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A METHOD FOR MULTI-PULSE TRANSMISSION OF SIGNALS IN MIMO-SYSTEM

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A new principle is suggested for shaping pulse signals in the transmitting antenna of the MIMO-system. The new method differs from the known ones in introducing, in every channel, a certain time shift of signals. As a result, in space there occurs superposition of pulses overlapping in time. At the reception side, after analog-digital conversion of the signal mixture, by known times of signal arrival we can estimate their amplitude components, and perform demodulation of the transmitted messages.

In the last few years, much attention has been paid to investigations related to application for wireless access of so-called MIMO-systems (Multiple Input — Multiple Output) based on usage of digital antenna arrays (DAA) with a small number of channels. These systems permit to realize different variants of orthogonal frequency discrete modulation (OFDM) of signals in the form of bursts of oscillations, which are extended in time and orthogonal in frequency. At the same time, little attention was paid to the use of pulse signals in communication systems based on MIMO-principle.

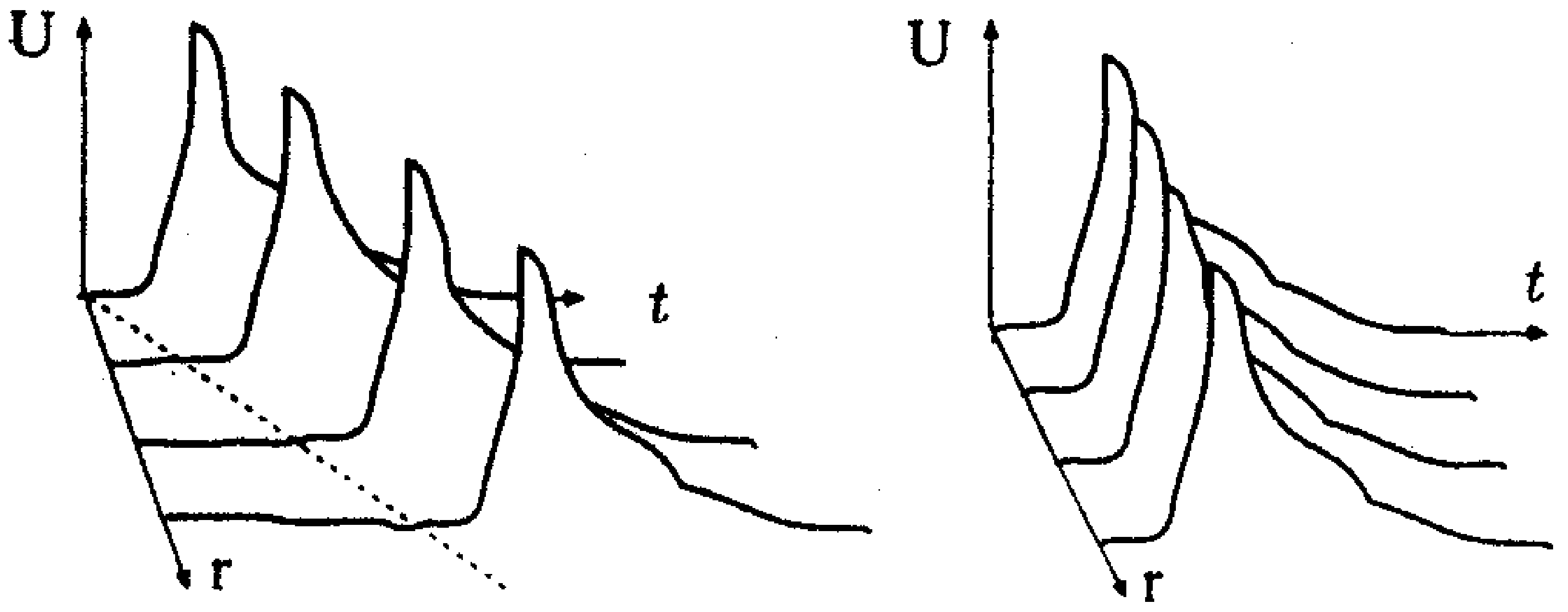
The purpose of this paper is description of a new approach to implementation of MIMO-systems, which differs from known ones in that we use pulse signals radiated by M partial antenna elements of DAA with a determinate relative inter-channel shift of signals in time.

This paper is an extension of the methods described in [1] and is devoted to synthesis of procedures of demodulation of the multi-signal mixture at the reception DAA output in the case of pulsed mode of operation of a MIMO-system.

All subsequent derivations will be performed as applied to the uniform or non-equidistant interchannel time shift of pulse signals. Figure 1*a* illustrates the suggested principle of radiation of pulse signals by the antenna array (the signals in r transmitting channels are generated at different time instants, but their mutual shift never exceeds the duration of a single pulse). Figure 1*b* represents a traditionally used scheme of pulse radiation by the transmitting antenna array (the signals in all r channels are radiated at the same time instant).

The rules of variation of envelopes of the pulses shaped in different channels may be identical to each other, or different, but in any case they are assumed exactly known. Prior to radiation, the amplitudes of the partial pulses undergo multilevel amplitude or quadrature amplitude modulation (M-QAM). Here, as distinct from OFDM, there is no need in orthogonality of signal carrier frequencies, which makes it possible to narrow the spectral band of the radio communication line. In addition, we may relieve requirements to the instantaneous dynamic range of DAA transmitting channels, since the radiated pulses are overlapping in time not in the analog-type transmitting channel (as in [1]), but in space.

In the case of such operation of the transmitter, the receiving DAA will contain a mixture of M signals overlapping in time (Figure 2 shows schematically an M-pulse signal mixture at the output of the partial reception channel). In order to demodulate the received messages, this mixture must be processed simultaneously over all the antenna channels. Particularly, based on signal mixture samples, picked out from the outputs of analog-to-digital converters (ADC),



a *b*

Fig. 1

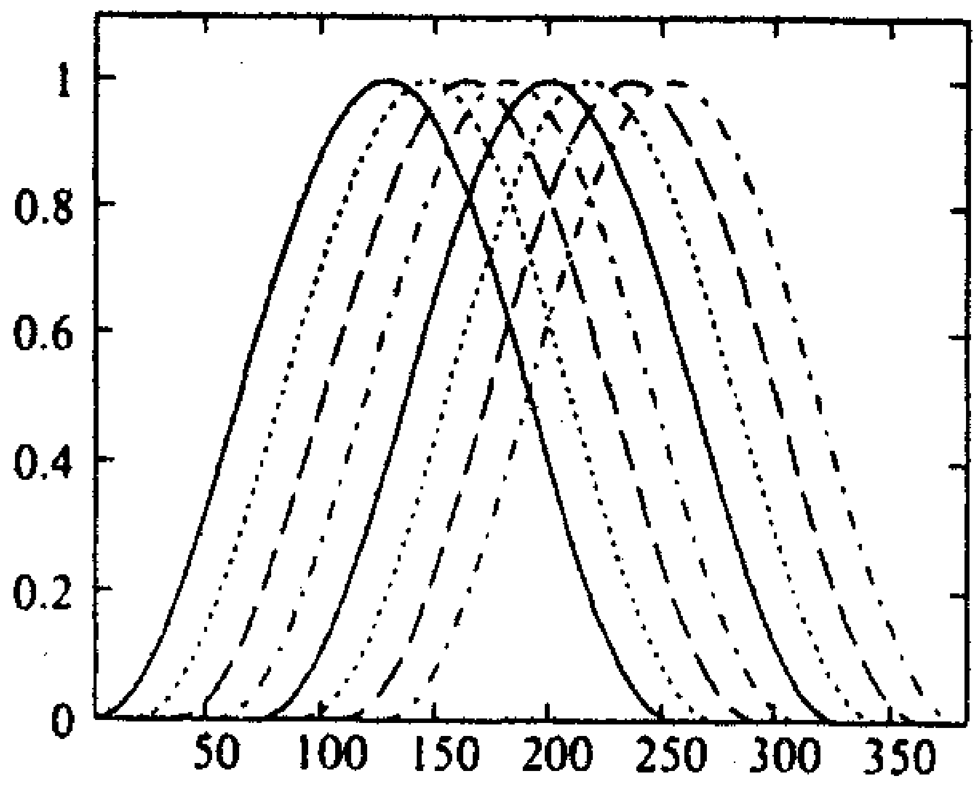


Fig. 2

synchronized in each reception channel of the antenna array, we shape the DAA response, which can be represented in the matrix form

$$U = P \cdot A + n \tag{1}$$

where U is the vector of complex samples of the signal mixture at the outputs of R reception channels of DAA,

$$P = Q \blacksquare K = \begin{bmatrix} Q_1(x_1) & \dots & Q_1(x_M) \\ \vdots & \vdots & \vdots \\ Q_r(x_1) & \dots & Q_r(x_M) \end{bmatrix} \blacksquare \begin{bmatrix} K(s_1 - z_1) & \dots & K(s_1 - z_M) \\ \vdots & \vdots & \vdots \\ K(s_t - z_1) & \dots & K(s_t - z_M) \end{bmatrix} =$$

$$= \begin{bmatrix} Q_1(x_1) \cdot \begin{bmatrix} K(s_1 - z_1) \\ \vdots \\ K(s_1 - z_1) \end{bmatrix} & \dots & Q_1(x_M) \cdot \begin{bmatrix} K(s_t - z_M) \\ \vdots \\ K(s_t - z_M) \end{bmatrix} \\ \vdots & \vdots & \vdots \\ Q_r(x_1) \cdot \begin{bmatrix} K(s_1 - z_1) \\ \vdots \\ K(s_t - z_1) \end{bmatrix} & \dots & Q_r(x_M) \cdot \begin{bmatrix} K(s_t - z_M) \\ \vdots \\ K(s_t - z_M) \end{bmatrix} \end{bmatrix}, \tag{2}$$

"$\blacksquare$" denotes the Chatri-Rao product [2]; $Q_r(x_m)$ is the known directivity characteristic of the rth antenna element of the reception DAA in the direction of the mth radiator with the known angular coordinate x_m; $K(s_t - z_m)$ is the known value of the normalized discrete function of the envelope of the mth pulse signal in the tth time reading; s_t is the ordinal number of ADC sample; z_m is the shift of the first reading of the measurement sample with respect to the starting point of the mth pulse; $A = [a_1, ..., a_M]^T$ is the vector of complex amplitudes of the signal, bearing the information about the message transmitted; and n is the vector of complex values of the measurement noise.

One possible implementation is when every of M channels of the active DAA radiates the packets filled with V pulses, overlapping in time and modulated in amplitude. The inter-channel shift of the signal packets in time should be matched to the interval between the pulses.

If in each transmitting channel we use superposition of V signals with their different time positions, then for analytical description of response of the receiving DAA we must use the blockwise Kronecker product. In this case the matrix of directivity characteristics Q is broken into blocks corresponding to different columns:

$$P = \begin{bmatrix} Q_1(x_1) & \cdots & Q_1(x_M) \\ \vdots & \vdots & \vdots \\ Q_R(x_1) & \cdots & Q_R(x_M) \end{bmatrix} [\otimes] \begin{bmatrix} K_1(z_{11}) & \dots & K_1(z_{V1}) & \dots & K_1(z_{1M}) & \dots & K_1(z_{VM}) \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ K_T(z_{11}) & \dots & K_T(z_{V1}) & \dots & K_T(z_{1M}) & \dots & K_T(z_{VM}) \end{bmatrix} =$$

$$= \begin{bmatrix} Q_1(x_1)\cdot\begin{bmatrix} K_1(z_{11}) & \dots & K_1(z_{V1}) \\ \vdots & \vdots & \vdots \\ K_T(z_{11}) & \dots & K_T(z_{V1})\end{bmatrix} & \dots & Q_1(x_m)\cdot\begin{bmatrix}K_1(z_{1M}) & \dots & K_1(z_{VM})\\ \vdots&\vdots&\vdots\\ K_T(z_{1M}) & \dots & K_T(z_{VM})\end{bmatrix} \\ \vdots & \vdots & \vdots \\ Q_r(x_1)\cdot\begin{bmatrix} K_1(z_{11}) & \dots & K_1(z_{V1}) \\ \vdots & \vdots & \vdots \\ K_T(z_{11}) & \dots & K_T(z_{V1})\end{bmatrix} & \dots & Q_R(x_m)\cdot\begin{bmatrix}K_1(z_{1M}) & \dots & K_1(z_{VM})\\ \vdots&\vdots&\vdots\\ K_T(z_{1M}) & \dots & K_T(z_{VM})\end{bmatrix} \end{bmatrix}. \qquad (3)$$

Here we used a more compact notation of discrete envelope — $K_t(z_{vm})$, where t denotes the number of ADC reading, and v is the number of a pulse in the V-signal packet radiated by the mth transmission channel.

It is important that the vector of complex amplitudes also takes a block structure:

$$A = [a_{11} \dots a_{V1} \vdots \dots \vdots a_{1M} \dots a_{VM}] \qquad (4)$$

In the general case, for every mth transmitting channel we can allocate its own (not occurring in other channels) envelope of signals. In the matrix expression (3) of DAA response such envelope will be described by the function $K_{tm}(z_{vm})$ having an additional index m.

If we have to account the discrepancies between AFR of reception channels, resulting in distortions of the laws of variation of pulse envelopes depending on the outputs of the partial receivers, relationships (3) have to be supplemented with block partition of the matrix Q over the ordinal numbers of reception channels:

$$P = \begin{bmatrix} Q_1(x_1) & \cdots & Q_1(x_M) \\ \vdots & \vdots & \vdots \\ Q_R(x_1) & \cdots & Q_R(x_M) \end{bmatrix} [\otimes] \begin{bmatrix} K_{111}(z_{11}) & \cdots & K_{111}(z_{V1}) & \cdots & K_{1M1}(z_{1M}) & \cdots & K_{1M1}(z_{VM}) \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ K_{T11}(z_{11}) & \cdots & K_{T11}(z_{V1}) & \cdots & K_{TM1}(z_{1M}) & \cdots & K_{TM1}(z_{VM}) \\ \vdots & \cdots & \vdots & \cdots & \vdots & \cdots & \vdots \\ K_{11R}(z_{11}) & \cdots & K_{11R}(z_{V1}) & \cdots & K_{1MR}(z_{1M}) & \cdots & K_{1MR}(z_{VM}) \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ K_{T1R}(z_{11}) & \cdots & K_{T1R}(z_{V1}) & \cdots & K_{TMR}(z_{1M}) & \cdots & K_{TMR}(z_{VM}) \end{bmatrix} =$$

$$= \begin{bmatrix} Q_1(x_1)\cdot\begin{bmatrix} K_{111}(z_{11}) & \cdots & K_{111}(z_{V1}) \\ \vdots & \vdots & \vdots \\ K_{T11}(z_{11}) & \cdots & K_{T11}(z_{V1})\end{bmatrix} & \cdots & Q_1(x_M)\cdot\begin{bmatrix}K_{1M1}(z_{1M}) & \cdots & K_{1M1}(z_{VM})\\ \vdots&\vdots&\vdots\\ K_{TM1}(z_{1M}) & \cdots & K_{TM1}(z_{VM})\end{bmatrix} \\ \vdots & \vdots & \vdots \\ Q_R(x_1)\cdot\begin{bmatrix} K_{11R}(z_{11}) & \cdots & K_{11R}(z_{V1}) \\ \vdots & \vdots & \vdots \\ K_{T1R}(z_{11}) & \cdots & K_{T1R}(z_{V1})\end{bmatrix} & \cdots & Q_R(x_M)\cdot\begin{bmatrix}K_{1MR}(z_{1M}) & \cdots & K_{1MR}(z_{VM})\\ \vdots&\vdots&\vdots\\ K_{TMR}(z_{1M}) & \cdots & K_{TMR}(z_{VM})\end{bmatrix} \end{bmatrix}, \qquad (5)$$

where $K_{tmr}(z_{vm})$ is the discrete envelope of the vth pulse in the V-signal packet, radiated by the mth transmitting channel, at the output of the rth reception channel at the time instant t.

It is well known that signal processing in the reception DAA may be performed after digital "RP-shaping", with transition to the "space of beams", i.e., at the outputs of secondary spatial channels synthesized with aid of the fast Fourier transform. In this case, instead of table values of discrete functions $Q_r(x_m)$, in (3) we must introduce the relationships for directivity characteristic of the spatial FFT-filter

$$Q_r(x_m) = \sin\frac{R}{2}\left(\frac{2d}{l}\pi\sin x_m - 2r\pi/R\right)/\sin\left(\frac{2d}{l}\pi\sin x_m - 2r\pi/R\right)/2$$

where R is the number of antenna elements, and d is the distance between antenna elements in the antenna array.

Then the equation system (1), which has been set up by any of the techniques considered above, can be resolved in unknown estimates of amplitude components of each partial pulse, which at QAM-modulation bear useful information.

For this purpose we use the maximum likelihood method permitting to obtain optimal estimates of signal amplitudes. In the presence of Gaussian non-correlated noise the respective estimates can be written in the known form

$$A^c = \mathrm{Re}(\{P^T P\}^{-1} P^T \dot{U}), \quad A^s = \mathrm{Im}(\{P^T P\}^{-1} P^T \dot{U}), \tag{6}$$

where $A^c = [a_1^c \cdots a_M^c]^T$, $A^s = [a_1^s \cdots a_M^s]^T$; Re is the real part of the complex vector; Im is its imaginary part; P is the signal matrix (2), (3), or (5), whose entries represent the product of the directivity characteristic by discrete samples of functions of pulse signal envelopes with regard for their known (with an accuracy of the discretization period) mutual position in time; U is the vector of complex samples of signal mixture voltages at ADC output; T denotes transposition; and a_m^c, a_m^s are quadrature components of signal amplitudes.

When the time of arrival of all signals is exactly known (the communication line in the locked mode of operation), the potential accuracy of measurement of quadrature components of the received pulse amplitudes is dictated by the Cramèr-Rào bound, for which the Fisher information matrix [2] has the form $I=\sigma^{-2}[P^T P]$, where σ^2 is the noise variance in an ADC sample, and P is the above-mentioned signal matrix.

Under non-locked reception conditions, when the exact time of arrival of the signal packet is unknown, and the shift between pulses remains determinate, for calculating the potential accuracy of quadrature components of pulse signals we use a more general representation of the Fisher information matrix [3]:

$$I = \frac{1}{\sigma^2} \left[\begin{array}{c:c} P^T P & (A^* \otimes P^T) \dfrac{\partial P}{\partial Y} \\ \left(\dfrac{\partial P}{\partial Y}\right)^T (A \otimes P) & \left(\dfrac{\partial P}{\partial Y}\right)^T (AA^* \otimes 1) \dfrac{\partial P}{\partial Y} \end{array} \right]$$

where $\partial P / \partial Y$ is the Neuedecker derivative of the signal matrix P with respect to the vector Y composed of the unknown parameters of time shift of M signals (in the simplest case, only the time of reception of the first signal in the packet is unknown, while the relative shift of the rest of the pulses is assumed known and non-modified in the DAA reception channels; 1 is the unit vector; A — the vector of signal amplitudes; "⊗" denotes Kronecker's multiplication; and "*" means complex-conjugate transposition.

In a more general case, for elements of the vector Y we may consider angular coordinates, which characterize unknown directions of signals' arrival.

The suggested approach to construction of MIMO-system permits to improve the immunity of communication channels to unsanctioned access, and to raise the rate of data transmission to longer distances (against several hundred meters inherent in the known MIMO-system implementations based on OFDM). Of importance is the fact that the "intra-system" partition of MIMO communication channels, operating with multi-pulse signals, is attained due to accounting the dependence of the inter-pulse time interval on the direction to subscriber.

Our further investigations will be aimed at analysis of potentialities of time division (compression) of signals in multi-pulse packets with the aid of imitative simulation of the MIMO-system.

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