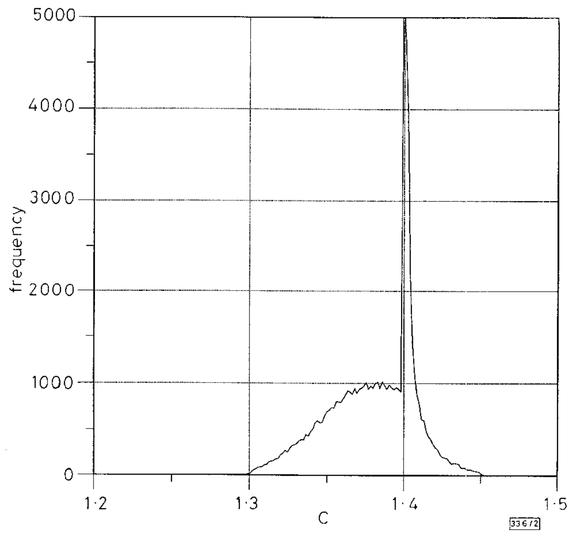

**Fig. 2** *Distribution of Crest-factor C of s(t) for 32 carrier 2-DPSK OFDM with optimised phases* $\{\Delta\varphi_{2m+1}\}$
65536 waveforms

the number of information bits per OFDM symbol is small a table look-up can be performed. In this case the optimised phases $\{\Delta\varphi_{2m+1}\}$ are stored in a read-only memory and are read out in real-time. The word of information bits $\{b_i\}$ specifies the memory addresses to be read out. If the number of information bits $K$ is large, a table look up is not possible because the size of the table becomes too large. In these cases the variables $\{\Delta\varphi_{2m+1}\}$ have to be optimised in real time. It has been found that for $T$ = 10ms with 32 carriers, a real-time optimisation on a fixed-point digital signal processor with a 20MHz cycle rate is feasible.

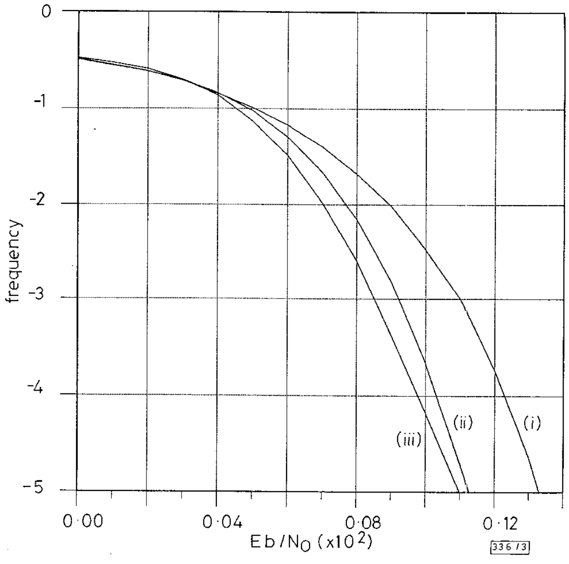

**Fig. 3** *Simulated bit error rate against signal-to-noise ratio*
(i) conventional 2-DPSK demodulation
(ii) and (iii) 2-DPSK demodulation making use of redundancy in transmitted waveform (ii) signals with up to 1 differing bit considered
(iii) signals with up to 2 differing bits considered

*Improved demodulation:* The optimised variables $\{\Delta\varphi_{2m+1}\}$ can be regarded as code redundancy, which can be exploited for reducing the bit error rate at the receiver. The improved demodulator obtains a first estimate $\{\bar{b}_i\}$ of the transmitted word $\{b_i\}$ by conventional 2-DPSK demodulation of the subcarriers. Therefore the coefficients $\{r_n\} = \{s_n + n_n\}$ are calculated from the received signal $r(t) = s(t) + n(t)$ by Fourier-series expansion of $r(t)$. Here $n(t)$ denotes complex additive white Gaussian noise (AWGN) with two-sided spectral power density $N_0$, and $n_n$ denotes the contribution of the noise to the $r_n$. Then the phase differences $\{\Theta_{2m}\} = \{\arg(r_{2m+1}) - \arg(r_{2m})\}$ are calculated from the vector $\{r_n\}$. Finally, the bitword $\{b_i\}$ is obtained by decisions from the vector $\{\Theta_{2m}\}$.

In addition, so-called test signals $\tilde{s}(t)$ with corresponding bitwords $\{b_i\}$ are considered; which can be regarded as possible candidates for the correct word $\{b_i\}$ if the first estimate $\{\bar{b}_i\}$ should contain errors. All test signals with corresponding bitwords $\{b_i\}$, that differ in up to $q$ bits (e.g. $q = 1, 2$) from the first estimate $\{b_i\}$ are considered and the receiver decides in favour of that word $\{b_i\}$ which minimises

$$Q(\{\Theta_n\},\{\tilde{\Theta}_n\}) = \sum_{n=0}^{N-2} \sin^2((\Theta_n - \tilde{\Theta}_n)/2) \qquad (2)$$

In eqn. 2, $\Theta_n = \arg(r_{n+1}) - \arg(r_n)$ denotes the $n$-th phase difference in the received vector of coefficients $\{r_n\}$ and $\Theta = \arg(\tilde{s}_{n+1}) - \arg(\tilde{s}_n)$ the $n$-th phase difference in the specific test signal. In eqn. 2 all deviations between the expected phase difference $\Theta_n$ and the actual phase difference $\Theta_n$ are weighted and summed up. The sine term in eqn. 2 reflects the fact that a phase difference $\alpha$ on the unit circle corresponds to a squared Euclidean distance equal to $4\sin^2(\alpha/2)$. Fig. 3 shows the simulated bit error rate for conventional and improved demodulation when transmitting over an AWGN-channel. It is apparent that ~2.5dB in power efficiency can be gained by considering all signals with up to two differing bits from the first estimate $\{b_i\}$.

*Summary:* A novel scheme for OFDM modulation has been proposed, and it achieves signal waveforms with a PAPR <3.3 dB. The power efficiency of the transmission can be improved by exploiting the redundancy, which is inherent in the optimised waveform. The practical application of the proposed scheme is only limited by the complexity of the modulator and demodulator.

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# Multi-state chaos-shift-keying modulation system using feedback synchronising Chua's circuit

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*Indexing terms: Chaos, Modulation, Chua's circuit*

A new type of chaos-shift-keying (CSK) modulation, called multi-state CSK, is presented for the first time. In a classical CSK communication system, using this type of modulation combined with feedback synchronisation, the data rate can be greatly increased. Laboratory test results conform very well with theoretical analysis.

*Introduction:* The possibility of using synchronised chaotic circuits in secure communications has been studied by many authors [1]. For data communications, one system, called chaos-shift-keying (CSK) modulation, is particularly interesting [2]. In this system the binary data directly modulates one of the parameters of a Chua's oscillator: one of its state variables is transmmitted to a set of two subcircuits. However, the data rate of this kind of modulation cannot be very high. In this Letter, a new type of CSK modulation system, called multi-state CSK modulation, is presented for the first time. Using this type of modulation combined with feedback synchronisation, the data rate can be greatly increased.

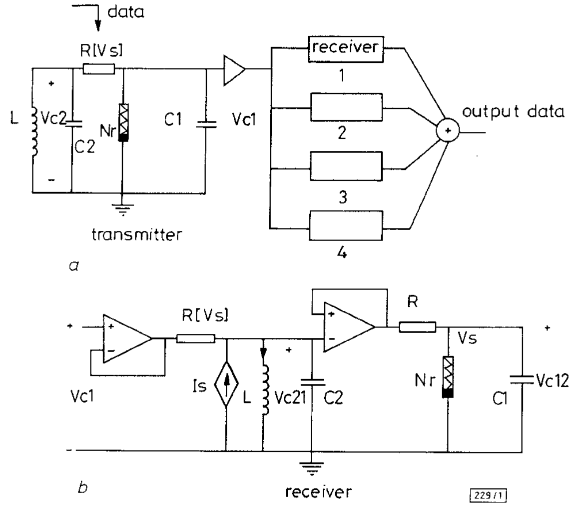

**Fig. 1** *Transmitter and receiver*

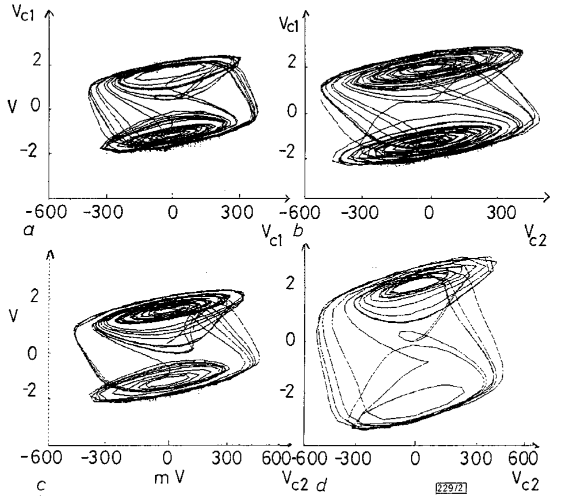

**Fig. 2** *Four states of $V_{c1}$ against $V_{c2}$*

*Transmitter block:* Fig. 1 shows the transmitter and receiver of the multi-state CSK communication system. Different values of the resistance $R$ make the circuit work in several states (or attractors). In our experiment, we define four values of $R$ where there is a 50 Ω gap between them. The value of $R$ presented in the circuit depends on the data. Two bits of data are formed into a digital word to indicate which value is adopted by the circuit. This is something like quaternary phase shift keying (QPSK) used in digital microwave communications. Fig. 2 shows the four states in the transmitter where $V_{c1}$ and $V_{c2}$ are the state variables.

*Receiver block:* This module consists of four subcircuits: they are all similar except that the values of the resistance $R$ are different. Each value is equal to one of the four transmitter resistance values. Therefore, when they are matched, the receiver will synchronise the received signal. The receiver circuits can be described by eqns. 2 – 4. In these equations $V_{c1}$ is the transmitted CSK signal.

$$f(V_r) = I_r = G_1 V_r + (G_0 - G_1)(|V_r + B_p| - |V_r - B_p|)/2 \qquad (1)$$

is the Vr-Ir characteristic of the three segment piecewise-linear resistor which has a slope $G_0$ in the central region and a slope $G_1$ in the outer region, $B_p$ is the breakpoint, $K$ is the feedback coefficient. Four subcircuits can detect four transmitter states individually. In the previous modulation method, the data rate is slow owing to the synchronisation time being too long. In this new method, synchronisation time does not change at all but twice as much information can be transmitted. Fig. 3*a* shows the relationship between the demodulated signal and the transmitted one when they are matched while Fig. 3*b* shows the relationship when they are not matched. We can see that the receiver can distinguish the different states correctly.

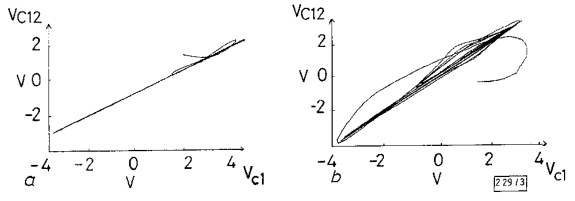

**Fig. 3** *Relationship between demodulated signal and transmitted signal*

$$C_1 \frac{dV_{c12}(t)}{dt} = \frac{1}{R(V_S)}(V_{c21}(t) - V_{c12}(t)) - f(V_{c12}(t)) \qquad (2)$$

$$C_2 \frac{dV_{c21}(t)}{dt} = -\frac{1}{R(V_S)}(V_{c21}(t) - V_{c1}(t)) + i_{L2}(t) + K\left(V_{c1}(t) - V_{c12}(t)\right) \qquad (3)$$

$$L\frac{di_{L2}(t)}{dt} = -V_{c21}(t) \qquad (4)$$

*Data rate:* The highest data rate depends on the synchronisation establishment time. In our circuit, the error feedback principle is applied to achieve this goal. But even so the data rate is not satisfying. A multi-state method is put forward to solve this problem. In this circuit, originating from Chua's circuit, the baud rate remains the same but it can carry twice the information. Therefore, the bit rate doubles.

*List of parts in our circuit:*

$R$ = 1500–1650Ω
$C_1$ = 10 NF
$C_2$ = 100NF
$L$ = 18mH

*Conclusion:* From the test we can conclude that a multi-state method helps to transmit more information. The more states used, the more information can be carried. We can deduce that an 8-state modulation carries three times as much information as the two-state one does. One point should be noted: all the states must assure that the circuit works in the chaos state, otherwise the modulation will lose its meaning.

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