CONTENTS

VOLUME 47 NUMBER 11 2004

RADIOELECTRONICS AND COMMUNICATIONS SYSTEMS

Radioelectronics and Communications Systems
Vol. 47, No. 11, pp. 21–26, 2004

Izvestiya VUZ. Radioelektronika
Vol. 47, No. 11, pp. 30–38, 2004
UDC 621.396.967

TIME COMPRESSION OF COMMUNICATION CHANNELS BASED ON SUPER-RAYLEIGH RESOLUTION OF SIGNALS WITH ADDITIONAL GATING OF ADC SAMPLES

V. I. Slyusar, D. V. Slyusar, and Yu. V. Stolyarchuk

Kiev, Ukraine

Several computational procedures are suggested permitting to carry out time compression of narrow-band communication channels based on additional gating of ADC samples. The procedures can be realized in communication systems with digital antenna arrays.

Improvement of traffic capacity of narrow-band communication lines with time compression of channels can be achieved [1] based on the methods of super-Rayleigh resolution of pulse signals in their times of arrival. We can increase many-fold the traffic volumes by using information packets, each representing a totality of pulses, one following after another with mutual overlap. However, if the speed of analog-to-digital conversion is high enough, realization of such processing in real time presents considerable difficulties because of large volumes of the data obtained. Taking into account that a decrease in the sampling frequency (to rarify the information flow) is attended with a loss of energy, the purpose of this paper is the development of methods of super-Rayleigh compression of channels based on procedures of additional gating of ADC samplings [2].

In essence, the suggested approach is a further extension of the method of M-ary amplitude-pulse modulation (M-PAM), when the coding of messages is performed by means of putting the intervals of partition of pulse amplitudes into one-to-one correspondence with the symbols of the M-ary alphabet [1].

The additional gating of ADC samples is carried out in the receiver in respect to the received signals, and consists in their periodic accumulation (T elementary samples, or readings, in a group) during strictly set time intervals (called strobes), permitting to reduce the dimension of the information sample by T times. In the case of video pulses, the respective processing can be represented in the form

$$U_g = \sum_{s=1}^{T} U_s \qquad (1)$$

where U_s is the signal voltage in the sth reading of ADC; T is duration of the accumulated sample of the readings; and g is the ordinal number of the strobe.

Since the information-bearing parameter, in the event of amplitude-pulse modulation, represents the amplitude of each of the signals, consider the methods of calculation of the respective amplitude estimates by an example of a discrete function of pulse envelope $P_g(z_m)$, obtained after implementing the procedure of additional gating of ADC samples taken from the primary envelope:

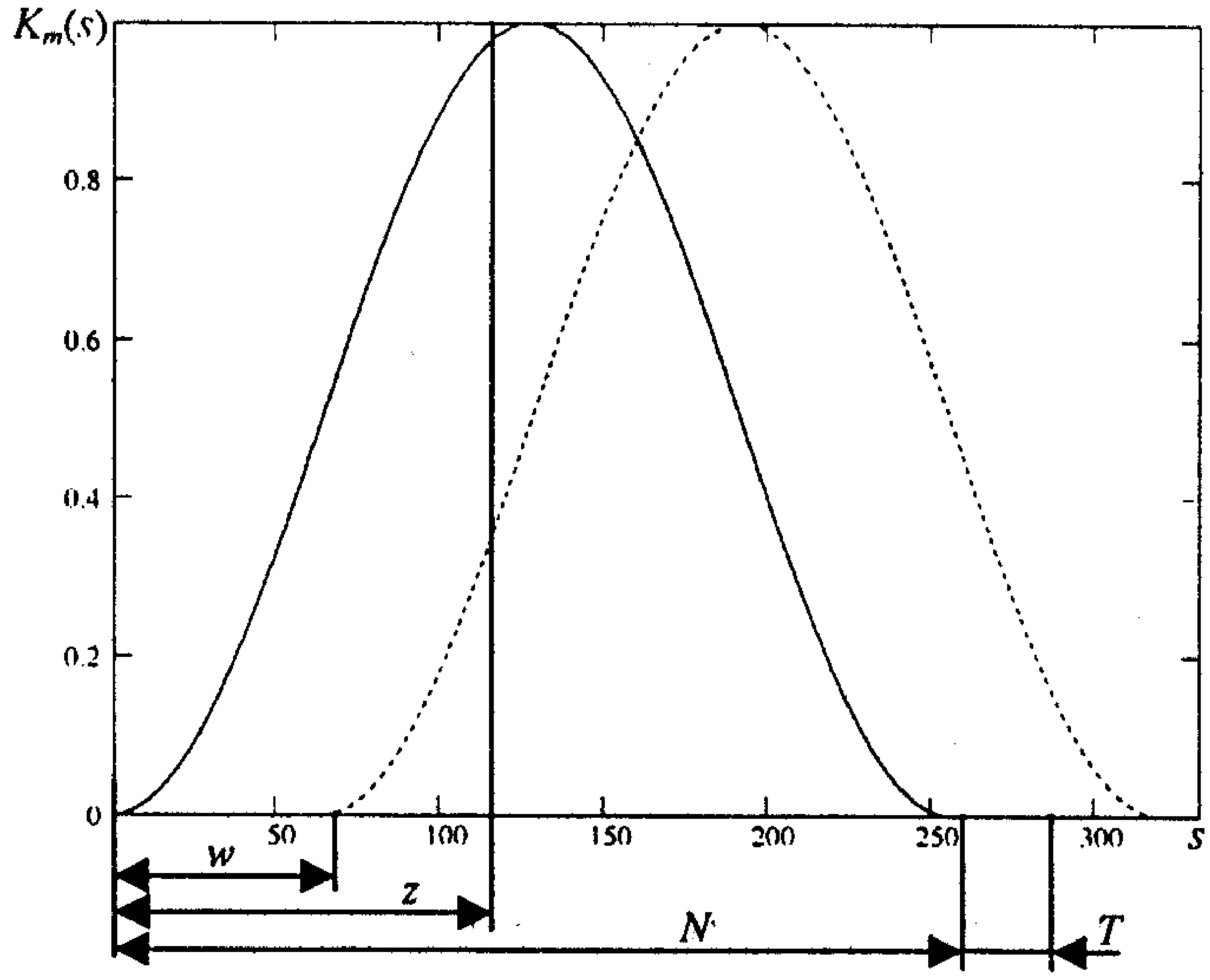

Fig. 1

$$P_g(z_m)=\begin{cases}\sum\limits_{s=0}^{z_m-1} K_m(s) & \text{at } g=t_{Hm},\\ \sum\limits_{s=z_m+T(g-1-t_{Hm})}^{z_m+T(g-t_{Hm})-1} K_m(s) & \text{at } t_{Hm}<g\le t_{Km},\\ 0 & \text{at } g\le t_{Hm}, t_{Km}<g,\end{cases} \quad (2)$$

where t_{Hm} is the ordinal number of the first strobe among the strobes (intervals of accumulation (i.e., additional gating) of ADC readings), in which the mth signal is present; z_m is the known bias of the mth pulse in the ADC readings with respect to the beginning of the strobe with the ordinal number $g = t_{Hm} + 1$; T is the strobe duration expressed in the ADC readings; t_{Km} is the ordinal number of the last strobe among those in which the mth pulse is present; and $K_m(s)$ is the value of the discrete envelope of the mth pulse, referred to its maximum, directly at the ADC output.

At first we dwell on the simplest cases of the two-pulse and three-pulse signal burst and then extend the respective variants of the amplitude measurement procedures to the many-pulse case. Consider the simplest two-pulse scheme of reception (Fig. 1), when a short information message is transmitted by a pair of pulses overlapping in time and following one after the other with a known time shift. In other words, assume that the time of arrival of each signal is known exactly. The law of variation of the envelope of each of the pulses at the ADC output will be written as applied to a narrow-band channel in the form

$$K_m(s)=\begin{cases}\sin^2\dfrac{\pi}{N}s\cdot\Delta t, & s_{b_m}\le s\le s_{b_m}+N-1,\\ 0, & s<s_{b_m}, s\ge s_{b_m}+N,\end{cases} \quad (3)$$

where s in the ordinal number of ADC reading; s_{b_m} is the number of the first reading of ADC within the domain of the mth pulse (m = 1, 2), N is the pulse duration, and Δt is the period of ADC digitization.

For convenience sake, instead of discrete representation of signals, in Fig. 1 we use continuous functions.

When passing to the operation of additional gating of ADC samplings, we require that on the interval between the initial instants of the two pulses, one following after the other, an integral number of strobes can be placed (i.e., the intervals of additional gating of ADC readings, whose duration in Fig. 1 is denoted as T). Then, because of transformation due to accumulation in a strobe, the pulse envelope function (3) can be reduced, with the aid of (2), to the form

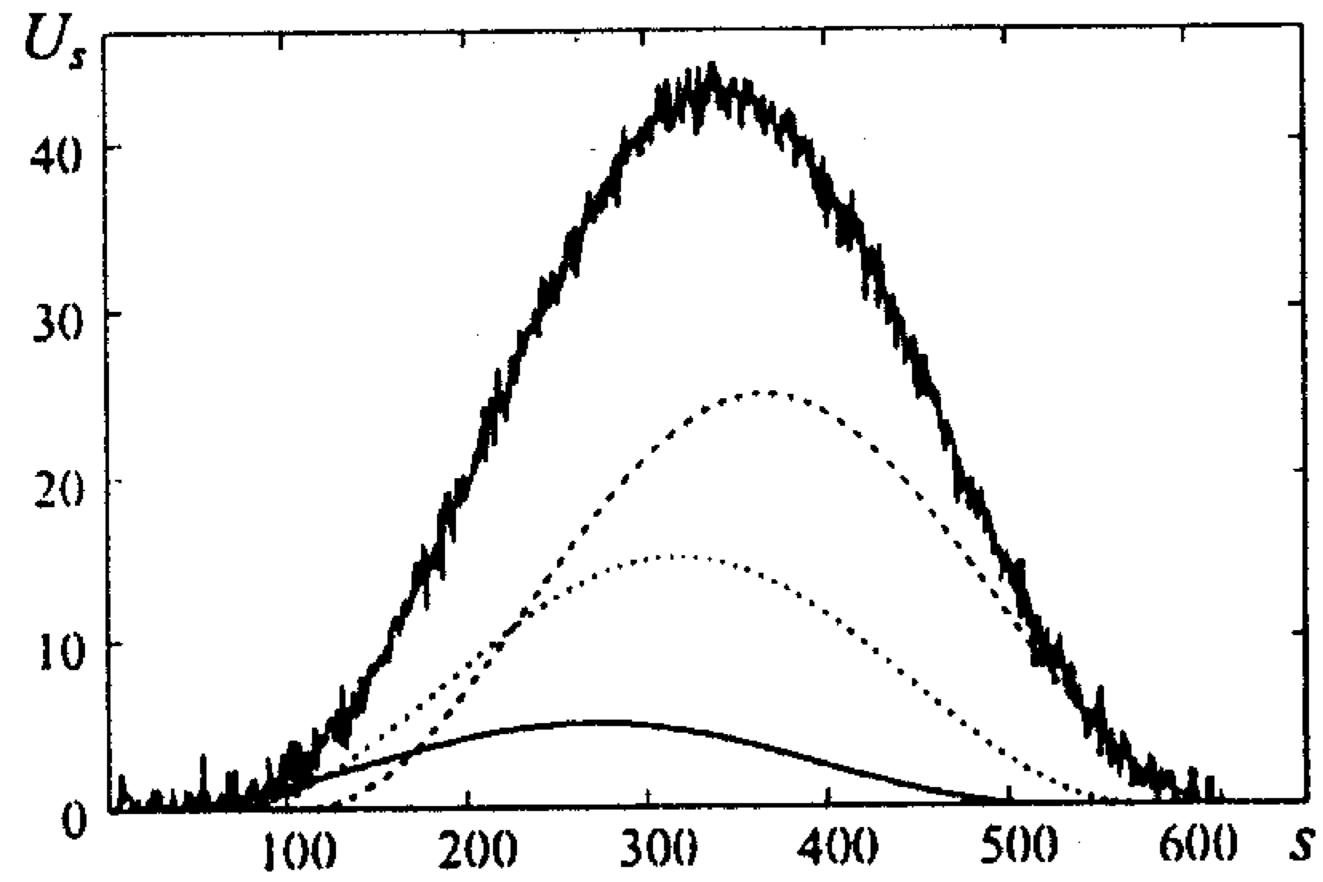

Fig. 2

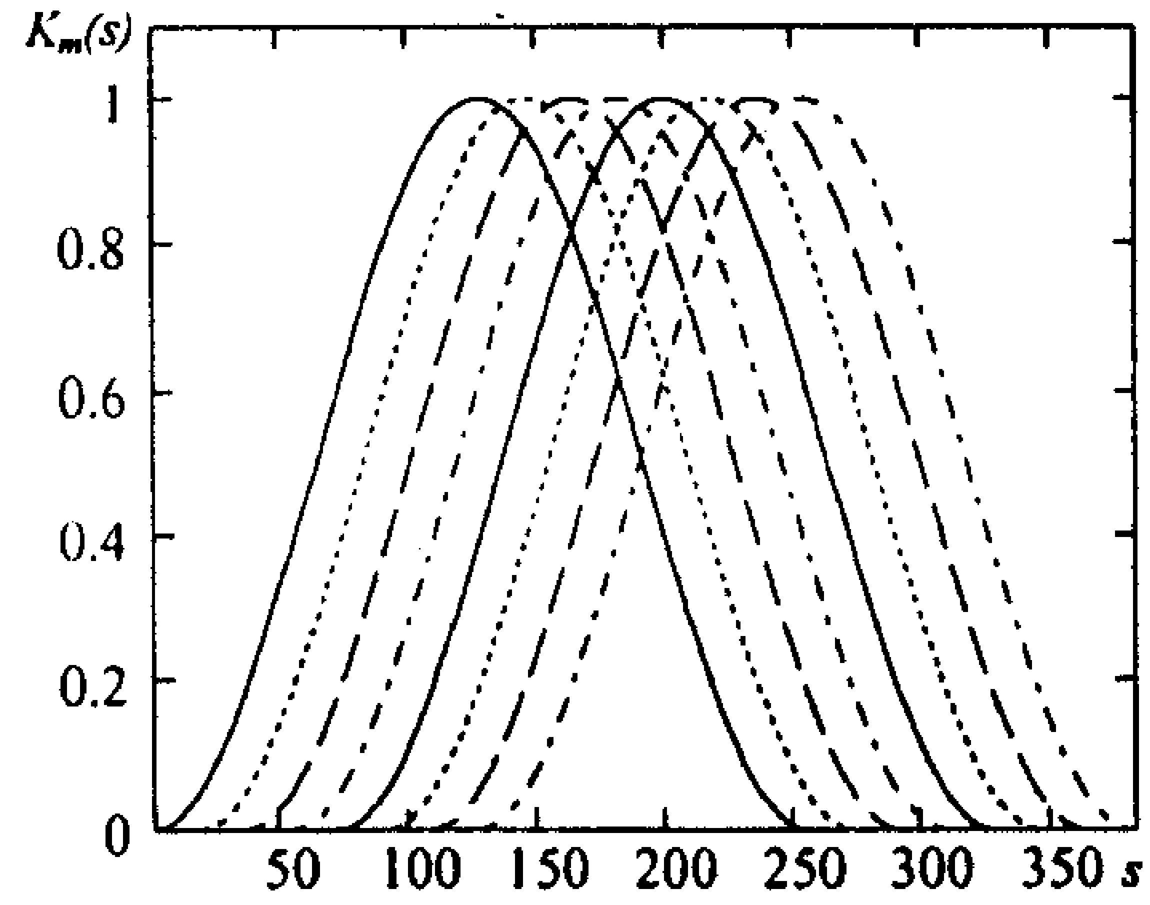

Fig. 3

$$P_g(z_m)=\begin{cases}\sum\limits_{s=0}^{z_m-1}\sin^2\frac{\pi}{N}s\cdot\Delta t, & \text{at } g=t_{Hm},\\ \sum\limits_{s=z_m+T(g-1-t_{Hm})}^{z_m+T(g-t_{Hm})-1}\sin^2\frac{\pi}{N}s\cdot\Delta t & \text{at } t_{Hm}<g\le t_{Km},\\ 0 & \text{at } g\le t_{Hm}, t_{Km}<g.\end{cases} \quad (4)$$

For the notation introduced in Fig. 1, $z_1 = z$ and $z_2 = z - w$, where z is the shift of the beginning of the measuring sample with respect to the beginning of the first pulse, and w is the shift of the beginning of the second pulse with respect to the initial point of the first pulse, where the shift is expressed in ADC readings.

Taking into account the above, let us write the equation system based on two readings of the signal mixture — U_i and U_{i+1}, obtained in the course of additional gating of readings at the output of the analog-to-digital converter on the interval of simultaneous presence of the two signals:

$$U_i = x_1\cdot P_i(z_1)+x_2\cdot P_i(z_2),\quad U_{i+1}=x_1\cdot P_{i+1}(z_1)+x_2\cdot P_{i+1}(z_2), \quad (5)$$

where x_1 and x_2 are signal amplitudes, i is the ordinal number of the first strobe among those used for measurement, and $P_i(z_m)$ is the function of the transformed envelope of the mth pulse in the ith strobe described by (4). The measurement noise is not considered in this case.

To simplify the further mathematics, introduce the notation $A_1 = P_i(z_1)$, $B_1 = P_i(z_2)$, $A_2 = P_{i+1}(z_1)$, $B_2 = P_{i+1}(z_2)$. As a result, the initial equation system in terms of unknown amplitudes of the pair of video pulses can be rewritten as

$$U_i = A_1x_1 + B_1x_2,\quad U_{i+1} = A_2x_1 + B_2x_2. \quad (6)$$

To resolve the above linear equation system, we use Cramer's rule. Upon calculation of the principal and partial determinants of system (6), we arrive at the required estimates of amplitudes of the signals:

$$x_1 = (U_iB_2 - U_{i+1}B_1)/(A_1B_2 - A_2B_1),$$
$$x_2 = (A_1U_{i+1} - U_iA_2)/(A_1B_2 - A_2B_1). \quad (7)$$

Then the obtained estimates of the amplitudes must be compared with the scale of partition of amplitude levels, and used to decode the message transmitted.

Extend the above results of processing to the case of three pulses in a burst. In Fig. 2 we can see a variant of arrangement of three pulses on the time axis, where for the signals having different amplitudes the resulting envelope of the pulse mixture in the presence of noise is shown (the zigzag-shaped curve). The pictures have been obtained by calculations with the aid of Mathcad package.

Based on the signal mixture voltage samples (the upper curve in Fig. 2), set up a system of equations in unknown amplitudes of the three video pulses provided that the signal readings, obtained after additional gating and taken for measurement, correspond to the interval of simultaneous presence of the three pulses:

$$\begin{cases} U_i = x_1 \cdot P_i(z_1) + x_2 \cdot P_i(z_2) + x_3 P_i(z_3), \\ U_{i+1} = x_1 \cdot P_{i+1}(z_1) + x_2 \cdot P_{i+1}(z_2) + x_3 \cdot P_{i+1}(z_3), \\ U_{i+2} = x_1 \cdot P_{i+2}(z_1) + x_2 \cdot P_{i+2}(z_2) + x_3 \cdot P_{i+2}(z_3). \end{cases}$$

Due to a large signal-to-noise ratio, we also neglect the noise effect. Introduce the following notation:

$$A_1 = P_i(z_1),\ B_1 = P_i(z_2),\ C_1 = P_i(z_3),\ A_2 = P_{i+1}(z_1),\ B_2 = P_{i+1}(z_2),$$
$$C_2 = P_{i+1}(z_3),\ A_3 = P_{i+2}(z_1),\ B_3 = P_{i+2}(z_2),$$
$$C_3 = P_{i+2}(z_3),\ U_1 = U_i,\ U_2 = U_{i+1},\ U_3 = U_{i+2}.$$

Using Cramer's rule, define the unknown amplitudes of each signal. The principal and partial determinants take the form

$$d = \begin{vmatrix} A_1 & B_1 & C_1 \\ A_2 & B_2 & C_2 \\ A_3 & B_3 & C_3 \end{vmatrix}, \quad d_{x_1} = \begin{vmatrix} U_1 & B_1 & C_1 \\ U_2 & B_2 & C_2 \\ U_3 & B_3 & C_3 \end{vmatrix},$$

$$d_{x_2} = \begin{vmatrix} A_1 & U_1 & C_1 \\ A_2 & U_2 & C_2 \\ A_3 & U_3 & C_3 \end{vmatrix}, \quad d_{x_3} = \begin{vmatrix} A_1 & B_1 & U_1 \\ A_2 & B_2 & U_2 \\ A_3 & B_3 & U_3 \end{vmatrix},$$

from which we obtain the amplitude estimates

$$x_1 = \frac{d_{x_1}}{d} = \frac{U_1 B_2 C_3 + B_1 C_2 U_3 + U_2 B_3 C_1 - U_3 B_1 C_3 - B_3 C_2 U_1 - U_3 B_2 C_1}{A_1 B_2 C_3 + A_3 B_1 C_2 + A_2 C_1 B_3 - A_3 B_2 C_1 - A_1 B_3 C_2 - C_3 A_2 B_1},$$

$$x_2 = \frac{d_{x_2}}{d} = \frac{A_1 U_2 C_3 + U_1 C_2 A_3 + A_2 U_3 C_1 - A_3 U_2 C_1 - A_2 U_1 C_3 - U_3 C_2 A_1}{A_1 B_2 C_3 + A_3 B_1 C_2 + A_2 C_1 B_3 - A_3 B_2 C_1 - A_1 B_3 C_2 - C_3 A_2 B_1},$$

$$x_3 = \frac{d_{x_3}}{d} = \frac{A_1 B_2 U_3 + B_1 U_2 A_3 + A_2 B_3 U_1 - A_3 B_2 U_1 - A_2 B_1 U_3 - B_3 U_2 A_1}{A_1 B_2 C_3 + A_3 B_1 C_2 + A_2 C_1 B_3 - A_3 B_2 C_1 - A_1 B_3 C_2 - C_3 A_2 B_1}.$$

The further procedure of message decoding is identical to that inherent in the above two-pulse processing.

By analogy with the cases considered above, let us use the output voltages obtained from the procedure of additional gating of ADC readings for setting up the system of M equations in unknown amplitudes of M pulse signals (Fig. 3):

$$\begin{cases} U_i = x_1 P_i(z_1) + x_2 P_i(z_2) + \ldots + x_M P_i(z_M), \\ U_{i+1} = x_1 P_{i+1}(z_1) + x_2 P_{i+1}(z_2) + \ldots + x_M P_{i+1}(z_M), \\ U_{i+2} = x_1 P_{i+2}(z_1) + x_2 P_{i+2}(z_2) + \ldots + x_M P_{i+2}(z_M), \\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \\ U_{i+M-1} = x_1 P_{i+M-1}(z_1) + x_2 P_{i+M-1}(z_2) + \ldots + x_M P_{i+M-1}(z_M). \end{cases}$$

Obviously, the duration of the measurement sample covering all M signals makes up no less than M strobes.

Introduce the following notation:

$$A_1 = P_i(z_1),\ B_1 = P_i(z_2),\ C_1 = P_i(z_3),$$
$$A_2 = P_{i+1}(z_1),\ B_2 = P_{i+1}(z_2),\ C_2 = P_{i+1}(z_3),$$
$$A_3 = P_{i+2}(z_1),\ B_3 = P_{i+2}(z_2),\ C_3 = P_{i+2}(z_3),$$

$$A_M = P_{i+M-1}(z_1),\ B_M = P_{i+M-1}(z_2),\ C_M = P_{i+M-1}(z_3),$$

$$U_1 = U_i,\ U_2 = U_{i+1},\ U_3 = U_{i+2}, \ldots, U_M = U_{i+M-1}.$$

With regard for the above notation, resolve the equation system in the pulse amplitudes $x_m = d_{x_m} / d$, $m = 1,\ldots, M$, where

$$d = \begin{vmatrix} A_1 & B_1 & \ldots & C_1 \\ A_2 & B_2 & \ldots & C_2 \\ A_3 & B_3 & \ldots & C_3 \\ \ldots & \ldots & \ldots & \ldots \\ A_M & B_M & \ldots & C_M \end{vmatrix},\quad d_{x_1} = \begin{vmatrix} U_1 & B_1 & \ldots & C_1 \\ U_2 & B_2 & \ldots & C_2 \\ U_3 & B_3 & \ldots & C_3 \\ \ldots & \ldots & \ldots & \ldots \\ U_M & B_M & \ldots & C_M \end{vmatrix},$$

$$d_{x_2} = \begin{vmatrix} A_1 & U_1 & \ldots & C_1 \\ A_2 & U_2 & \ldots & C_2 \\ A_3 & U_3 & \ldots & C_3 \\ \ldots & \ldots & \ldots & \ldots \\ A_M & U_M & \ldots & C_M \end{vmatrix},\quad d_{x_M} = \begin{vmatrix} A_1 & B_1 & \ldots & U_1 \\ A_2 & B_2 & \ldots & U_2 \\ A_3 & B_3 & \ldots & U_3 \\ \ldots & \ldots & \ldots & \ldots \\ A_M & B_M & \ldots & U_M \end{vmatrix}.$$

The above procedures for estimating the amplitudes of the pulses overlapping in time can be extended to other situations of signal superposition, since the time of arrival of each signal is assumed to be known.

It can be easily seen that the above methods of measurement of pulse signal amplitudes are similar to one another in neglecting the noise effect of the measurement results. In actual conditions, the presence of noise in the reception path is inevitable, so it would be interesting to consider the synthesis of the measurement procedures best suitable for processing of signals against the noise background.

One of the approaches consists in using a well-known method of least squares (MLS). As applied to the two-pulse protocol of communication (Fig. 1), the MLS application assumes the search for the minimum of the residual function in terms of unknown amplitudes of signals:

$$F = \{U_i - x_1 P_i(z_1) - x_2 P_i(z_2)\}^2 + \{U_{i+1} - x_1 P_{i+1}(z_1) - x_2 P_{i+1}(z_2)\}^2 = \min. \tag{8}$$

The function of residuals is obtained from the differences between the left- and right-hand parts of the equalities comprising system (5).

In order to find the minimum of the function F, we have to determine its derivatives with respect to the sought variables x_1 and x_2. After differentiation and equating the derivatives to zero, we can form the system

$$\begin{cases} \tilde{U}_1 = \tilde{A}_1 x_1 + \tilde{B}_1 x_2, \\ \tilde{U}_2 = \tilde{A}_2 x_1 + \tilde{B}_2 x_2, \end{cases}$$

where

$$\tilde{U}_1 = U_i \cdot P_i(z_1) + U_{i+1} \cdot P_{i+1}(z_1),\ \tilde{U}_2 = U_i \cdot P_i(z_2) + U_{i+1} \cdot P_{i+1}(z_2),$$

$$\tilde{A}_1 = P_i^2(z_1) + P_{i+1}^2(z_1),\ \tilde{A}_2 = \tilde{B}_1 = P_i(z_1) \cdot P_i(z_2) + P_{i+1}(z_1) \cdot P_{i+1}(z_2) = C,$$

$$\tilde{B}_2 = P_i^2(z_2) + P_{i+1}^2(z_2).$$

Using Cramer's rule, we can easily find the estimates of amplitudes, which minimize the sum of squared residuals (8):

$$x_1 = (\tilde{U}_1 \tilde{B}_2 - \tilde{U}_2 C)/(\tilde{A}_1 \tilde{B}_2 - C^2),\ x_2 = (\tilde{U}_2 \tilde{A}_1 - \tilde{U}_1 C)/(\tilde{A}_1 \tilde{B}_2 - C^2). \tag{9}$$

These estimates are statistically optimal and more appropriate for implementation than those described by (7).

It is essential that application of MLS permits to use in the processing all the samples of the signal mixture (instead of two), where the two pulses are present simultaneously. To do this, we only have to rewrite the residual function in the form

$$\widetilde{F} = \sum_{i=0}^{S-1} \{U_i - x_1 P_i(z_1) - x_2 P_i(z_2)\}^2 = \min,$$

hence

$$\frac{\partial \widetilde{F}}{\partial x_1} = -2 \cdot \sum_{i=0}^{S-1} U_i P_i(z_1) + 2 \cdot x_1 \cdot \sum_{i=0}^{S-1} P_i^2(z_1) + 2 \cdot x_2 \cdot \sum_{i=0}^{S-1} P_i(z_1) P_i(z_2);$$

$$\frac{\partial \widetilde{F}}{\partial x_2} = -2 \cdot \sum_{i=0}^{S-1} U_i P_i(z_2) + 2 \cdot x_1 \cdot \sum_{i=0}^{S-1} P_i(z_1) \cdot P_i(z_2) + 2 \cdot x_2 \cdot \sum_{i=0}^{S-1} P_i^2(z_2).$$

By setting the derivatives obtained as equal to zero and solving the respective equation system, we come to the same expressions (9) after the substitution

$$\widetilde{U}_1 = \sum_{i=0}^{S-1} U_i P_i(z_1), \; \widetilde{U}_2 = \sum_{i=0}^{S-1} U_i P_i(z_2), \; \widetilde{A}_1 = \sum_{i=0}^{S-1} P_i^2(z_1),$$

$$\widetilde{B}_2 = \sum_{i=0}^{S-1} P_i^2(z_2), \; C = \sum_{i=0}^{S-1} P_i(z_1) \cdot P_i(z_2).$$

In a similar manner, we can obtain the statistical optimal estimates of amplitudes for three and more overlapping pulses. Because of awkwardness of the mathematical rearrangements, we did not include them in the paper.

The suggested methods permit to diminish by T times the volume of the measuring sample used for time compression of channels at message decoding. Thus we facilitate the realization of compression based on the super-Rayleigh resolution of signals in the time domain, and form the basis for its application in communication systems using the principle of digital shaping of the beam.

The considered scheme of synthesis of measurement procedures can be extended to the asynchronous reception conditions, and to radio-frequency processing of communication signals in digital antenna arrays. Further inquiries should be oriented to the investigation of potentialities of time compression of signals, and to the extension of the suggested approach to the case of radio pulses.

REFERENCES

1. V. I. Slusar and Yu. V. Utkin, Izv. VUZ. Radioelektronika, Vol. 46, No. 5, pp. 40–48, 2003.

2. V. I. Slusar, Izv. VUZ. Radioelektronika, Vol. 39, No. 5, pp. 55–62, 1996.

3. Bernard Sklyar, Digital Communication. Theoretical Foundations and Practical Applications, 2nd revised edition [Russian translation], pp. 119–122, Izd-vo "Dom Williams", Moscow, 2003.

2 June 2004