_R}$ subsystem. The values of the parameters (in the experiments) are: $R_1 = 1.9$ kΩ, $C_1 = 15$ nF. $\mathrm{N_R}$ — nonlinear element with a three-segment piecewise-linear V–I characteristic, based (in the experiments) on Kennedy's two-operational amplifiers circuits [Kennedy, 1992]. The parameter values for this circuit are: $m_0 = -0.459$ mS, $m_1 = -0.757$ mS, $B_p = 1.56$ V. (d) Block-diagram of the communication system. It consist of a transmitter 1, a receiver 2 and a communication channel 3. The transmitter contains a summer (+), RLC and $\mathrm{RCN_R}$. The receiver contains a subtractor (−), RLC and $\mathrm{RCN_R}$. S — input information signal, S' — recovered information signal, N — transmitted signal.

and (c)] which are connected in series and closed in a loop [Fig. 2(a)]. Subsystem RLC is a band-pass filter and subsystem $\mathrm{RCN_R}$ is a low-frequency first-order filter loaded at a nonlinear resistance $\mathrm{N_R}$ with three-segment piecewise-linear voltage–current characteristics [Madan, 1993]:

$$I_N(V_{C1}) = G_{\mathrm{b}}V_{C1} + \frac{1}{2}(G_{\mathrm{b}} - G_{\mathrm{a}}) \times [|V_{C1} + E| - |V_{C1} - E|]\,, \qquad (1)$$

where I_N and V_{C1} are the current through and the voltage across the resistance, and G_{a}, G_{b} and E are constants. Buffer amplifiers (unit gain, high input and low output resistances) between the blocks play the role of insulators and provide unidirectional feedback loop in the generator.

Dynamic modes of the generator are described by the following system of differential equations:

$$\begin{aligned} C_1(dV_{C1}/dt) &= (V_{C2} - V_{C1})/R_1 - I_N(V_{C1}) \\ C_2(dV_{C2}/dt) &= (V_{C1} - V_{C2})/R_2 + I_L \qquad (2) \\ L(dI_L/dt) &= -V_{C2}\,. \end{aligned}$$

Resistances R_1 and R_2 are control parameters of the generator oscillation modes. With $R_1 = R_2 = R$, Eqs. (2) coincide with the equations for the canonical Chua's circuit [Madan, 1993].

The "double scroll" attractor mode (Fig. 3) was taken as a basic mode for the further investigations. The mode takes place at the parameter values set at $G_{\mathrm{b}} = -0.714$ mS, $G_{\mathrm{a}} = -1.143$ mS, $E = 1$ V, $L = 0.0625$ H, $C_2 = 1$ F, $C_1 = 0.10204$ F, $1/R_1 = 1/R_2 = 1$ S.

The communications system structure is presented in Fig. 2(d). It comprises a transmitter (transmitting chaotic module) 1, a receiver (receiving chaotic module) 2, and a communications channel 3 between them. The transmitting chaotic module is built from the initial chaos generator [Fig. 2(a)] by means of adding a summer (+) into the feedback loop. The receiver chaotic module is based on a copy of the same generator, with the feedback loop disconnected and a subtractor added (−). In the case of identical main elements of the transmitter and receiver circuits, the system operation is described by the following equations:

$$\begin{aligned} C_1(dV_{C1}/dt) &= (V_{C2} + S - V_{C1})/R_1 - I_N(V_{C1}) \\ C_2(dV_{C2}/dt) &= (V_{C1} - V_{C2})/R_2 + I_L \\ L(dI_L/dt) &= -V_{C2}\,. \end{aligned}$$

$$\begin{aligned} C_1(dV'_{C1}/dt) &= (V_{C2} + S - V'_{C1})/R_1 - I_N(V'_{C1}) \\ C_2(dV'_{C2}/dt) &= (V'_{C1} - V'_{C2})/R_2 + I'_L \qquad (3) \\ L(dI'_L/dt) &= -V'_{C2}\,. \end{aligned}$$

where S is an information signal fed to the transmitter, and

$$S' = V_{C2} + S - V'_{C2}$$

is a signal retrieved in the receiver, (V_{C1}, V_{C2}, I_L) and (V'_{C1}, V'_{C2}, I'_L) are voltages across capacitances

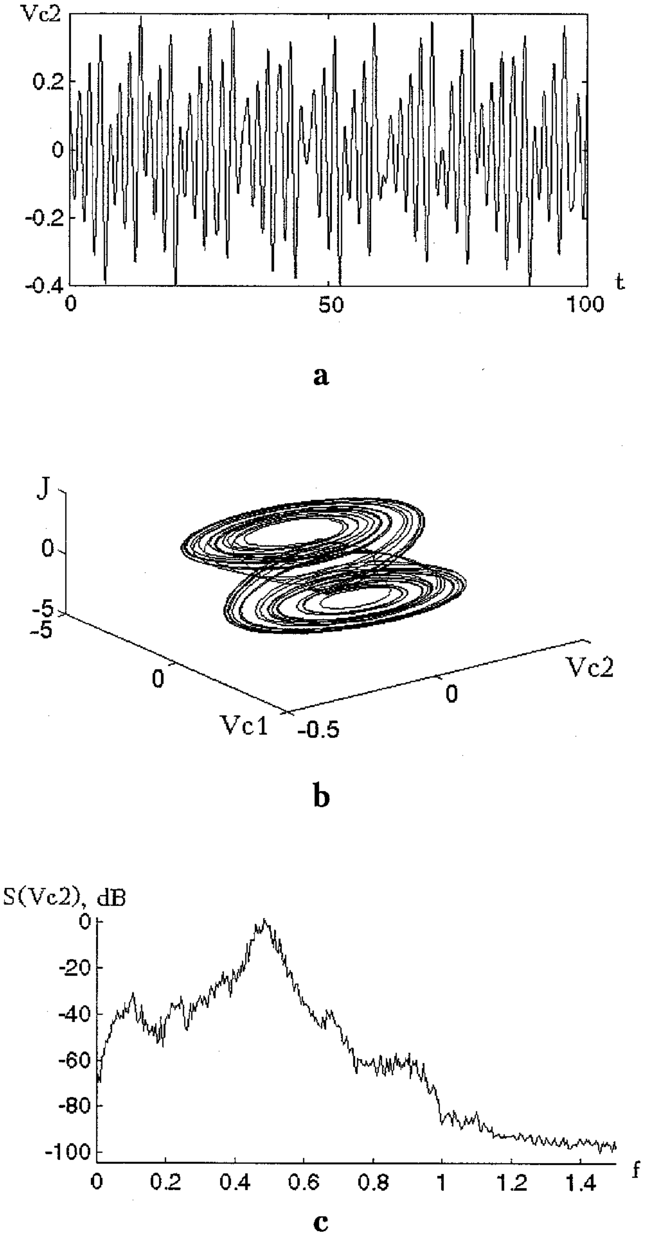
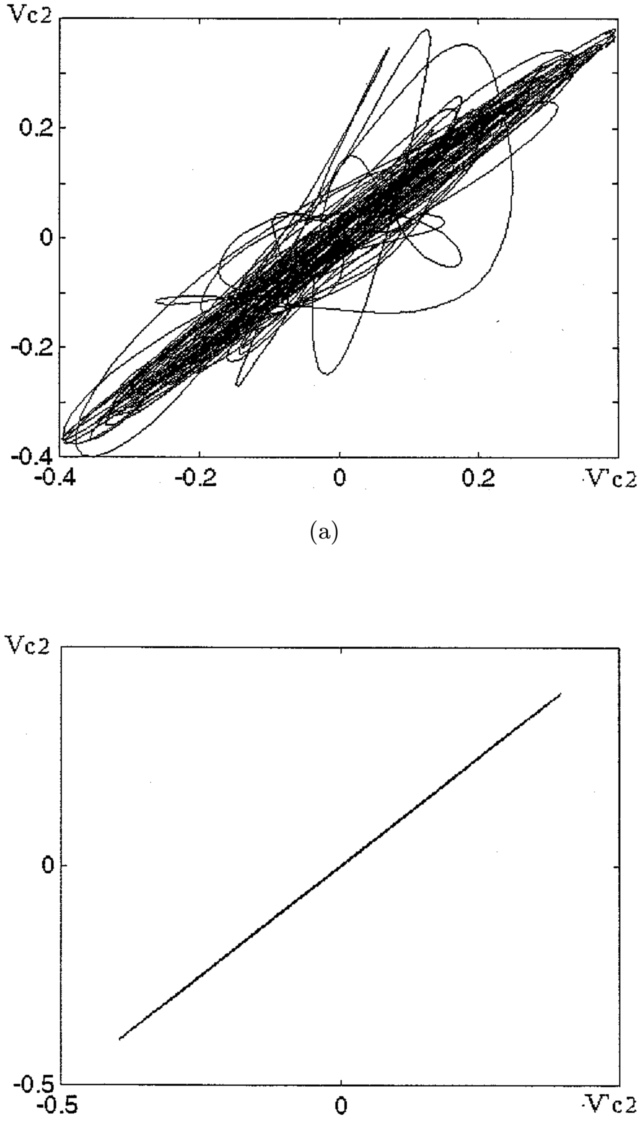


Fig. 3. Basic attractor mode of the chaotic generator. (a) Chaotic signal (V_{C2}). (b) Phase portrait of the generator signal in the (V_{C1}, V_{C2}, I_L) plane. (c) The power spectrum of the chaotic signal V_{C2}.

C_1 and C_2 and current through inductance L in the transmitter and receiver respectively, and $I_N(V_{C1})$ is a piecewise-linear current–voltage characteristics (1) of the nonlinear element $\mathrm{N_R}$.

The first three equations correspond to the transmitter, the other three to the receiver.

If the conditions for synchronous chaotic response are satisfied in the system, then $V_{C2} = V'_{C2}$ [Fig. 4(b)] and $S' = V_{C2} + S - V'_{C2} = S$. If the response is desynchronized [Fig. 4(a)], the output signal S' is a complex mixture of the information and chaotic signals.



(a)

(b)

Fig. 4. Chaotic response in the (V_{C2}, V'_{C2}) plane. (a) Desynchronized response. (b) Synchronous response.

3.2. *Synchronous response and on-off intermittency*

The necessary and sufficient conditions for synchronous chaotic response in the receiver are:

1. the trajectory $(V_{C1}, V_{C2}, I_L) = (V'_{C1}, V'_{C2}, I'_L)$ should exist;
2. the system motion (3) along this trajectory should be stable with respect to any small, transversal to the attractor, perturbations.

A trajectory satisfying the first condition is chaotic and belongs to the chaotic attractor. The motion at the attractor is characterized with exponential, in average, divergence of trajectories. At the same time, the attractor has a basin of attraction, and all trajectories starting from this basin attract to it. Consequently, sufficiently small perturbations do not destroy the attractor, i.e. it is stable with respect to small perturbations.

A necessary condition for the attractor stability is the negative value of the second Lyapunov exponent of system (3): $\lambda_2 < 0$. This condition guarantees that the trajectory, averaged over the attractor, will attract to it. Direct calculations show that the system (3) in "double scroll" mode has $\lambda_2 = -0.498 < 0$, i.e. the necessary condition for the existence of the synchronization mode attractor is fulfilled. However, there can be some special trajectories in the attractor with the condition $\lambda_2 < 0$ broken. Therefore the attractor can prove to be unstable by small transversal perturbations. This potential danger is inevitable, e.g. if the attractor's attraction basin has a positive Lesbesque measure but is not an open set. In this case, deviations of the receiver parameters with respect to the transmitter parameters or a low-amplitude noise added to the signal at the receiver input will lead to the effect of on-off intermittency [Platt *et al.*, 1993; Heagy *et al.*, 1994]. Calculations show that in the case of equal parameters of the transmitter and receiver and in the absence of additive noise, ideal synchronization is established in the system. However, in the case of perturbed parameters or additive noise in the channel, on-off intermittency actually occurs [Figs. 4(a) and 7(a)].

In order to find the reasons for this phenomenon, consider the system dynamics (3) near the synchronization attractor, whose trajectory satisfies the above conditions. Assume the trajectories

(V_{C1}, V_{C2}, I_L) and (V'_{C1}, V'_{C2}, I'_L) be close, and introduce new variables

$$\begin{aligned} V''_{C1} &= V'_{C1} + \delta V_{C1} \\ V''_{C2} &= V'_{C2} + \delta V_{C2} \\ I''_L &= I'_L + \delta I_L \end{aligned}$$

and transform the equation system by applying variables (V_{C1}, V_{C2}, I_L) and $(V''_{C1}, V''_{C2}, I''_L)$ as follows

$$\begin{aligned} C_1(dV_{C1}/dt) &= (V_{C2} - V_{C1})/R_1 - I_N(V_{C1}) \\ C_2(dV_{C2}/dt) &= (V_{C1} + S - V_{C2})/R_2 + I_L \\ L(dI_L/dt) &= -V_{C2}\,. \qquad (4) \\ C_1(d\delta V_{C1}/dt) &= (V_{C2} + S - \delta V_{C1})/R_1 - I_N(V_{C1}) \\ C_2(d\delta V_{C2}/dt) &= (\delta V_{C1} - \delta V_{C2})/R_2 + \delta I_L \\ L(d\delta I_L/dt) &= -\delta V_{C2}\,. \end{aligned}$$

The first three equations of (4) coincide with the first three of system (3). The other equations, linear with variable coefficients, describe small deviations of the trajectories of the "transmitter-receiver" system from the synchronization attractor. If a trajectory belongs to the attractor, $\delta V_{C1} = \delta V_{C2} = \delta I_L = 0$.

Consider the stability conditions for the solution $\delta V_{C1} = \delta V_{C2} = \delta I_L = 0$. The problem can be reduced to calculation of coefficient matrix eigenvalues for the last three linear equations of system (4). Formally,

$$M = \begin{pmatrix} -\dfrac{1}{C1}\left(\dfrac{1}{R1} + \dfrac{\partial I_N(V'_{C1})}{\partial V'_{C1}}\right) & 0 & 0 \\ \dfrac{1}{R2 \cdot C2} & -\dfrac{1}{R2 \cdot C2} & \dfrac{1}{C2} \\ 0 & -\dfrac{1}{L} & -\dfrac{R0}{L} \end{pmatrix} \qquad (5)$$

is a matrix with variable coefficients, which are determined by the nonlinear element characteristics. Since the characteristics is piecewise-linear, the coefficients can have the values only from two fixed sets:

$$M_{\mathrm{a}} = \begin{pmatrix} -\dfrac{(1/R1 + G_{\mathrm{a}})}{C1} & 0 & 0 \\ \dfrac{1}{R2 \cdot C2} & -\dfrac{1}{R2 \cdot C2} & \dfrac{1}{C2} \\ 0 & -\dfrac{1}{L} & -\dfrac{R0}{L} \end{pmatrix} \qquad (6)$$

and

$$M_{\mathrm{b}} = \begin{pmatrix} -\dfrac{(1/R1 + G_{\mathrm{b}})}{C1} & 0 & 0 \\ \dfrac{1}{R2 \cdot C2} & -\dfrac{1}{R2 \cdot C2} & \dfrac{1}{C2} \\ 0 & -\dfrac{1}{L} & -\dfrac{R0}{L} \end{pmatrix} \qquad (7)$$

Matrix eigenvalues for the first set (corresponding to the phase space part containing the origin) are $\alpha_1 = 1.4014$, $\alpha_2 = -0.5000 + 3.9686\mathrm{i}$, and $\alpha_3 = -0.5000 - 3.9686\mathrm{i}$, i.e. have both positive and negative real parts. For the second set (phase space part related to outer segments of the nonlinear element characteristics) $\alpha_1 = -2.8028$, $\alpha_2 = -0.5000 + 3.9686\mathrm{i}$, and $\alpha_3 = -0.5000 - 3.9686\mathrm{i}$. Thus, the system trajectory is stable with respect to small transversal perturbations when goes through the phase space part corresponding to matrix M_{b}, and is not stable when it is in the phase space region corresponding to matrix M_{a}. Hence the synchronization attractor is not absolutely stable with respect to transversal perturbations, and this is the cause of the effect of on-off intermittency occurring by deviation of the transmitter parameters from those of the receiver.

3.3. *Transmission of analog information*

Calculations of system (3) with identical parameters of the transmitter and receiver were performed with one-frequency (tone) signals

$$S(t) = A\,\cos(2\pi f t) \qquad (8)$$

and multi-frequency (frequency-modulated, FM) signals

$$S(t) = A\,\sin(2\pi f_0 t - \psi_m \cos(2\pi F t))\,, \qquad (9)$$

where f_0 is the signal spectrum mean frequency, ψ_m is FM index, and $F = 0.1 f_0$.

3.3.1. *Tone signal*

We performed modeling of a communications system with sinusoidal oscillations used as information signals. The ratio of the information signal power P_S to the chaotic signal power P_N

$$\mu = P_S/P_N \qquad (10)$$

was varied in the range 10^{-6} to 10^{-2}, and the frequency f was varied from 0.1 to 0.6. The frequency

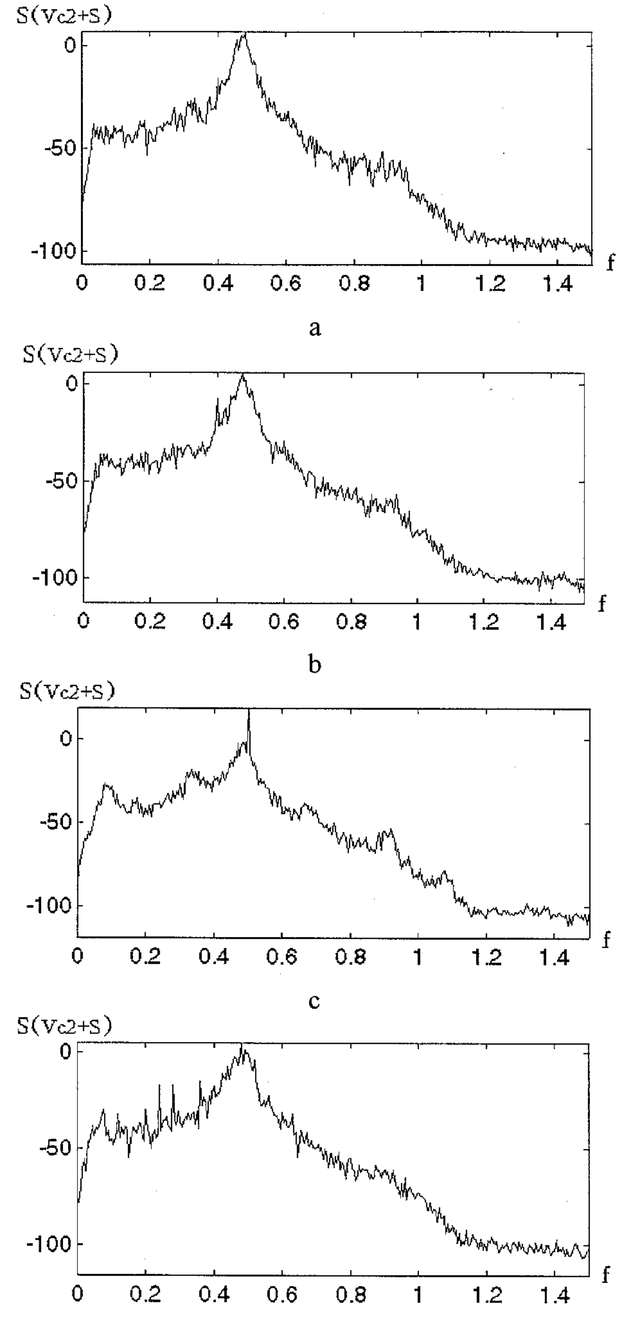


Fig. 5. The power spectra of the transmitted signal with input information signal. (a), (b), (c) Sinusoidal signal $S(t) = A\cos(2\pi ft)$ is input signal. [(a) $A = 2\cdot 10^{-2}$, $f = 0.4$; (b) $A = 2.5\cdot 10^{-2}$, $f = 0.4$; (c) $A = 2\cdot 10^{-2}$, $f = 0.5$). (d) Frequency modulated signal $S(t) = A\sin(2\pi f_0 t - \psi_m \cos(2\pi Ft)]$ (where $A = 2.5\cdot 10^{-2}$, $f_0 = 0.4$ is the signal spectrum mean frequency, $\psi_m = 0.3$ is FM index, and $F = 0.1 f_0$) is input signal.

$f = 0.6$ corresponds to normalized upper bound frequency of the chaotic signal [Fig. 3(c)].

When the sinusoidal signal was mixed in at $\mu > 10^{-2}$, the system trajectory, as a rule, rapidly went to infinity. So, the value of $\mu \approx 10^{-2}$ sets an upper admissible limit of the introduced sinusoidal signal power.

The calculations have shown that within the entire range of the parameter variation, the signal is retrieved in the receiver without distortions. In particular, "perturbation" of the transmitter dynamics by the information signal mixing does not lead to on-off intermittency.

In Figs. 5(a)–5(c) the power spectra of the mixture of chaotic and information signals fed to the receiver input are presented. As follows from these figures, the spectrum form is very sensitive to the introduced signal. For example, if the introduced signal frequency is far from the chaotic signal characteristic peaks, then its presence becomes visible at $\mu \approx 10^{-4}$ [Fig. 5(b)]. If the introduced signal frequency is close to a characteristic spectral peak of chaotic oscillations, then its presence becomes noticeable at $\mu \approx 10^{-5}$ [Fig. 5(c)] due to the effect of resonant amplification of the information signal.

3.3.2. *FM signal*

FM signal has a discrete power spectrum, so it better imitates the speech signal structure than the sinusoidal signal.

The calculations have shown that the maximum power of the introduced information signal, at which the system trajectory still remains in a finite zone of the phase space, is $\mu \approx 4\cdot 10^{-2}$, i.e. approximately four times higher here that in the case of sinusoidal signal.

As in the previous case, the information signal is retrieved without distortions in the receiver (Fig. 6).

Power spectra of the chaotic and information signal mixture at the receiver input are less sensitive to the introduced signal than in the case of tone signal: The components of information signal spectrum become noticeable only at $\mu \geq 2\cdot 10^{-2}$ [Fig. 5(d)].

3.4. *Communications quality estimation*

Nonideality (desynchronization) of chaotic response leads to a noise at the receiver output. This noise is the main cause of the received signal degradation. Therefore, in order to estimate the quality of communications, we use the ratio of the information signal power at the receiver output P_S to

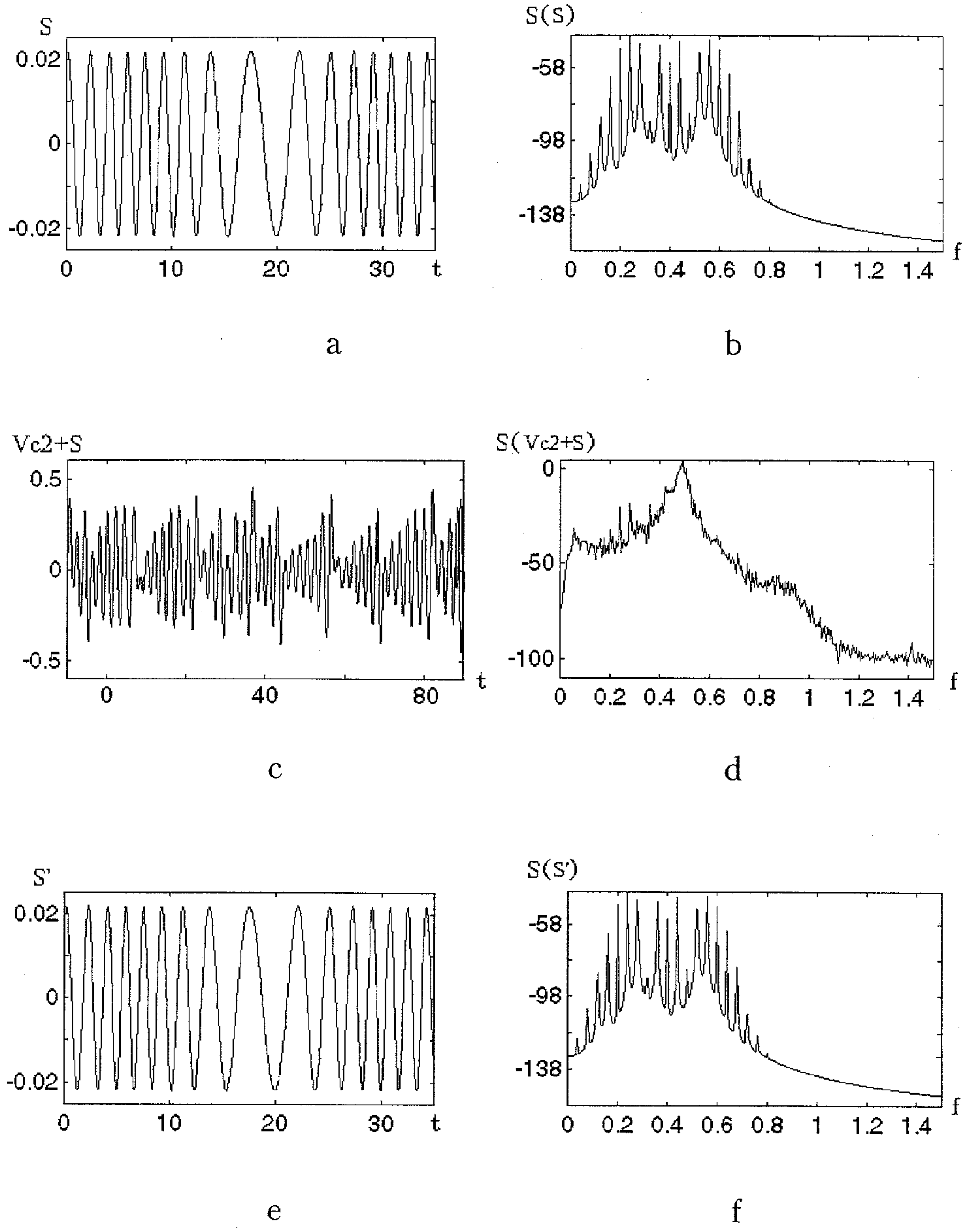


Fig. 6. FM signal transmission. (a) FM input signal ($A = 2 \cdot 10^{-2}$, $f_0 = 0.4$, $\psi_m = 0.3$). (b) The power spectrum of the FM signal. (c) The transmitted signal ($V_{C2} + S$). (d) The power spectrum of the transmitted signal. (e) The recovered FM signal (S'). (f) The power spectrum of the recovered FM signal.

the desynchronization noise power P_D (signal/noise ratio, SNR), defined by expression

$$\mathrm{SNR} = P_S/P_D\,. \tag{11}$$

The signal power in the channel weakly depends on the presence of the information signal in the transmitter, because the information signal power does not exceed several percents of the chaotic signal power, hence it is convenient for calibration. We will use it below as a normalization coefficient for the noise power. Namely, instead of the absolute power of the desynchronization noise, we will consider its relative value

$$\eta = P_D/P_N\,. \tag{12}$$

Obviously, SNR can be expressed through μ and η

$$\mathrm{SNR} = P_S/P_D = (P_S/P_N)\cdot(P_N/P_D) = \mu/\eta\,. \tag{13}$$

In the ideal case of exact equality of the transmitter and receiver parameters and the absence of distortions in the channel $\eta = 0$ and $\mathrm{SNR} = \infty$. Practically η is always different from zero, it characterizes the degree of distortions of the transmitted signal. For example, if relative information signal power is equal to $\mu = 10^{-2}$ and relative desynchronization noise power to $\eta = 10^{-4}$, then $\mathrm{SNR} = 10^2$.

3.5. *Effect of perturbations*

Typical perturbing factors that decrease the communications quality are: Nonidentical elements of the transmitter and receiver, nonlinear distortions, nonuniformity of amplitude–frequency characteristics of functional system elements, and external noises in the communications channel. Let us consider the effect of these factors on the quality of the synchronous chaotic response at the receiver output.

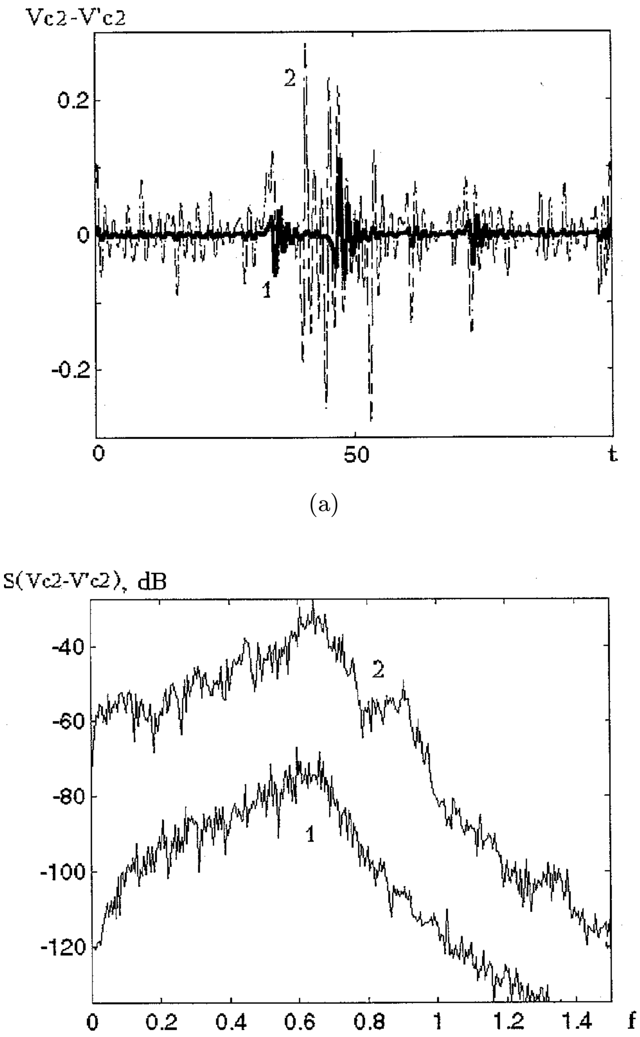
3.5.1. *Nonidentity of elements*

In real conditions, deviation of the circuit element parameters of the transmitter and receiver is inevitable. Deviation of at least one transmitter circuit element with respect to the corresponding receiver element leads to desynchronization signal at the receiver output. Characteristic fragments of the desynchronization signals and their power spectra are presented in Fig. 7 for deviations of the resistance value R in the receiver and transmitter by 0.1% (curve 1) and 1% (curve 2).

As was noted in Sec. 3.2, nonidentical parameters of the transmitter and receiver circuits lead to "on-off" intermittency. So, in the waveforms in Fig. 7, besides a low-amplitude desynchronization signal, proportional to the value of parameter deviation, we can observe high-amplitude irregular bursts comparable to the amplitude of chaotic oscillations at the receiver input. Average frequency of these bursts increase with increasing parameter deviation, and leads to a sharp increase of relative mean power of the desynchronization signal η at the receiver output.

3.5.2. *Nonuniformity of amplitude–frequency characteristics*

Nonuniformity of amplitude–frequency characteristics of functional elements of the transmitter and receiver leads to signal filtering and transformations of its spectral characteristics. As a rule, this effect is caused by RC-circuits that play the role of low-pass filters. Therefore, the problem of the effect of amplitude–frequency characteristics nonuniformity is discussed here on an example of low-pass filter characteristics.



(a)

(b)

Fig. 7. The receiver output with zero input information signal and nonidentity of elements. (a) The fragments of the desynchronization signal at the receiver output ($V_{C2} - V'_{C2}$). (b) The power spectra of the receiver output. 1 — 0.1% deviation of the resistance value R in the receiver and transmitter. 2 — 1% deviation of the resistance value R in the receiver and transmitter.

Assume the parameters of the transmitter and receiver be identical, the transmitter output signal be passed through a first-order low pass filter, and the reason for the response desynchronization be only the signal distortion by the filter. The signal transformation in the filter is described by the following equation

$$T\dot{x} + x = y\,, \tag{14}$$

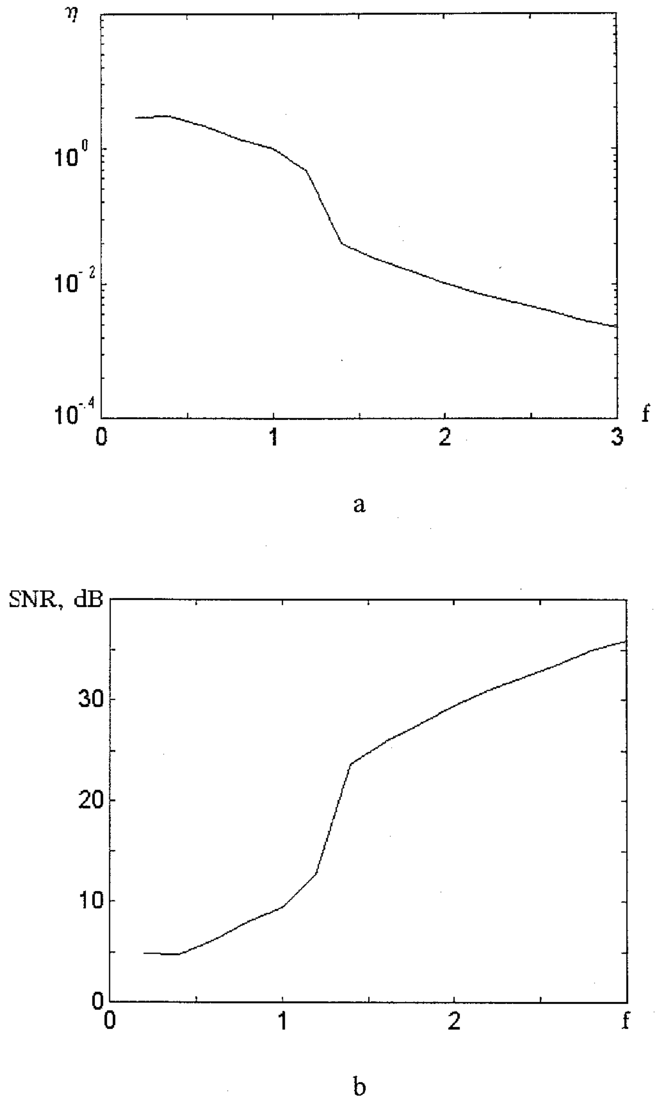
where y is the signal at the transmitter output (V_{C2}), x is the signal at the receiver input. Time constant T defines the low-pass filter cutoff frequency $f = 1/T$.

Analysis shows that in this case the quality of the synchronous response is determined by the relation of the filter cutoff frequency f and upper bound frequency F of the signal power spectrum at the transmitter output. At $f \gg F$, the presence of the filter does not destroy the system operation. Since $F \approx 0.6$ [see Fig. 3(c)], already at $f > 4$ the communications system does not feel the filter presence. On the other hand, comparable values of F and f lead to degradation of the synchronous response quality, and this tendency pertains as f decreases.

Desynchronization noise relative power η and SNR (at $\mu = 1$) are presented in Fig. 8 as a function of cutoff frequency f. As is seen from the figure, meansquare error rapidly decreases and SNR quickly increases with increasing f.

3.5.3. *Nonlinear distortions in the communications channel*

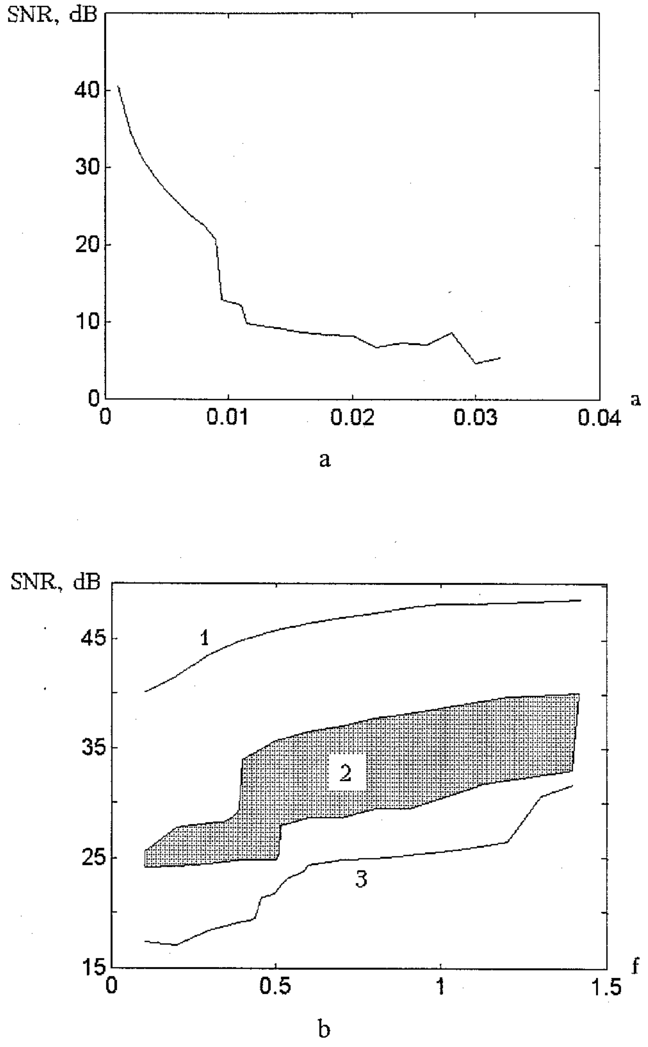
The effect of nonlinear distortions was investigated on example of cubic nonlinearity.



a

b

Fig. 8. Nonuniformity of amplitude–frequency characteristic of the communications channel. (a) Desynchronization noise relative power η and (b) SNR (at $\mu = 1$) as a function of cutoff frequency f (low-frequency filter).



a

b

Fig. 9. SNR (at $\mu = 1$). (a) Nonlinear distortions in the communications channel (a is a parameter of nonlinear distortion). (b) Additive noise in the communications channel (f — cutoff frequency of the noise level). 1 — noise level -60 dB. 2 — noise level -50 dB (uncertainty zone associated with finite length of the time series and irregular occurrence of desynchronization bursts). 3 — noise level -40 dB.

$$x = y \cdot (1 - a \cdot y^2)\,, \tag{15}$$

where y is the signal at the transmitter output, and x is the signal at the receiver input. Parameter a is varied in the range 0.001 to 0.03 that corresponds to nonlinear distortion level varied from 0.1% to 3% of the signal amplitude at the transmitter output. SNR (at $\mu = 1$) at the receiver output is presented in Fig. 9(a) as a function of nonlinear distortions. It has the same tendency as in the case of amplitude–frequency distortions. In particular, in both cases the maximum achievable SNR is equal to 35–40 dB.

3.5.4. *Effect of additive normally-distributed noise*

The effect of external noises on the system operation by wireless communications is considered here. The noise frequency bandwidth was restricted with a first-order low-pass filter, and the noise power was fixed at the filter output.

Signal/noise ratio at $\mu = 1$ is presented in Fig. 9(b) as a function of cutoff frequency for the noise levels of −40 dB, −50 dB, −60 dB. Analysis of these dependencies indicates that the presence of external noises within the carrier signal frequency band decreases SNR at the receiver output (here, by 13–15 dB) with respect to the situation in the channel (or receiver input). This is observed at different noise power levels, and is explained by losses in quality by retrieval of the information signal from the mixture with chaotic signal.

4. Experiments

The main purpose of the experiments was to realize conditions for transmission of analog information (e.g. speech) in RF band via dynamic chaos.

The idea is the use of low-frequency chaotic modules discussed in [Dmitriev *et al.*, 1994, 1995] together with functional elements of one of the standard RF band communications systems.

4.1. *Experimental devices and their characteristics*

4.1.1. *Basic communications system*

Portable pocket-size AM transceiver stations (“walkie-talkie”), carrier frequency 27 MHz, capable of transmitting speech signals with the bandwidth 2 kHz, were used as a basic system (Fig. 10). The transceivers perform the following manipulations with the signal.

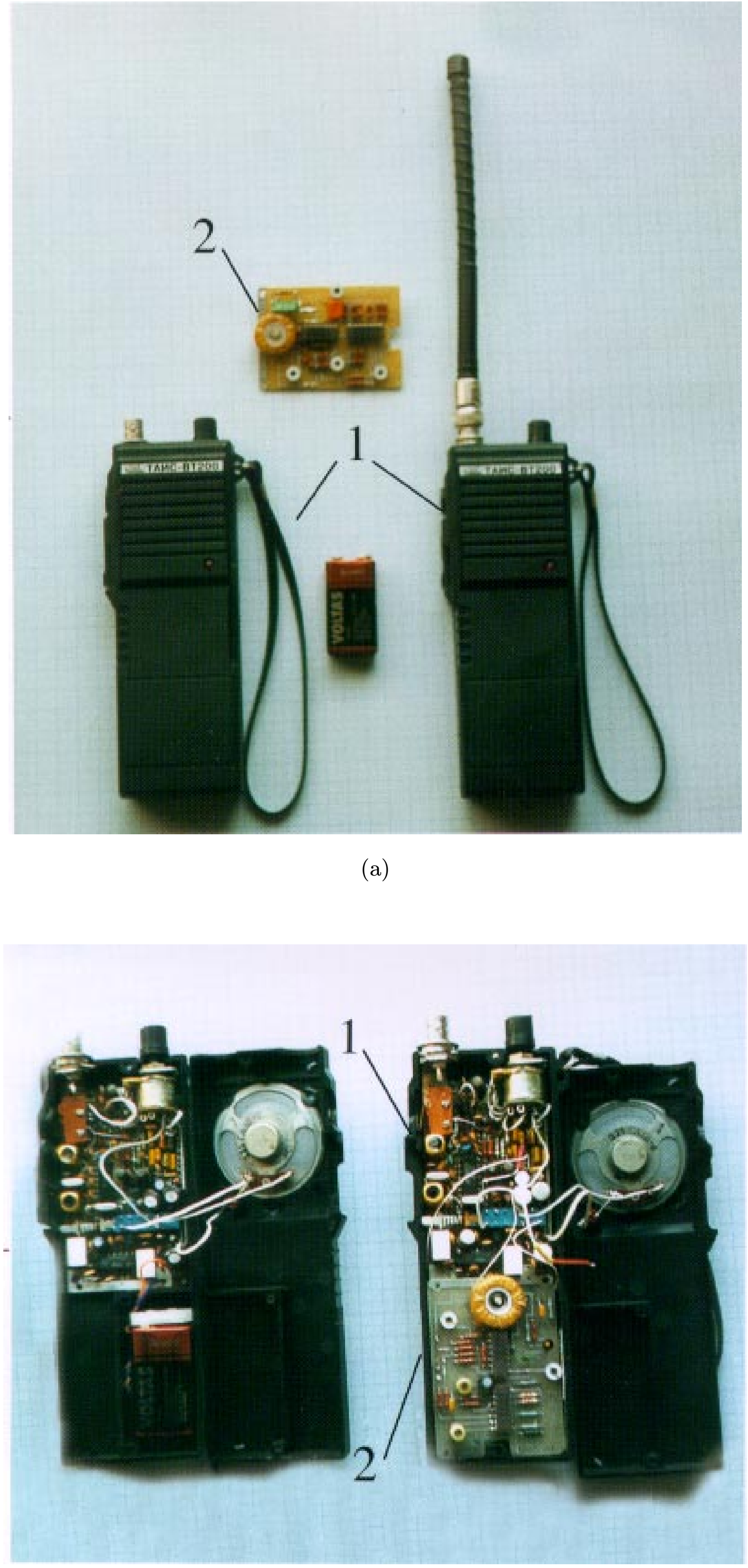
In transmission mode, the speech signal from the built-in microphone is amplified and fed to the modulator. The modulator is a transistor amplifier; a crystal generator signal (27 MHz) is fed to its input, and low-frequency speech (modulating) signal is added to the amplifier bias voltage, thus modulating its gain. Then, the radio signal is amplified and fed to the system antenna.

In receiver mode, the radio signal from the antenna is amplified and fed to a demodulator. The demodulator is a mixer (multiplier) made as two pairs of differential transistors; the crystal generator signal is fed to one of its input, while the said radio signal is fed to the other input. The demodulator output signal is filtered, and only the low-frequency component is left. Then the signal is passed through an amplifier with automatic gain control, and is sent to the speaker.

4.1.2. *Chaotic modules of the transmitter and receiver*

Chaotic modules of the experimental devices had the same construction [Fig. 2(d)] as was used in experiments on speech and music signal transmission in the frequency range 0 to 5 kHz [Dmitriev *et al.*, 1994, 1995]. Since the used transceivers were capable to transmit signals with the bandwidth to 2 kHz, the chaotic module band was correspondingly decreased. For this purpose, the values of the elements L, C_1 and C_2 were increased [$L = 40$ mH, $C_1 = 0.015$ μF, $C_2 = 0.1$ μF, see Figs. 2(b) and 2(c)]. Thus, the chaotic module of the transmitter in autonomous mode was generating chaotic oscillations in the range 0 to 2 kHz [Fig. 11(a)].

The function of the receiver chaotic module [Fig. 2(d)] is to extract the speech signal from the mixture with chaotic signal. The module is a passive device, it consists of the same elements (with the same values) as the transmitter module. The mixture of chaotic and information signals is fed to an amplifier with tunable gain, and then to the module. The purpose of the amplifier is to restore the input signal level (by means of gain control) and to make it equal to the level of the transmitter chaotic module output signal, which is a necessary condition for restoring speech signal at the receiver module output.



(a)

(b)

Fig. 10. Basic communications system. (a) The appearance of the transceivers and chaotic module. (b) The chaotic module built-in transceiver. 1 — transceiver. 2 — chaotic module.

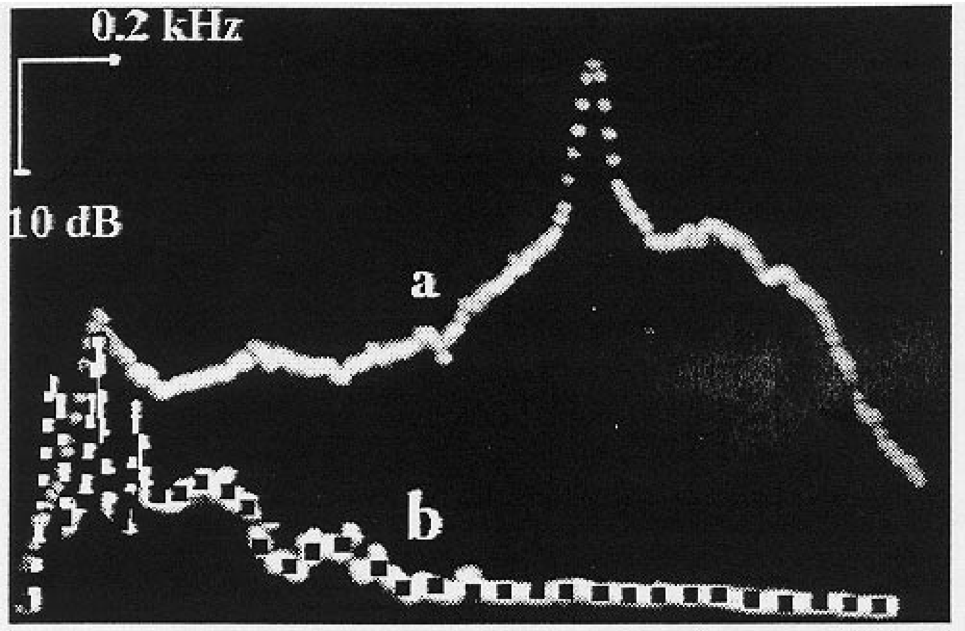


Fig. 11. (a) The power spectrum of the transmitter's chaotic module in the autonomous mode. (b) The spectrum of the speech signal.

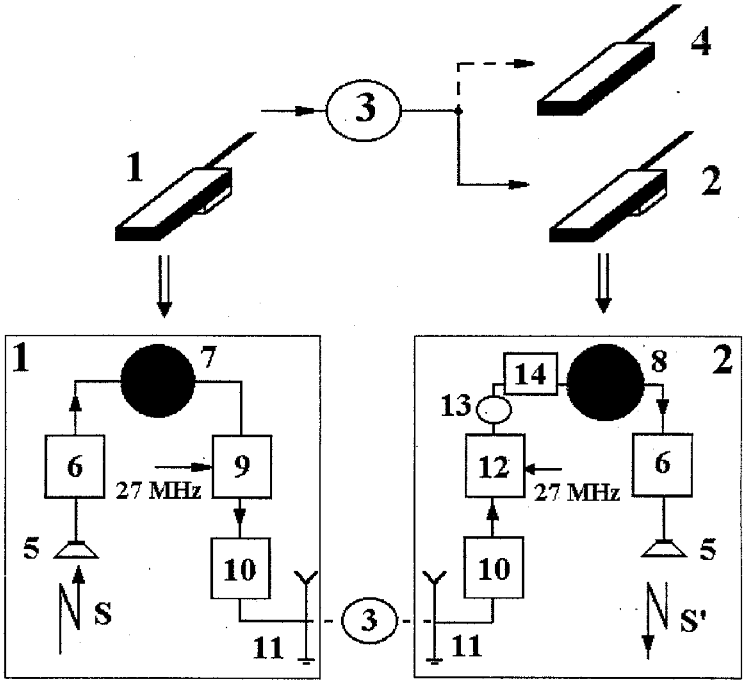


Fig. 12. Block-diagram of the communication system: 1 — transmitter, 2 — receiver, 3 — attenuator, 4 — comparison unit, 5 — built-in microphone, 6 — low frequency amplifier, 7 — transmitter chaotic module, 8 — receiver chaotic module, 9 — modulator, 10 — RF amplifier, 11 — antenna, 12 — demodulator, 13 — filter, 14 — automatic gain control amplifier, S — input information signal, S' — recovered signal.

4.1.3. *Communications devices*

Three transceiver stations were used in experiments (Fig. 12). The first one, with an added chaotic module, played the role of the communications system transmitter. The speech signal from its built-in microphone was fed to the chaotic module input as an information signal. At the same time, the module output signal, a mixture of speech and chaotic

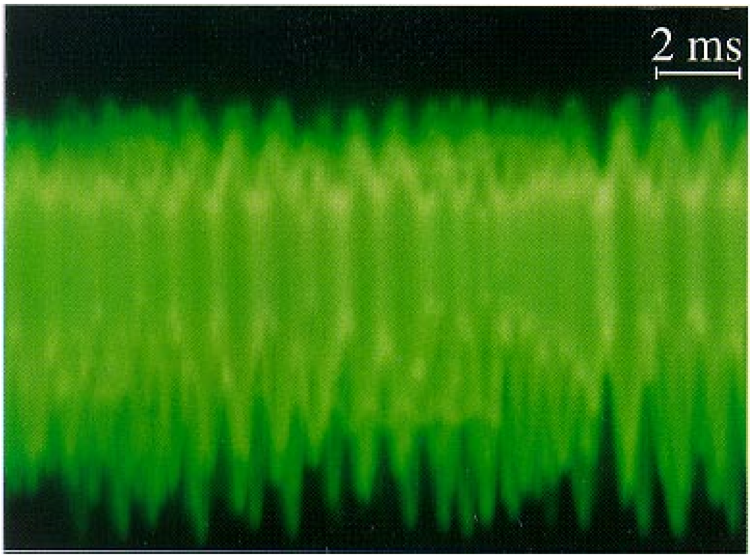


Fig. 13. The transmitter RF output signal in the presence of a speech signal input.

signals, played the role of an information signal with respect to the station: After amplification, it modulated the carrier amplitude (27 MHz) and then through antenna system went to the communications channel (Fig. 13).

The role of the second station was to receive the radio signal from the communications channel, to amplify and demodulate it, to filter and then to amplify the low-frequency mixture of the speech and chaotic signals, and to retrieve the information component from the mixture. The last manipulation is performed by a chaotic module also added to the station. The signal after an amplifier with automatic gain control was fed to the module input, and its output signal was sent to the station speaker. Thus, the station played the role of the receiver of the communications system.

Finally, the third station had no chaotic modules and played the role of a reference receiver.

4.2. *Transmission of speech information in RF band by a cable*

The first group of experiments was devoted to transmission of speech information in radio frequency band by cable lines. The communications channel was represented by a long piece of a radio cable with an attenuator, their total attenuation was up to 70 dB. The experiments were to solve the following problems:

— investigation of the effects associated with transfer of low-frequency signals to RF band and back,
— obtaining synchronous chaotic response and speech information transmission,
— tuning chaotic modules and minimization of the transmitted signal distortions in the radio channel, preparations to wireless experiments.

Just before the chaotic modules were connected to the stations, they were carefully tuned in order to provide equality of their parameters with accuracy 0.5–0.8%. This is necessary in order to facilitate the signal propagation in the radio channel, but is not sufficient to obtain synchronous response in the receiver.

As a result of chaotic module tuning and supplementary low-frequency experiments, we obtained the synchronous response with $\eta \approx 9 \cdot 10^{-4}$. However, when the modules were built into the stations, in RF band experiments η increased to 10^{-2}. This increase in η is explained by the signal distortions in the radio channel. In order to minimize the distortions, we corrected the amplitude–frequency characteristics of the functional elements of the basic communications system. For this purpose, we analyzed the input and output signals of the functional elements, and if there were any distortions in the structure of the low-frequency signal component, we additionally tuned it. This procedure allowed us to obtain the amplitude–frequency characteristics of the entire radio channel practically independent of frequency within the range of the chaotic carrier signal spectrum [Fig. 11(a)]. This has led to a decrease in η down to $1.6 \cdot 10^{-3}$.

At the next stage, we performed experiments on speech signal transmission. In the transmitter, we varied the ratio μ of the speech signal level (power) to the chaotic module signal level. At $\mu < 2.5 \cdot 10^{-3}$ the speech signal in the receiver was hardly observable, and was absolutely imperceptible in the reference station. An increase in μ led to an improvement of the quality of the retrieved speech signal in the receiver. Waveform fragments of the initial speech signal and the signal at the receiver output are shown in Fig. 14 for $\mu = 2.25 \cdot 10^{-2}$ (SNR $\approx$ 11.5 dB in the receiver). Finally, at $\mu > 4 \cdot 10^{-2}$ the signal becomes perceptible, though hardly, in the reference station. The receiver chaotic module allowed us to increase μ up to $1.6 \cdot 10^{-1}$ without a change in the chaotic mode. SNR at the receiver module output was then equal to 20 dB.

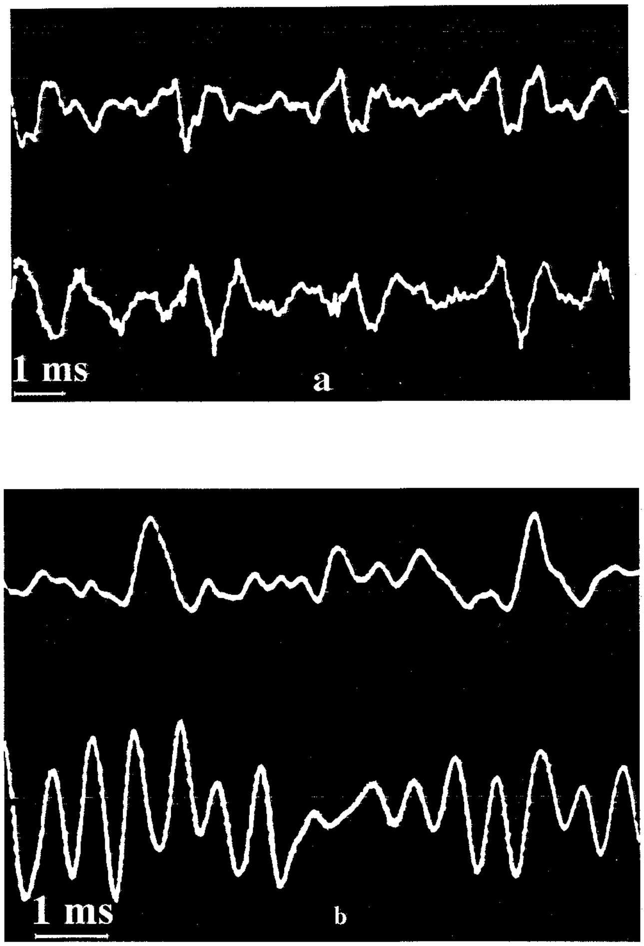


Fig. 14. Information retrieval in the receiver and the comparison unit: (a) speech input signal S (top trace) versus recovered signal S' (bottom trace), (b) speech input signal S (top trace) versus low frequency output signal of the comparison unit (bottom trace).

4.3. *Wireless transmission of speech information in RF band*

In the experiments on wireless transmission of speech signals in RF band, the cable connecting the transmitter and receiver stations was removed, and the radio signal was radiated and received by antennas of the transmitter and receiver, respectively. The distance between the stations was varied within the range of the laboratory room (10–15 m). In the absence of the information signal, desynchronization signal level at the receiver subtractor output was measured. An increase in this level up to the value of $\eta = 1.2 \cdot 10^{-2}$ was found. We were not able to obtain a better response in the receiver by means

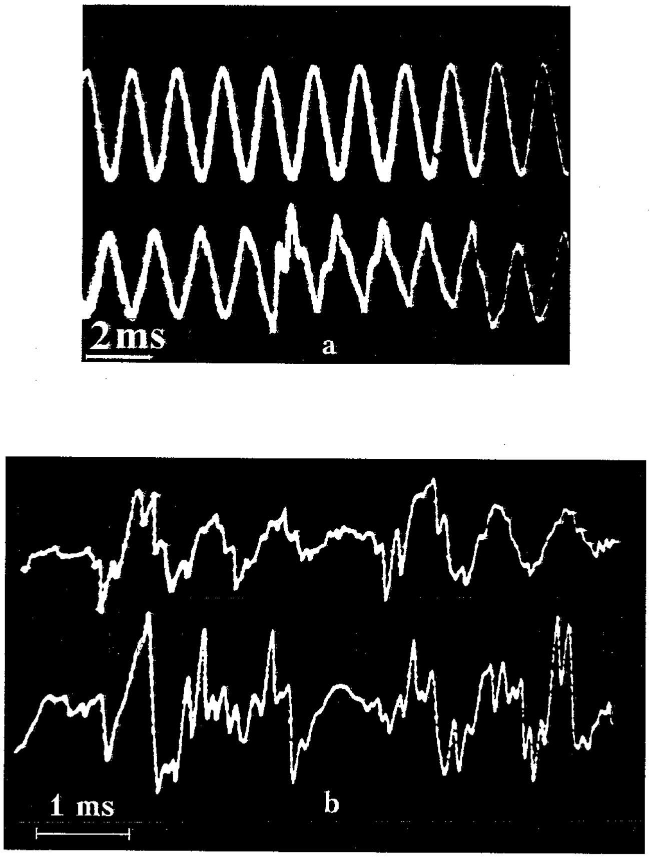


Fig. 15. Information retrieval in the receiver by the wireless communication. (a) The top trace is a test signal S. The bottom trace is the recovered signal S'. (b) Speech input signal S (top trace) versus recovered signal S' (bottom trace).

of module tuning or information channel bandwidth restriction. The main reasons for the noise level increase are strong external noises in the frequency range occupied by the transceivers (27 MHz), and reflections of the radiated signal within the laboratory room, that appear due to operation in the near zone of the employed transceivers.

In order to investigate the effect of external factors on the transmission quality, we performed experiments with a sinusoidal signal. In Fig. 15(a), the waveforms of the initial and retrieved 600 kHz tone signals are presented, $\mu = 4 \cdot 10^{-2}$. As is seen, the test signal is visible, but some of its fragments are essentially distorted. So, with the increased η taken into account, in order to retrieve a legible signal, we had to increase the speech signal level at the transmitter chaotic module to the value of $\mu = 1.2 \cdot 10^{-1} - 1.6 \cdot 10^{-1}$ [Fig. 15(b)]. This level of the information signal gave SNR $\approx$ 11 dB, but also led to partial speech legibility in the reference station, where SNR $= -10$ dB.

5. Conclusions

Thus, in this paper we present the results of experiments on wire-line and wireless transmission of analog signals in RF band.

The effect of perturbing factors on the transmission quality is investigated theoretically. It is shown that the main reason of the transmission quality degradation is the chaotic response desynchronization associated with the phenomenon of "on–off" intermittency.

It is found that under the effect of the perturbing factors, we have to increase the level of the information signal fed to the transmitter in order to obtain a qualitative information transmission. However, in order to provide confidential communications, one should decrease the information signal level. A compromise for these contradictory requirements is the improvement of the quality of the synchronous chaotic response in the receiver (lower η).

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