Forming the response of two-channel demodulators

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***Annotation*—This document proposes a technique for forming the response of two-channel demodulators. At the same time, a string vector is used, the elements of which are the weighting coefficients of the demodulator, which are used to form the quadrature components, as well as a wedge-shaped matrix with an inversely symmetrical sequence of elements. The amplitude-frequency characteristics (frequency response) of new synthesized I/Q-demodulators were studied. The possibility of significant suppression of the frequency response side lobes was confirmed, which confirms the noise immunity.**

***Index Terms*—counting filter, digital quadrature demodulator, weighting factors, frequency response**

I. Introduction

One of the promising areas of development of 6G cellular communication technologies [1–4] is the use of spectrally efficient signals. In particular, we are talking about the technology of non-orthogonal frequency discrete multiplexing of signals (N-OFDM) [5]. One of the important conditions for its effective use is the reduction of out-of-band interference and the corresponding suppression of out-of-band channels for receiving radio signals. As part of digital signal processing, this can be ensured by digital filtering of the main reception channels using digital filters or I/Q demodulators [6–13], which combine the functions of quadrature demodulation with digital filtering.

II. Method of forming the response of two-channel demodulators

The simplest method of digital quadrature demodulation is the digitization of signals through an odd number of quarters of the period of their fill frequency, followed by the division of the stream of counts into even and odd by routing number. At the same time, counts adjacent in time in a pair can be considered cosine and sine components. The mathematical description of the simplest quadrature demodulator can be obtained based on the use of a pair of unit weighting coefficients with opposite signs.

The next version of the demodulator is a 4-count demodulator with unit coefficients alternating in sign (1; -1), described at a single-channel input by expressions [14]:

$$U1_0^c = A1_1 U_1 - A1_0 U_3, \quad (1)$$

$$U1_0^s = A1_0 U_0 - A1_1 U_2. \quad (2)$$

A similar option with a two-channel analog input and the use of 4 ADC counts will be written in the form [14–15]:

$$U1_0^c = A1_1 U_1^c - A1_0 U_3^c, \quad (3)$$

$$U1_0^s = A1_0 U_0^c - A1_1 U_2^c, \quad (4)$$

$$U2_0^c = A1_1 U_1^s - A1_0 U_3^s, \quad (5)$$

$$U2_0^s = A1_0 U_0^s - A1_1 U_2^s, \quad (6)$$

where U_n – ADC-counts, n=0,1,..3, A_0=1, A_1= -1.

$$W^s = U_0^c - U_2^c - U_1^s + U_3^s, \quad (7)$$

$$W^c = U_1^c - U_3^c + U_0^s - U_2^s, \quad (8)$$

More complex options for quadrature demodulation require the involvement of 2P ADC readings, where P is the order (size) of the demodulator. For example, at P=3, to form the response of the quadrature demodulator, 6 readings of the 2-channel ADC that digitizes the outputs of the sine and cosine analog channels should be used. At the same time, their sequence {1;4;3}, which is the same for both quadrature channels of forming the I/Q response of the demodulator, can be used as weighting factors. The appropriate processing of signal readings is described by a set of equations:

$$U1_0^c = A1_2 U_1^c - A1_1 U_3^c + A1_1 U_5^c; \quad (9)$$

$$U1_0^s = A1_0 U_0^c - A1_1 U_2^c + A1_2 U_4^c; \quad (10)$$

$$U2_0^s = A1_0 U_0^s - A1_1 U_2^s + A1_1 U_4^s; \quad (11)$$

$$U2_0^c = A1_2 U_1^s - A1_1 U_3^s + A1_0 U_5^s; \quad (12)$$

$$W^s = U_0^c - U_5^s + 4(-U_2^c + U_3^s) + 3(U_4^c - U_1^s); \quad (13)$$

$$W^c = U_0^s + U_5^c - 4(U_3^c + U_2^s) + 3(U_1^c + U_4^s). \quad (14)$$

As can be seen, the description of the responses of the quadrature demodulator in the unfolded record becomes more complicated with the increase in the order of the demodulator, which makes it difficult to visually perceive and analyze the corresponding operations on the signals. Therefore, to obtain more compact records of quadrature demodulation procedures, it is suggested to use their vector-matrix representation.

In particular, the already mentioned method of digital formation of quadrature components can be presented in an equivalent vector and block-vector form:

$$W^s = [1\ 4\ 3] \begin{bmatrix} U_0^c \\ -U_2^c \\ U_4^c \end{bmatrix} + [1\ 4\ 3] \begin{bmatrix} -U_5^s \\ U_3^s \\ -U_1^s \end{bmatrix} = [1\ 4\ 3 \vdots 1\ 4\ 3] \begin{bmatrix} U_0^c \\ -U_2^c \\ U_4^c \\ \cdots \\ -U_5^s \\ U_3^s \\ -U_1^s \end{bmatrix} =$$

$$= [1\ 4\ 3 \vdots 3\ 4\ 1] \begin{bmatrix} U_0^c \\ -U_2^c \\ U_4^c \\ \cdots \\ -U_1^s \\ U_3^s \\ -U_5^s \end{bmatrix}; \quad (15)$$

$$W^c=[1\ 4\ 3]\begin{bmatrix}U_5^c\\ -U_3^c\\ U_1^c\end{bmatrix}+[1\ 4\ 3]\begin{bmatrix}U_0^s\\ -U_2^s\\ U_4^s\end{bmatrix}=[1\ 4\ 3\,\vdots\,1\ 4\ 3]\begin{bmatrix}U_0^s\\ -U_2^s\\ U_4^s\\ \cdots\\ U_5^c\\ -U_3^c\\ U_1^c\end{bmatrix}=$$

$$=[1\ 4\ 3\,\vdots\,3\ 4\ 1]\begin{bmatrix}U_0^s\\ -U_2^s\\ U_4^s\\ \cdots\\ U_1^c\\ U_3^c\\ U_5^c\end{bmatrix}. \qquad (16)$$

Similarly, the response of the two-channel input variant of the well-known 8-count (P=4) demodulator, which has coefficients {1;11;15;5} [6–7], can be described:

a) expanded view

$$U1_0^c=A1_3U_1^c-A1_2U_3^c+A1_1U_5^c-A1_0U_7^c; \qquad (17)$$

$$U1_0^s=A1_0U_0^c-A1_1U_2^c+A1_2U_4^c-A1_3U_6^c; \qquad (18)$$

$$U2_0^s=A1_0U_0^s-A1_1U_2^s+A1_2U_4^s-A1_3U_6^s; \qquad (19)$$

$$U2_0^c=A1_3U_1^s-A1_2U_3^s+A1_1U_5^s-A1_0U_7^s; \qquad (20)$$

$$W^s=U_0^c-5(U_6^c+U_1^s)+15(U_4^c+U_3^s)-11(U_1^c-U_5^s)+U_7^c; \qquad (21)$$

$$W^c=-U_7^c+U_0^s+11(U_5^c-U_2^s)+15(-U_3^c+U_4^s)+5(U_1^c-U_6^s); \qquad (22)$$

b) vectors and block-vectors recording

$$W^s=[1\ 11\ 15\ 5]\begin{bmatrix}U_0^c\\ -U_2^c\\ U_4^c\\ -U_6^c\end{bmatrix}+[1\ 11\ 15\ 5]\begin{bmatrix}U_7^s\\ -U_5^s\\ U_3^s\\ -U_1^s\end{bmatrix}=$$

$$=[1\ 11\ 15\ 5\,\vdots\,5\ 15\ 11\ 1]\begin{bmatrix}U_0^c\\ -U_2^c\\ U_4^c\\ -U_6^c\\ \cdots\\ U_7^s\\ -U_5^s\\ U_3^s\\ -U_1^s\end{bmatrix}=[1\ 11\ 15\ 5\,\vdots\,5\ 15\ 11\ 1]\begin{bmatrix}U_0^c\\ -U_2^c\\ U_4^c\\ -U_6^c\\ \cdots\\ -U_1^s\\ U_3^s\\ -U_5^s\\ U_7^s\end{bmatrix}; \qquad (23)$$

$$W^c=[1\ 11\ 15\ 5]\begin{bmatrix}-U_7^c\\ U_5^c\\ -U_3^c\\ U_1^c\end{bmatrix}+[1\ 11\ 15\ 5]\begin{bmatrix}U_0^s\\ -U_2^s\\ U_4^s\\ -U_6^s\end{bmatrix}=$$

$$=[1\ 11\ 15\ 5\,\vdots\,5\ 15\ 11\ 1]\begin{bmatrix}U_0^s\\ -U_2^s\\ U_4^s\\ -U_6^s\\ \cdots\\ -U_7^c\\ U_5^c\\ -U_3^c\\ U_1^c\end{bmatrix}=[1\ 11\ 15\ 5\,\vdots\,5\ 15\ 11\ 1]\begin{bmatrix}U_0^s\\ -U_2^s\\ U_4^s\\ -U_6^s\\ \cdots\\ U_1^c\\ -U_3^c\\ U_5^c\\ -U_7^c\end{bmatrix}. \qquad (24)$$

A well-known 8-count version of the I/Q demodulator with weighting coefficients {1; 11; 15; 5} [6–7], as it turned out, ceased to be the only possible and even the best one from the point of view of minimizing the frequency response line.

Consider an undefined system of equations with unknown coefficients of an 8-count quadrature demodulator, formed by reducing the number of equations while observing the condition that the sign-changing sum of coefficients is equal to zero:

UR1:=a+3b+5c+7d==2d+4c+6b+8a; (25)

UR2:=a+32 b+52 c+72 d==22 d+42 c+62 b+82 a; (26)

UR5:=a-b+cd=0. (27)

As can be seen, the solution of the specified system is the general form of the coefficients of the 8-count demodulator, expressed in terms of two independent variables:

a=C[1]; b=2C[1]+3C[2]; c=3C[1]+4C[2]; d=2 C[1]+C[2]. (28)

Value of independent variables C[1]=1; C[2]=1 correspond to new weighting factors{1; 5; 7; 3}, and variables C[1]=2; C[2]=1 is easy to obtain the desired weighting factors{2; 7; 10; 5}. Frequency response plots for the two specified new sets of coefficients {1; 5; 7; 3}and {2; 7; 10; 5} are shown in Fig. 1. It is not difficult to see that these Amplitude-Frequency Responses will be more effective at suppressing out-of-band interference than the procedure AFCs.

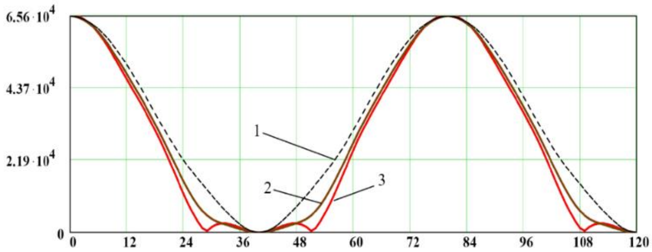
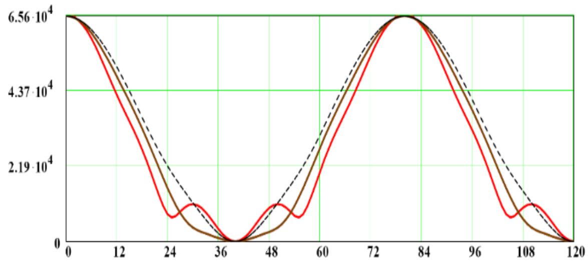


Fig. 1. Frequency response graphs of the 8-count weight window with coefficients **{1; 11; 15; 5}** – line 1; line 2 – for coefficients **{1; 5; 7; 3}**; line 3 – for coefficients **{2; 7; 10; 5}**

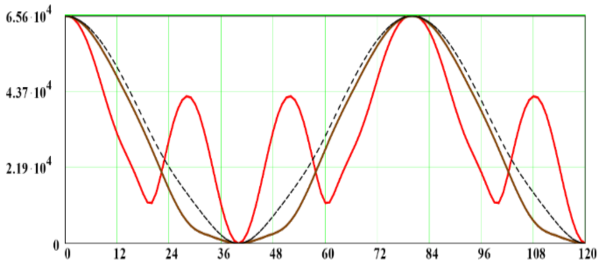
A new version of the solution of the specified system, expressed in terms of two independent variables:

a=C[1]; b=-C[1]+3 C[2]; c=-C[1]+4C[2]; d=C[1]+C[2]. (29)

Value of independent variables C[1]=1; C[2]=1 in correspond to the new weighting coefficients{1; 2; 3; 2}–worse, and for variables C [1]=2; C[2]=1 is easy to obtain the desired weighting factors{2; 1; 2; 3}- not suitable at all (Fig. 2).



a) red line – filter with coefficients **{1; 2; 3; 2}**



b) red line – filter **{2; 1; 2; 3}**

Fig. 2. Graphs of frequency response 8-count weight window with coefficients **{1; 2; 3; 2}** and **{2; 1; 2; 3}**

Coefficients of the 10-count filter:

a=C[1], b=22C[1], c=56C[1], d=42C[1], e=7C[1]. (30)

If in case C[1]=1, then

$$U_t^c=U_t-22U_{t+2}+56U_{t+4}-42U_{t+6}+7U_{t+8}, \quad (31)$$

$$U_t^s=-7U_{t+1}+42U_{t+3}-56U_{t+5}+22U_{t+7}-U_{t+9}. \quad (32)$$

A 10-count filter through two new independent variables obtained from an uncertain system of equations

a=C [1]; b=2 C[1]+5C[2]; c=-4C[1]+15C[2];
d=-2C[1]+11 C[2]; e=3 C[1]+C[2]. (33)

Value of independent variables C[1]=1; C[2]=1 correspond to new weighting factors{1; 7; 11; 9; 4}, and variables C[1]=2; C[2]=1 it is not difficult to obtain the desired weight factors {2; 9; 7; 7; 7} (Fig. 3).

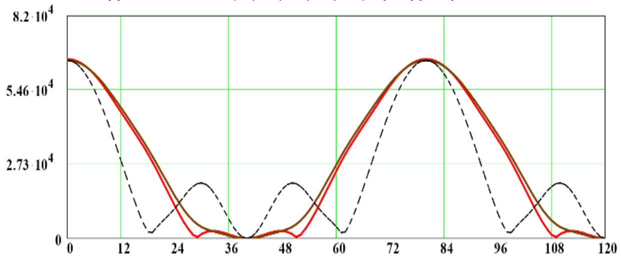


Fig. 3. Frequency response graph of a 10-count filter (black line – coefficients **{1; 7; 11; 9; 4}**, red line – coefficients **{1; 22; 56; 42; 7}**, dotted line –coefficients **{2; 9; 7; 7; 7}**)

a = C [1]; b = C [2]; c=-2 C[1]-C[2]+5 C[3];
d=-C[2]+4 C[3]; e=C[1]+C[2]-C[3]. (34)

Value of independent variables C[1]=1; C[2]=1; C[3]=1 correspond to new weighting factors{1; 1; 2; 3; 1}, and variables C[1]=2; C[2]=1 is easy to obtain the desired weighting factors{2; 9; 7; 7; 7}.

Two series-connected cascades of 8-count I/Q-demodulators with coefficients {1; 5; 7; 3} identical to the serially connected 6-count I/Q-demodulator with coefficients {1; 4; 3} and a 10-count I/Q demodulator with coefficients {1; 6; 12; 10; 3}. In both cases, a 15-count equivalent demodulator with coefficients takes place {6; 44; 122; 168; 122; 44; 6}in one quadrature and {1; 19; 81; 155; 155; 81; 19; 1}- in another. To illustrate what has been said, you should refer to the calculation results in the Mathcad package:

a) cosine component

$$(1\ 4\ 3\ 1\ 4\ 3)\begin{pmatrix} 1 & 6 & 12 & 10 & 3 & 0 & 0 & 0 \\ 0 & 1 & 6 & 12 & 10 & 3 & 0 & 0 \\ 0 & 0 & 1 & 6 & 12 & 10 & 3 & 0 \\ 0 & 0 & 0 & 3 & 10 & 12 & 6 & 1 \\ 0 & 0 & 3 & 10 & 12 & 6 & 1 & 0 \\ 0 & 3 & 10 & 12 & 6 & 1 & 0 & 0 \end{pmatrix}=(1\ 19\ 81\ 155\ 155\ 81\ 19\ 1), \quad (35)$$

$$(1\ 5\ 7\ 3\ 1\ 5\ 7\ 3)\begin{pmatrix} 1 & 5 & 7 & 3 & 0 & 0 & 0 & 0 \\ 0 & 1 & 5 & 7 & 3 & 0 & 0 & 0 \\ 0 & 0 & 1 & 5 & 7 & 3 & 0 & 0 \\ 0 & 0 & 0 & 1 & 5 & 7 & 3 & 0 \\ 0 & 0 & 0 & 0 & 3 & 7 & 5 & 1 \\ 0 & 0 & 0 & 3 & 7 & 5 & 1 & 0 \\ 0 & 0 & 3 & 7 & 5 & 1 & 0 & 0 \\ 0 & 3 & 7 & 5 & 1 & 0 & 0 & 0 \end{pmatrix}=(1\ 19\ 81\ 155\ 155\ 81\ 19\ 1). \quad (36)$$

b) sine component

$$(1\ 4\ 3\ 1\ 4\ 3)\begin{pmatrix} 3 & 10 & 12 & 6 & 1 & 0 & 0 \\ 0 & 3 & 10 & 12 & 6 & 1 & 0 \\ 0 & 0 & 3 & 10 & 12 & 6 & 1 \\ 0 & 0 & 1 & 6 & 12 & 10 & 3 \\ 0 & 1 & 6 & 12 & 10 & 3 & 0 \\ 1 & 6 & 12 & 10 & 3 & 0 & 0 \end{pmatrix}=(6\ 44\ 122\ 168\ 122\ 44\ 6), \quad (37)$$

$$(1\ 5\ 7\ 3\ 1\ 5\ 7\ 3)\begin{pmatrix} 3 & 7 & 5 & 1 & 0 & 0 & 0 \\ 0 & 3 & 7 & 5 & 1 & 0 & 0 \\ 0 & 0 & 3 & 7 & 5 & 1 & 0 \\ 0 & 0 & 0 & 3 & 7 & 5 & 1 \\ 0 & 0 & 0 & 1 & 5 & 7 & 3 \\ 0 & 0 & 1 & 5 & 7 & 3 & 0 \\ 0 & 1 & 5 & 7 & 3 & 0 & 0 \\ 1 & 5 & 7 & 3 & 0 & 0 & 0 \end{pmatrix}=(6\ 44\ 122\ 168\ 122\ 44\ 6). \quad (38)$$

As can be seen from the set of weighting factors {1; 6; 12; 10; 3) corresponds to a smooth shape of frequency response, without advantages (Fig. 4, 5).

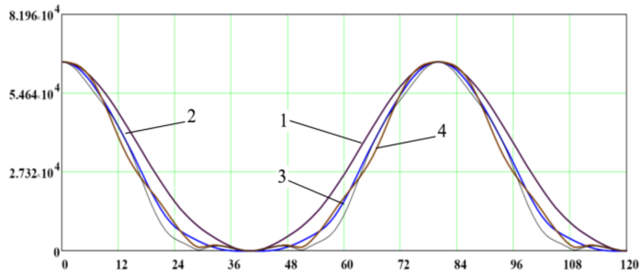


Fig. 4. Frequency response graph of a 10-count demodulator (1 – corresponds to a set of factors **{1; 22; 56; 42; 7}**; 2 – **{1; 6; 12; 10; 3}**, 3 – **{1; 6; 11; 10; 4}**; 4 – **{1; 7; 12; 9; 3}**)

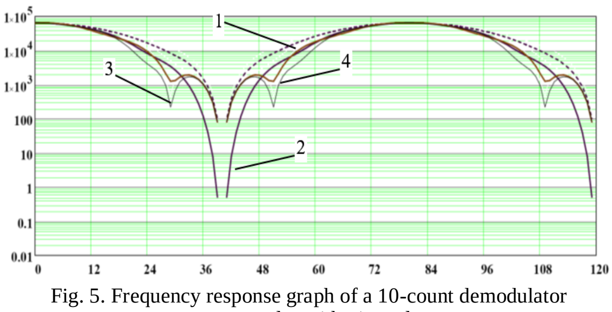


Fig. 5. Frequency response graph of a 10-count demodulator on a logarithmic scale

A new successful combination of coefficients for a 10-count demodulator {1; 6; 12; 10; 3} was obtained in the process of synthesizing the coefficients of a 15-count demodulator using sequential sorting using the initial array of coefficients {1; 7; 11; 9; 4}. During the sorting process, the requirement that the sum of the coefficients should be equal to zero was observed.

The purpose of the search was to find such a set of coefficients that, in combination with a serially connected 6-

count I/Q demodulator with coefficients {1; 4; 3} obtain the coefficients of a 15-count demodulator equivalent to two series-connected cascades of 8-count I/Q-demodulators with coefficients {1; 5; 7; 3}.

The calculation results in the Mathcad package below illustrate the iterative process of successive approximation to the combination of weighting factors. At the same time, the primary task was to achieve equality of 6 of the first and last coefficients in the resulting vector-string of weighting factors.

a) coefficients of the second cascade {1; 7; 11; 9; 4}

$$(1\ 4\ 3\ 1\ 4\ 3)\begin{pmatrix} 4\ 9\ 11\ 7\ 1\ 0\ 0 \\ 0\ 4\ 9\ 11\ 7\ 1\ 0 \\ 0\ 0\ 4\ 9\ 11\ 7\ 1 \\ 0\ 0\ 1\ 7\ 11\ 9\ 4 \\ 0\ 1\ 7\ 11\ 9\ 4\ 0 \\ 1\ 7\ 11\ 9\ 4\ 0\ 0 \end{pmatrix} = (7\ 50\ 121\ 156\ 121\ 50\ 7). \tag{39}$$

b) coefficients of the second cascade {1; 6; 11; 10; 4}

$$(1\ 4\ 3\ 1\ 4\ 3)\begin{pmatrix} 4\ 10\ 11\ 6\ 1\ 0\ 0 \\ 0\ 4\ 10\ 11\ 6\ 1\ 0 \\ 0\ 0\ 4\ 10\ 11\ 6 1 \\ 0\ 0\ 1\ 6\ 11\ 10\ 4 \\ 0\ 1\ 6\ 11\ 10\ 4\ 0 \\ 1\ 6\ 11\ 10\ 4\ 0\ 0 \end{pmatrix} = (7\ 48\ 121\ 160\ 121\ 48\ 7). \tag{40}$$

c) coefficients of the second cascade {1; 6; 12; 10; 3}

$$(1\ 4\ 3\ 1\ 4\ 3)\begin{pmatrix} 3\ 10\ 12\ 6\ 1\ 0\ 0 \\ 0\ 3\ 10\ 12\ 6\ 1\ 0 \\ 0\ 0\ 3\ 10\ 12\ 6\ 1 \\ 0\ 0\ 1\ 6\ 12\ 10\ 3 \\ 0\ 1\ 6\ 12\ 10\ 3\ 0 \\ 1\ 6\ 12\ 10\ 3\ 0\ 0 \end{pmatrix} = (6\ 44\ 122\ 168\ 122\ 44\ 6). \tag{41}$$

For the practical implementation of the considered I/Q-demodulators, it is suggested to use the methods of digital signal processing proposed in [16–18]. A particularly relevant solution is the use of a Field-Programmable Gate Array.

Conclusions

The considered vector-matrix form of the two-channel demodulator response request allows you to get a compact representation of the corresponding signal processing procedures in I/Q demodulators with the analog formation of quadrature components.

Regarding the optimal form of representation of the vector-matrix form of recording quadrature responses, we can conclude that it is possible to obtain a ratio for cosine quadrature by expressing sine and vice versa. This makes it possible to significantly simplify the synthesis process of two-channel demodulators.

A peculiarity of the matrices used to describe the response of two-channel I/Q demodulator circuits is their wedge-shaped shape with an inversely symmetrical sequence of elements.

The achieved suppression of frequency response side lobes allows for recommending appropriate pre-processing for the demodulation of N-OFDM signals, which will increase the spectral efficiency of such signals.

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