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ACCURACY ESTIMATION OF METHOD FOR PARAMETERS MEASUREMENT OF PULSE SIGNALS AND OFDM (N-OFDM) SIGNALS

For the first time, with the help of mathematical modelling, clarified the properties of the received analytical relations and set the limits possibilities of OFDM (N-OFDM) signal demodulation method in the background of impulse signals in the integrated radar and telecommunication systems. It was found out that at angular spacing's of sources of pulsed and OFDM signals at a value that not less than 0,75 width of a secondary beam. The same applies to the effects of active interference.

Keywords: *digital antenna array, lower bound of Cramer-Rao, block matrix, directional pattern.*

Introduction

Over recent years, digital beam forming technology has been widely developed in communication and radar sectors, software reconfiguration of equipment and MIMO (multiple input - multiple output). In this case uses similar and in some cases identical circuit design solutions. This approach prompted a number of prominent scientists to promote the idea of creation of Integrated Radar-Telecommunication Systems or Radcom Systems [1-9]. Such an idea corresponds to the Altshuler and Petrov's law of transition of the system to the super system [10-12]. This law implies that each system integrates with another system after some time, thus creating a new, enriched with additional properties over-the-system.

Analysis of latest research and publications.

Famous technologies for the creation of Radcom systems are widely described in the literature [1-9]. In authors opinion, the most progressive view on the integration of communication systems has been proposed in the work [1], where it was proved that traditional methods of radar have exhausted themselves and justified the transition to integrated radar and telecommunication systems based on the technology of digital antenna arrays (DAA) and MIMO in combination with OFDM signals. However, in [13, 14] in 2010, it was proposed to create a multi-position communication and radar system using OFDM and N-OFDM signals. To implement the proposed system was developed several appropriate methods of digital signal processing [15-19, 21-23]. One of the developed methods involves, for example, a time-aligned version of the processing of telecommunication and radar signals [15]. Proposed in [15] the method of separate selection of pulse and N-OFDM signals in radar and telecommunication systems allows simultaneous demodulation of both these signals types when on the receiving side used the digital antenna array. However, finding out the conditions for using this method requires additional theoretical studies that aimed, in particular, at identifying the potential evaluating parameters for each of the signal types in the event of their simultaneous presence on the air.

Therefore, the purpose of the paper is to investigate the potentialities of accuracy proposed in [15] method.

The main material.

To estimate the level of potential errors in measuring the amplitudes of the received signals proposed in [15] method is to use the lower bound of Cramer-Rao (CRLB) to disperse the measurement errors of the amplitudes quadrature component of the received signals, which is formed by the inverse of the Fisher's information matrix [20]. For the ratios given in [15], the information matrix for estimating the variances of the amplitude components of the signals is written in a known form:

$$I = \frac{1}{\sigma_{\text{noise}}^2} \cdot P^* P, \tag{1}$$

where P – is the signals matrix, σ^2 – the dispersion of noise according the Gaussian distribution law.

In order to obtain Cramer-Rao lower bound for evaluation of pulse and N-OFDM signals, which simultaneously enter the receiving DAA at their separate spatial selection in radar and telecommunication systems, consider the case where angular coordinates signal sources accurately known. In this case, for the separate selection of pulsed and N-OFDM signals, it is necessary to evaluate the generalized signal amplitudes for each type of signals [15].

Imagine a vector of voltages for signals at the output of a linear DAA with an equidistant arrangement of antenna elements in the presence of disturbances in expression [15]

$$U = QW + n, \tag{2}$$

where $Q = [Q_S \;\vdots\; Q_P \;\vdots\; Q_J]$ – is the block matrix characteristics of the direction (CD) of the secondary spatial channels of the DAA, created by the operation of digital beam forming, in directions towards the N-

OFDM signal source (block Q_S), pulse signal reflectors (block Q_P) and active noise jammers (block Q_J); $W^T = [W_S \mid W_P \mid W_J]$ – block-vector of generalized amplitudes of N-OFDM signals (block W_S), amplitudes of pulse signals (block W_P) and the amplitudes of active jammers (block W_J); "T" – symbol of the matrix transposition operation; n – voltage vector of noise.

In the presence of M sources of N-OFDM signals, P reflectors of pulse signals and J producers of jammers, matrix blocks Q CD for R secondary spatial channels DAA in (2) can be written as [15]:

$$Q_S = \begin{bmatrix} Q_1(x_{1S}) & Q_1(x_{2S}) & \cdots & Q_1(x_{MS}) \\ Q_2(x_{1S}) & Q_2(x_{2S}) & \cdots & Q_2(x_{MS}) \\ \vdots & \vdots & \vdots & \vdots \\ Q_R(x_{1S}) & Q_R(x_{2S}) & \cdots & Q_R(x_{MS}) \end{bmatrix},$$

$$Q_J = \begin{bmatrix} Q_1(x_{1J}) & Q_1(x_{2J}) & \cdots & Q_1(x_{JJ}) \\ Q_2(x_{1J}) & Q_2(x_{2J}) & \cdots & Q_2(x_{JJ}) \\ \vdots & \vdots & \vdots & \vdots \\ Q_R(x_{1J}) & Q_R(x_{2J}) & \cdots & Q_R(x_{JJ}) \end{bmatrix},$$

$$Q_P = \begin{bmatrix} Q_1(x_{1P}) & Q_1(x_{2P}) & \cdots & Q_1(x_{PP}) \\ Q_2(x_{1P}) & Q_2(x_{2P}) & \cdots & Q_2(x_{PP}) \\ \vdots & \vdots & \vdots & \vdots \\ Q_R(x_{1P}) & Q_R(x_{2P}) & \cdots & Q_R(x_{PP}) \end{bmatrix}.$$

where $Q_r(x_m) = \left[\sin\left(\frac{R}{2}[r - x_m]\right)\right]\left[\sin\frac{1}{2}(r - x_m)\right]^{-1}$ – CDr secondary spatial channel synthesized using the Fast Fourier Transform (FFT) operation;

$x_{mS(pP)} = \frac{2\pi}{\lambda} d\left(r - \frac{R-1}{2}\right)\sin\theta_{mS(pP)}$ – generalized angle coordinate of $m(p)$ signal source relative to the normal to the CD; λ – the wavelength of the central carrier signals N-OFDM and pulse signals, d – distance between antenna elements of the CD, R – the number of elements in the antenna array, $\theta_{mS(pP)}$ – angular coordinates $m(p)$ signal sources relative to normal to CD, θ_{jJ} – angular coordinates j jammers relative to the normal to CD.

Then the expression for the CRLB estimates of the vector variance of generalized amplitudes can be written as [20]

$$\sigma_W^2 \geq \sigma_n^2 \mathrm{diag}\left[[Q_S \mid Q_P \mid Q_J]^T [Q_S \mid Q_P \mid Q_J]\right]^{-1}, \quad (3)$$

where σ_n^2 – noise dispersion in a separate time frame voltage signal mixture to output secondary spatial channel of the linear DAA, $\mathrm{diag}[Z]$ – a vector formed from the diagonal elements of the matrix Z.

While counting expression (3) to the dispersion of noise at the output of an analog-to-digital converter (ADC) should take into account the effect of growth dispersion in the performance FFT noise according to expression $\sigma_n^2 = R\sigma_{ADC}^2$, where R – the dimension of spatial fast Fourier transform (FFT), in this case it is the number of elements of the DAA, σ_{ADC}^2 – dispersion of noise at the output of the ADC.

Therefore, the relation (3) will be rewritten as

$$\sigma_W^2 \geq \sigma_{ADC}^2 \cdot R \cdot \mathrm{diag}\left[[Q_S \mid Q_P \mid Q_J]^T [Q_S \mid Q_P \mid Q_J]\right]^{-1}. \quad (4)$$

Similarly, can be calculated the dispersion estimates of pulse signal parameters, in particular the Doppler frequency shift, the time of receipt.

In the course of further research, the properties of the obtained analytical relations were determined by mathematical modelling in the MathCAD package and the boundary possibilities of demodulating N-OFDM signals on the background of the pulse signals action of air targets selections are established. In this case, to simplify the calculations were made assuming that there is no active interference.

In the course of mathematical modelling, theme a square deviation (SDM) of the amplitudes estimates was determined in the ADC quantum. In this case, the bit of ADC does not matter, because for any bit should be made an agreement between sizes of quantum ADCs with SDM noise (for example, they should be equal in size). Angular diversity of signal sources (Δ) was given in the fractions of the main petal of chart of direction (CD) of the DAA. In this case, to reduce the volume of computing during research change step of angular diversity of signal sources was set equal to 0.1 width of the main beam of CD at an interval of angular distances from 1 to 0.1 of the width of the secondary beam CD and 0.01 - in the range from 0.1 to 0.01 beam width.

In fig. 1 – 6 illustrated the results of mathematical modelling of the evaluation process of quadrature component amplitudes of OFDM signal in a separate reference ADC frame on the background of the action of the pulsed radiation source with different angular distance between the relevant sources (horizontal axis). Obtained with this value SDM estimates of amplitude components postponed vertically. Number of antenna elements in DAA for these illustrations was 4, 16 and 64. In addition to the obtained values of SDM estimates of amplitudes, the figures show the estimated value of the CRLB and the limits of its confidence interval for reliability of 0.95.

The obtained results confirm the well-known scientific position, that with increasing number of antenna elements of the DAA in R times CRLB of magnitude SDM estimation of amplitudes decreases in $\sqrt{R}$ times. Most precisely this pattern works for orthogonal angular diversity, that mean, the width of the secondary beam, however, it so stent is noticeable with smaller differences in the angular coordinates too.

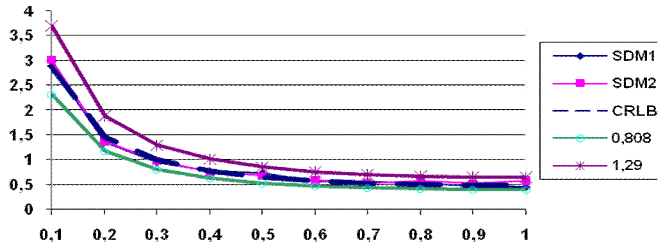

Fig. 1. Dependence of SDM error estimating amplitudes of signals from angular diversity of signal sources (4-element DAA)

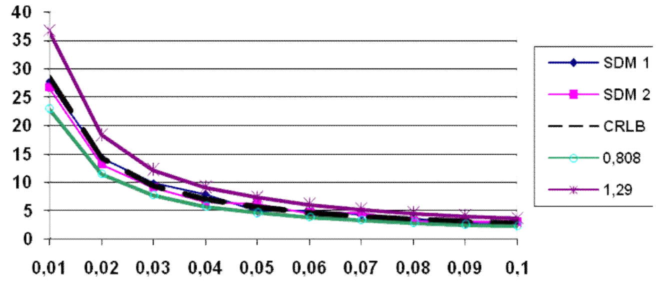

Fig. 2. Dependence of SDM error estimating amplitudes of signals from angular diversity of signal sources (4-element DAA)

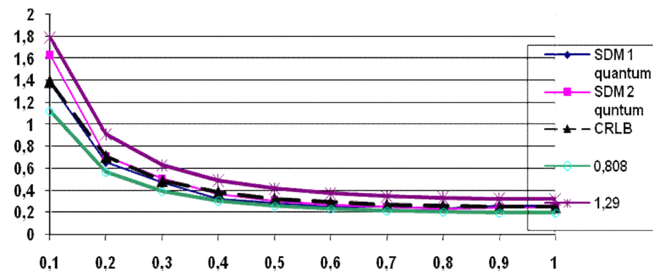

Fig. 3. Dependence of SDM error estimating amplitudes of signals from angular diversity of signal sources (16-element DAA)

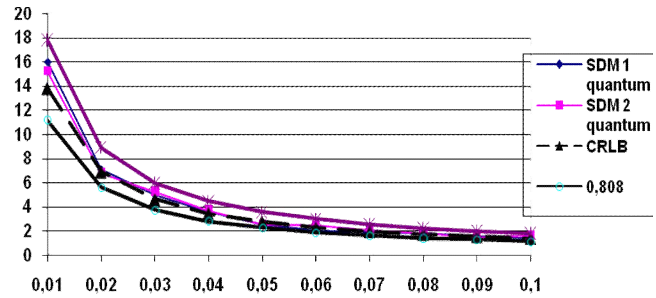

Fig. 4. Dependence of SDM error estimating amplitudes of signals from angular diversity of signal sources (16-element DAA)

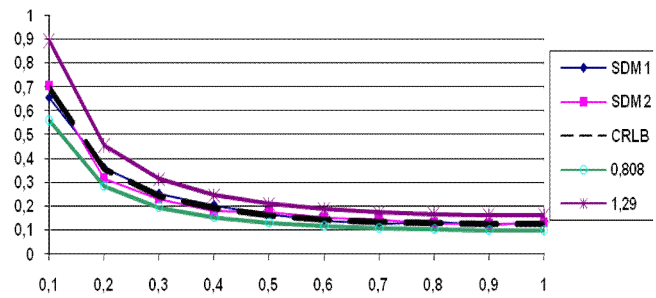

Fig. 5. Dependence of SDM error estimating amplitudes of signals from angular diversity of signal sources (64-element DAA)

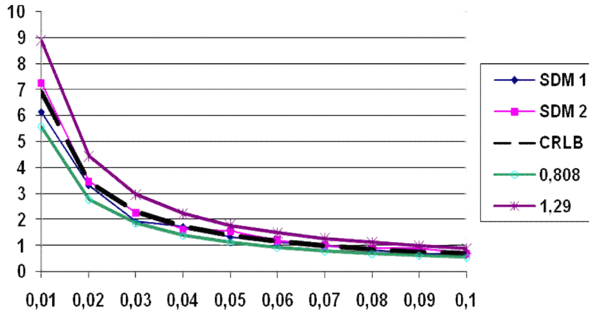

Fig. 6. Dependence of SDM error estimating amplitudes of signals from angular diversity of signal sources (64-element DAA)

For example, at angular separation of sources of signals at 0.1 widths of the secondary beam CD the upper limit of the confidence interval is about 1.8 quantum ADC for a 16-elements DAA and 0.9 for a 64-elements DAA, an increase of the number of antenna elements by 4 times to a two-fold decrease in the magnitude of the SDM estimates of amplitude.

However, for the first time, for the two-stage evaluation of signal parameters, it is established, that regardless of the number of antenna elements DAA at the magnitude of the angular diversity of two sources is less than 0.1the width of the secondary beam CD of the CRLB for SDM estimation of quadrature components signal amplitudes decreases directly proportional to the reduction of angular diversity.

For example, in fig. 5 and 6 the upper limit of the confidence interval of the SDM (0.9 quantum ADC) at angle distributions 0.01 is 10 times less than the corresponding magnitude (9 quantum of ADC) for angular resolution 0.1. The same can be traced on the charts for the 16-elements and 4-elements DAA. In more detail, the corresponding pattern is illustrated in table 1 for a 16-elements DAA case.

Table 1

Results of a mathematical experiment to estimate quadrature component of amplitudes of signals from two sources of radiation for a 16-elements DAA

Angle distributions	0,01	0,02	0,03	0,04	0,05
SDM Re-part	16,00762364063	7,08273378525	4,96604507259	3,55101217215	2,48308680676
SDM Im-part	15,21118998969	6,82238152971	5,27592568829	3,72152332322	2,55936412585
CRLB	13,811125245	6,90691784153	4,60611803314	3,45617050588	2,76656431932
0,808 CRLB	11,15938919796	5,58078961596	3,72174337078	2,79258576875	2,23538397001
1,29 CRLB	17,81635156605	8,90992401557	5,94189226276	4,45845995259	3,56886797192
Angle distributions	0,06	0,07	0,08	0,09	0,1
SDM Re-part	2,06512572943	1,89773861823	1,82312482486	1,58170743279	1,3855681331
SDM Im-part	2,45087930186	2,08224513074	1,84814456956	1,51387786047	1,63548621551
CRLB	2,30712926193	1,97922104478	1,73351759985	1,54261784623	1,39008119658
0,808 CRLB	1,86416044364	1,59921060418	1,40068222068	1,24643521976	1,12318560683
1,29 CRLB	2,97619674789	2,55319514776	2,2362377038	1,98997702164	1,79320474358
Angle distributions	0,2	0,3	0,4	0,5	0,6
SDM Re-part	0,65633827706	0,47396662017	0,32744893379	0,29026547432	0,25658532661
SDM Im-part	0,70939775604	0,50715891436	0,36641200421	0,30901120082	0,27510699818
CRLB	0,70878204683	0,48812909244	0,38301680246	0,32453559254	0,28978868853
0,808 CRLB	0,57269589384	0,39440830669	0,30947757639	0,26222475877	0,23414926033
1,29 CRLB	0,91432884041	0,62968652924	0,49409167517	0,41865091438	0,3738274082
Angle distributions	0,7	0,8	0,9	1,0	
SDM Re-part	0,25733587778	0,23621369299	0,26534275327	0,26626281599	
SDM Im-part	0,25384552527	0,2360208778	0,24495568963	0,24150272577	
CRLB	**0,26898727825**	**0,25719243828**	**0,25152254019**	**0,25**	
0,808 CRLB	0,21734172082	0,20781149013	0,20323021248	0,202	
1,29 CRLB	0,34699358894	0,33177824539	0,32446407685	0,3225	

Based on the obtained results, it is possible to formulate an approximate empirical dependence to calculate the potentially possible value of SDM estimates of quadrature components of signal amplitudes σ_a for the case of angular diversity of two sources by magnitude, less than 0.05 width of the secondary beam CD DAA:

$$\sigma_a \approx 0{,}552\frac{\sigma_{ADC}}{\Delta\sqrt{R}},$$

where σ_{ADC} – SDM noise at the output of the ADC in the fractions of the ADC quantum; Δ – angular separation of radiation sources in fractions of the secondary beam of the CD of DAA; R – number of antenna elements in the DAA.

Directly proportional to the angular range difference on the number of antenna elements of the DAA in determining the CRLB SDM of amplitude components is possible approximately to the angular distance of 0.2 width of beam of CD DAA.

For example, according to the results of a mathematical experiment, that at an angle of differentiation of 0.1 in 64-elements DAA values of CRLB SDM amplitudes (0.6937914361) is approximately equal to the value of the CRLB SDM (0.70878204683)for a 16-elementsDAA at an angle between sources 0.2.That is, in the specified interval of changes of the angular distances at a fixed value of SDM amplitudes achieving decrease in the maximum permissible angular diversity of signal sources in N times requires an increase of the number of antenna elements of the DAA in N2 times.

Conclusions. The conducted mathematical experiment allowed to certify that at angular diversity of sources of pulse and OFDM signals by a value that not less than 0.75 width of a secondary beam CD DAA the presence of the second source is almost unaffected on the accuracy of the estimation of signal amplitudes. The same applies to the effects of active interference. If in DAA applied N-bit ADC, one of the digits of which is sign, then in the specified spatial sector provided there is no output signal of the signal mixture beyond the aperture the ADC can potentially provide a breakdown from impulse exposure or a noise source at the level of 6× (N-1) dB. For example, by a 16-bit ADC it's the limit in 6×15=90dB, which is quite sufficient for the selection of small-scale air targets by means of a pulse signal with the simultaneous reception of OFDM (N-OFDM) communication signals.

If narrow the specified corner sector, then the recovery efficiency from an additional source of signals, the indicator of which is the level of SDM estimates of amplitudes, will worsen. This necessitates the separation of the OFDM communication task are as and radar based on pulse signals. Analyzing, for example, the data of the table 1, it is easy to notice, that the transition from orthogonal angular diversity from Δ=1 to Δ=0,07 leads to an increase in the level of SDM approximately in 8 times (from 0.25 to 2). Thus, such a significant narrowing of the spatial diversity of the pair of signal sources leads to an increase SDM of 18 dB amplitude ratings, that for further signal processing in a two-stage procedure should actually be considered as the corresponding increase in noise measurements of signal parameters. Additional compression of the spatial sector to Δ=0.035 adds 6 dB to the level of SDM estimates of the amplitudes that make total 24 dB, which reduces the level of disassembly continuous (OFDM) signal from pulse (intermittent). In the above case, the 16-bit ADC this will lead to a potentially possible disassembly level of 90 – 24 = 66 dB, which is also quite acceptable.

It should also be noted that due to the accumulation of OFDM signals in time in the synthesis of frequency filters using the Fast Fourier Transform procedure the specified values, that delay from the pulse (noise) signal will increase. However, as noted in [21], in the practical implementation of the proposed approach given estimates of the achievable level of oppression mutual influence of the sources of the two signals will need to be adjusted taking into account the negative factors, that is due to the non-identity of the frequency response of the receiving channels and the antenna elements direction diagrams of the DAA, limited accuracy of information about angular coordinates of signal sources, nonlinearity of analog segment of receiving channels in conjunction with non-linearity of aperture ADC and so on. Detailed assessments of the impact of these and other negative factors go beyond the scope of this work.

These studies will provide an additional stage of the mathematical description of ICS, which would then be the basis for advanced network protocols and technologies, as well as help to consistently manage settings specific protocols at various layers to ensure the exchange of data in the TCP-sessions. For the end user this will mean a decrease sessions disconnections, delays, network devices and channels congestion, packet loss and, consequently, improve quality of service.

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ОЦІНКА ТОЧНОСТІ МЕТОДУ ВИМІРЮВАННЯ СУКУПНОСТІ ПАРАМЕТРІВ ІМПУЛЬСНИХ ТА OFDM (N-OFDM) СИГНАЛІВ

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Вперше за допомогою математичного моделювання з'ясовані властивості отриманих раніше аналітичних співвідношень та встановлені граничні можливості методу демодуляції OFDM (N-OFDM) сигналів на фоні дії імпульсних сигналів в інтегрованих радіолокаційно-телекомунікаційних системах. З'ясовано, що при кутових рознесеннях джерел імпульсного та OFDM сигналів на величину не менше 0,75 ширини вторинного променя діаграми направленості цифрової антенної решітки присутність другого джерела майже не впливає на точність оцінювання амплітуд сигналів. Те ж саме стосується й впливу активних завад.

Ключові слова: *цифрова антена решітка, нижня межа Крамер-Рао, блочна матриця, діаграма спрямованості.*

Література

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