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QPSK-Modulation Modem Invariant to the Rotation of the Signal Constellation Plane

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***Abstract* – In order to increase the efficiency of dedicated frequency channels, i.e. to increase the specific data transfer rate, multipositional quadrature phase shift keying (QPSK, aka 4-PSK) should be used. The problems with QPSK signal demodulation is a rotation of the signal constellation plane by an angle multiple of 90° and a slow response of the carrier oscillation recovery scheme. The study considers the existing methods for eliminating the phase ambiguity of the recovered carrier frequency in typical QPSK modems, and identifies the shortcoming of a low-speed response oscillation recovery circuit. The authors propose a QPSK demodulator circuit with a fast adjustment of the reference oscillator, which is due to the fact that no loop filter is used in the feedback and that a digital calculator of the required phase shift is used. An algorithm for the frame synchronization restoration with the simultaneous elimination of the phase ambiguity multiple of 90° was also developed using synthesized binary sequences with an ideal non-periodic autocorrelation function (NACF) at even shifts that do not have the rotary symmetry property. The phase ambiguity elimination algorithm proposed in the article can be used as an alternative to standard modems with differential coding.**

***Keywords* – Autocorrelation; Binary sequences; Matched filters (MF); Phase shift keying modems.**

I. Introduction

Recently, radio technologies that make an integral part of the Internet of Things have been rapidly developing. Examples of the Internet of Things application include systems for data acquisition from wireless energy sensors, water and gas meters and other wireless devices making up the Smart House system.

Typical features of such communication systems are the following: the pulse operation mode requiring fast synchronization under short-term operation (potentially, data exchange can be activated according to schedule several times a day to transmit a limited data packet); high noise immunity, and a relatively large amount of information that can be transmitted during a relatively short time. To increase the efficiency of dedicated frequency channels, i.e. to increase the specific data transfer rate, it becomes necessary to use multi-position (combined) manipulation, in which each symbol of the message carries more than 1 bit of information. However, as the number of signal positions increases, the complexity of technical implementation of the decoding device inevitably increases and the noise immunity of the communication system decreases [1], [2], [17].

Therefore, a reasonable compromise providing high noise immunity and acceptable rate would be the use of the quadrature phase shift keying (QPSK or 4-PSK). The phase of the signal versus time dependence is shown in Fig. 1.

QPSK uses a constellation of four points placed at equal distances on the circle. As shown in Fig. 2, there are two bits per symbol in QPSK due to using 4 phases. The analysis shows that at the same signal bandwidth the speed can be increased by a factor of two with respect to the Binary Phase Shift Keying (BPSK), or it is possible to reduce the bandwidth by half if the speed remains unchanged.

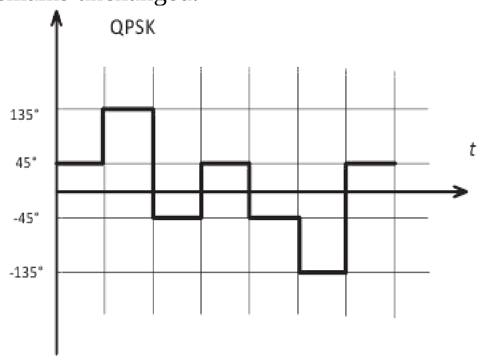

Fig. 1. Multiple position manipulation.

Although QPSK can be considered quadrature manipulation (QAM-4), it is sometimes easier to treat it as two independent modulated carriers shifted by 90°. Within this approach, even (odd) bits are used to modulate the in-phase component of *I*, and odd (even) bits are used to modulate the quadrature component of carrier *Q*.

The QPSK signal space can be represented as shown in Fig. 2 [19].

The formation of this signal is usually carried out using a quadrature modulator circuit, and the reception is performed using a quadrature demodulator.

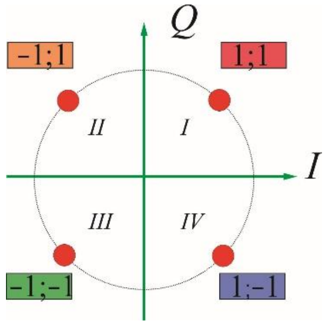

Fig. 2. QPSK signal space.

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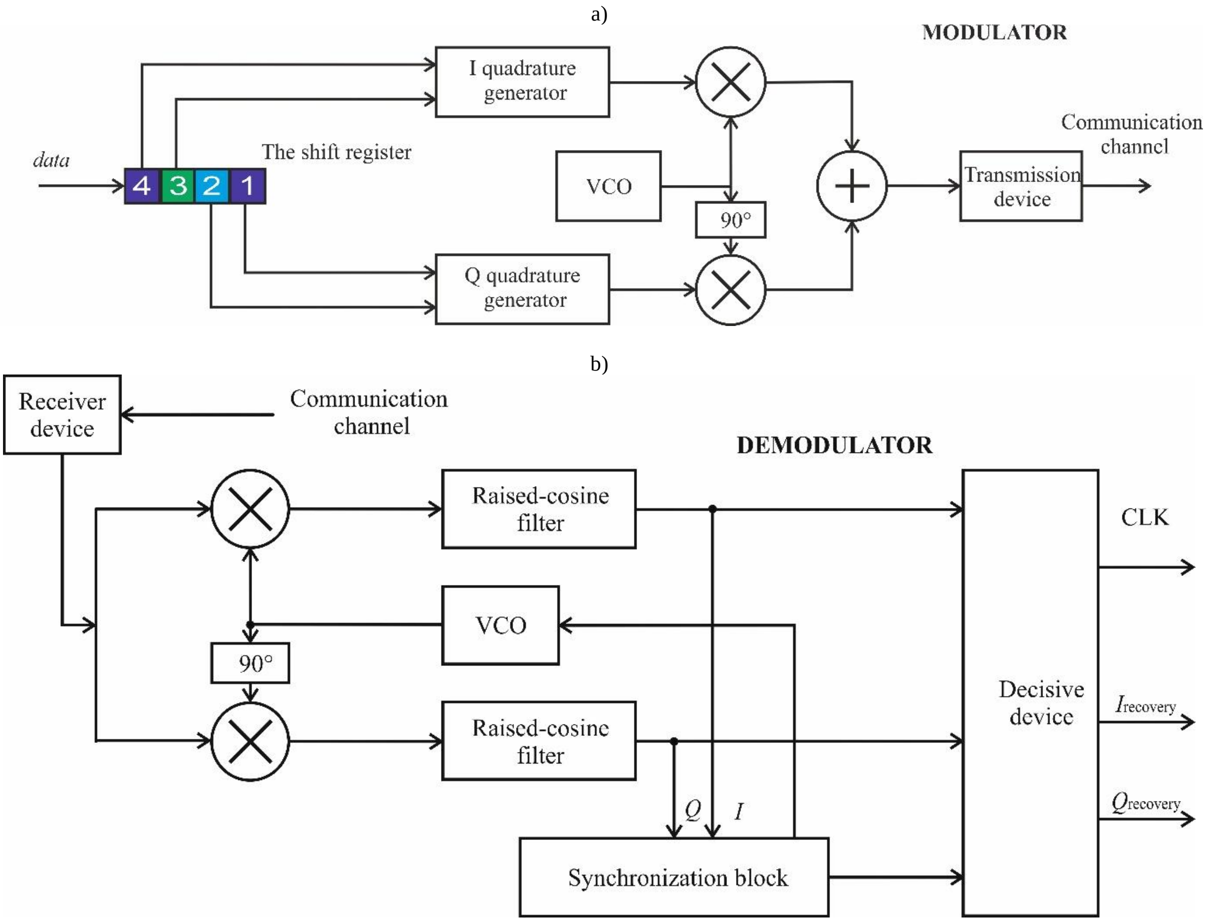

Fig. 3. Generalized functional diagram of a typical QPSK modem: a) modulator, b) demodulator.

The purpose of this study was to create an efficient method for reconstructing the carrier wave and frame synchronization of the demodulator with QPSK modulation.

II. QPSK Quadrature Modem

The generalized functional diagram of a typical QPSK modem [1], [3], [11]–[13] is shown in Fig. 3.

In Fig. 3a the input bit sequence is converted into two parallel sequences that are fed to the *I*, *Q* quadrature formers.

After quadrature components are multiplied with reference orthogonal oscillations, quadrature signals are generated in the balanced modulators. These signals are then summed and form a quadrature modulated signal.

In the demodulator shown in Fig. 3 b to isolate the quadrature components, the input signal is parallelized and also multiplied by the orthogonal components at the signal frequency. The use of the quadrature demodulator raises questions of choosing the optimal frame synchronization recovery circuit and the phase ambiguity elimination algorithm.

III. The Phase Ambiguity of the Reconstructed Carrier Frequency in Typical QPSK Modems

There are several ways to restore the reference oscillation, according to the Siforov, Pistolkors and Costas diagrams [4], [14]. In the integrated version, the PLL system based on the Costas loop [5] is most often used (Fig. 4).

Each branch of the circuit contains a regenerator and an additional multiplier. The second pair of multipliers multiplies the output voltages of the in-phase and the quadrature channels. The output voltages of the multipliers add up in antiphase in the adder. As a result of this processing, the voltage at the output of the adder turns out to be unmodulated.

The voltage is used to control the phase of the reference oscillator. In this case, the in-phase and quadrature channels must have the same impulse response and add the same delay.

It is obvious that the phase ambiguity at the output of the voltage-controlled oscillator in the Costas loop is $2\pi/M$. For QPSK, the phase ambiguity is 90°, which makes it necessary to perform preliminary differential coding during the transmission and differential decoding after demodulation at reception [5]. In other words, in a signal with relative coding, the original digital information is contained not in the value of the symbol, but in the variation of its value. The frame synchronization can also be recovered according to a certain synchronization sequence, which is allocated at the receiving end by a matched filter (MF). The general approach to the reconstruction of frame synchronization using the Barker, Gold, and M-sequences was considered in [6]–[10]. However, the use of the corresponding MFs for the video frequency, i.e. at the output of the quadrature demodulator, becomes possible only after the phase of the carrier frequency is restored. One solution to this problem can be the consistent use of differential and sync code, which leads to a decrease in the noise immunity of the synchronization signal, an increase in locking in synchronism time, and a decrease in the data transfer rate [14], [15], [18], [20].

IV. Modified QPSK Demodulator Circuit With the Solved Problem of the Reconstructed Carrier Frequency Phase

In this paper, we propose a composite circuit that simultaneously solves the problems of phase ambiguity and frame synchronization reconstruction (Fig. 5).

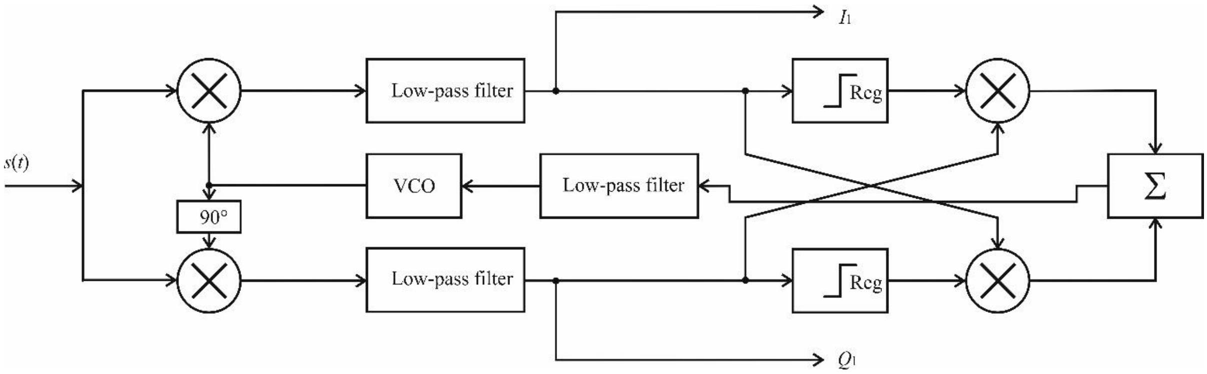

Fig. 4. Structural block diagram of carrier recovery for QPSK signal based on Costas loop (VCO is voltage controlled generator; Reg is regenerator).

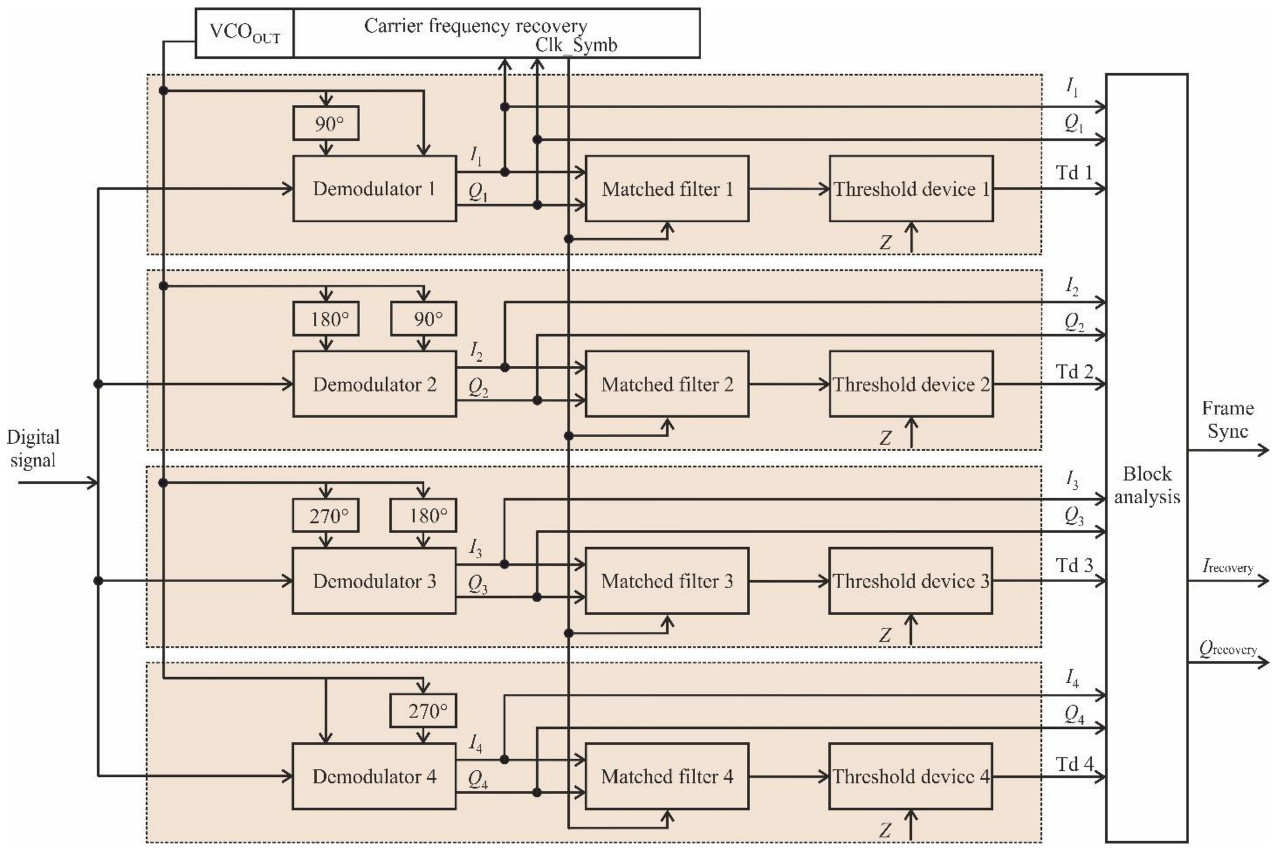

Fig. 5. Block diagram of a composite circuit of QPSK demodulator.

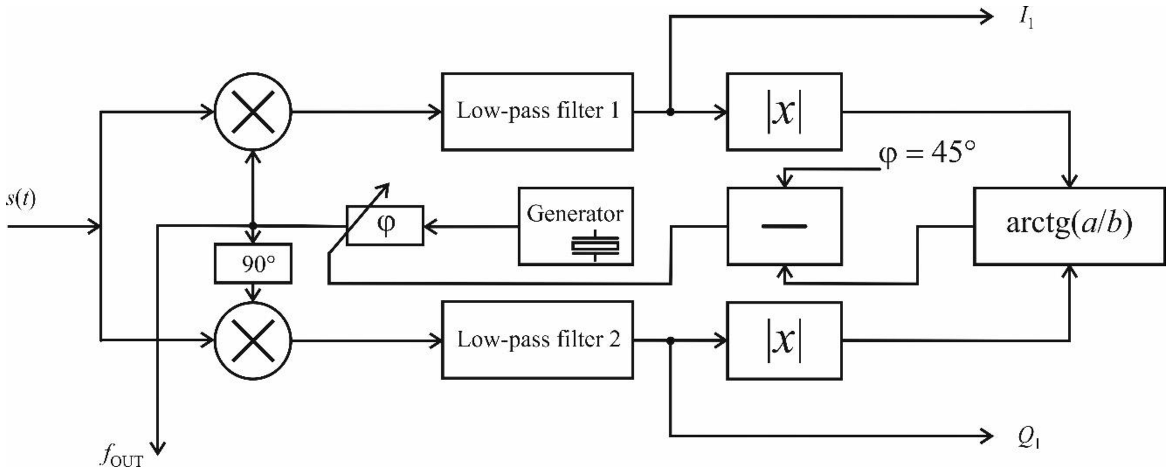

Fig. 6. Structure block diagram of a circuit for carrier frequency recovery for the QPSK signal with an adjustable phase shifter.

Fig. 5 presents a diagram of a quadrature QPSK demodulator with a built-in frame and a phase synchronization unit.

For stable operation of the demodulator, synchronous sequences with good non-periodic autocorrelation properties

are used. Such sequences are extracted from the information message by the matched filter operating at low frequency.

Since the phase of the carrier frequency is reconstructed using the Costas loop with an accuracy multiple of 90°, the circuit contains 4 identical channels tuned to 4 possible realizations of the plane rotation of the signal constellation.

The relative rotation of the input signal constellation is realized at 0°, 90°, 180° and 270° and is carried out using phase shifters, the input of which receives a restored harmonic signal from the carrier frequency recovery block.

From the output of each channel quadrature demodulator, the signals of *I*, *Q* quadratures are fed to identical circuits of matched filters, and then to the threshold devices. At the output of the first of the threshold devices, a pulse will appear at the moment of the maximum voltage value on the first of the 4 filters. When a pulse appears at the output of the first of the decision devices, the analysis block generates the output frame synchronization pulse and connects to the blocks of further processing of the quadrature signal of only the channel where the threshold has occurred. Interchange of *I, Q* quadrature commutation occurs only at the moment of synchronization signal reception, i.e. not quicker than once per frame.

V. Fast-Response Circuit for Phase Recovery of the Carrier Frequency

Since it is assumed that the communication system with QPSK modulation operates in a pulsed mode, a circuit for the carrier frequency recovery is proposed (Fig. 6), which has a faster response in comparison with the Costas loop.

The circuit for the carrier recovery shown in Fig. 6 has a phase ambiguity that is a multiple of 90°, same as the Costas loop does. The diagram contains 2 balanced multipliers, a low-pass filter with a Nyquist strip to eliminate inter-symbol interference, quadrature module calculation units (module X), an unregulated stable quartz oscillator (G), an arctg calculation unit and a controllable phase shifter. The position of the point of the signal constellation is adjusted by tuning the output signal phase of a stable quartz oscillator by means of an adjustable phase shifter.

The required phase shift is determined by calculating the arctg of the quadrature modules ratio. The calculated value is subtracted from 45 degrees, since real values of the constellation points are 45°, 135°, 225° and 315°. It is evident that the circuit reduces the computations of all angles to the analysis of the first quarter, and the criterion for the correct setting is the equality of the quadrature modules $|I| = |Q|$. Thus, the zero phase shift of the adjustable phase shifter corresponds to 45° (arctg (1) = 45°), and if this condition is not met, the generator phase is compensated for the required angle.

Let us assume that the signal constellation of the received signal has a phase shift relative to the transmitted signal, as shown in Fig. 7. Let us determine the required angle of the additional turn of the phase of the reference oscillator. For a given position of the signal points, *I*, *Q* quadrature projections in the first plane have the following values:

$$I = I_{\text{shift}},\ Q = Q_{\text{shift}}.$$

Then, at the output of the arctg calculation block, we have a voltage proportional to the angle in accordance with

$$U \sim \alpha_{\text{shift}} = \text{arctg}\,(Q_{\text{shift}}/I_{\text{shift}}) = 50°.$$

After the decrement adder block, we obtain the control signal for the phase shifter corresponding to the additional phase turn

$$U_1 \sim \alpha - \alpha_{\text{shift}} = 45° - 50° = -5°.$$

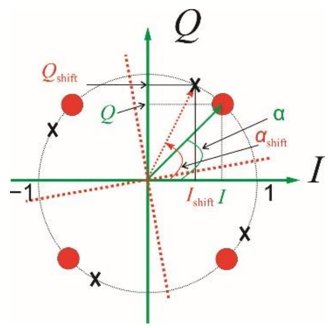

Fig. 7. Example of calculation of the required angle of the signal constellation phase shift compensation of the received signal.

VI. Algorithm for Synthesis of Synchronization Sequences With the Required Properties

Let us define the requirements that the synchronization sequences must meet for the best operation of the circuit shown in Fig. 5.

- Sequences must have an ideal non-periodic autocorrelation function (NACF) of the form of

$$R(k)=\sum_{k=0}^{\frac{N-2}{2}}\sum_{m=0}^{N-1}S(m)S(m-2k)=\begin{cases}N \ \text{if}\ k=\dfrac{N}{2}-1;\\ 0 \ \text{if}\ k\neq\dfrac{N}{2}-1,\end{cases} \tag{1}$$

where S is a binary sequence of length N.

- Sequences must be balanced according to the expression

$$\sum_{i=0}^{N-1}S(i)=0. \tag{2}$$

- Sequences must be binary and contain only elements +1 and –1.
- The length of the sequences must be even.
- NACF of the sequences should not have the rotational symmetry property when the signal constellation is rotated by an angle multiple of 90°.

Let us consider the problem of synthesizing the required synchronization sequences for a length of $N = 8$.

Let us write down the initial system of constraint equations

$$\begin{cases}S_0S_6+S_1S_7=0,\\ S_0S_4+S_1S_5+S_2S_6+S_3S_7=0,\\ S_0S_2+S_1S_3+S_2S_4+S_3S_5+S_4S_6+S_5S_7=0,\\ S_0{}^2+S_1{}^2+S_2{}^2+S_3{}^2+S_4{}^2+S_5{}^2+S_6{}^2+S_7{}^2=8,\\ S_0+S_1+S_2+S_3+S_4+S_5+S_6+S_7=0,\end{cases} \tag{3}$$

in accordance with the properties listed above.

As a result of solving this system of equations, we find 16 nontrivial sequences, the elements of which are given in Table I.

TABLE I

Balanced Binary Sequences With Ideal NACF and a Length of N = 8 (Full Class)

S_0	S_1	S_2	S_3	S_4	S_5	S_6	S_7
−1	−1	−1	1	1	1	−1	1
−1	−1	1	−1	1	1	1	−1
−1	−1	1	1	−1	1	−1	1
−1	−1	1	1	1	−1	1	−1
−1	1	−1	−1	−1	1	1	1
−1	1	−1	1	−1	−1	1	1
−1	1	−1	1	1	1	−1	−1
−1	1	1	1	−1	1	−1	−1
1	−1	−1	−1	1	−1	1	1
1	−1	1	−1	−1	−1	1	1
1	−1	1	−1	1	1	−1	−1
1	−1	1	1	1	−1	−1	−1
1	1	−1	−1	−1	1	−1	1
1	1	−1	−1	1	−1	1	−1
1	1	−1	1	−1	−1	−1	1
1	1	1	−1	−1	−1	1	−1

After excluding the inverse sequences, we have the remaining 8 nontrivial solutions given in Table II.

TABLE II

Balanced Binary Sequences With Ideal NACF and a Length of N = 8 Excluding the Inverse Sequences

S_0	S_1	S_2	S_3	S_4	S_5	S_6	S_7
−1	−1	−1	1	1	1	−1	1
−1	−1	1	−1	1	1	1	−1
−1	−1	1	1	−1	1	−1	1
−1	−1	1	1	1	−1	1	−1
−1	1	−1	−1	−1	1	1	1
−1	1	−1	1	−1	−1	1	1
−1	1	−1	1	1	1	−1	−1
−1	1	1	1	−1	1	−1	−1

VII. MF Implementation and Some Aspects of Correlation Functions

The implementation of the MF operating in accordance with expression (4) is shown in Fig. 8

$$R(k)=\sum_{k=0}^{\frac{N-2}{2}}\sum_{m=0}^{N-1}S(m)h(m-2k)=\begin{cases}N \ \text{if}\ k=\dfrac{N}{2}-1;\\ 0 \ \text{if}\ k\neq\dfrac{N}{2}-1,\end{cases} \tag{4}$$

where S is a binary sequence of $N = 8$ length;
$k = 0, ..., N – 1$;
h is the impulse response characteristic of the MF.

A distinctive feature of the MF construction is that there are two parallel lines of delay for T_{symb} and simultaneous multiplication of quadrature values by ±1 (h_i).

To estimate the arrangement stability of the signal positions of the QPSK constellation relative to I, Q axes, we need to build phase transition diagrams.

The obtained binary sequences and phase step diagrams of the signal with QPSK modulation for the first sequence from Table II, with all its rotations, are given in Table III and Fig. 9.

TABLE III

All Possible Combinations of Binary Sequences for the First Sequence From Table II

Rotation	S_0	S_1	S_2	S_3	S_4	S_5	S_6	S_7	*Transitions in quarters*
0°	−1	−1	−1	1	1	1	−1	1	III > II > I > II
90°	1	−1	−1	−1	−1	1	−1	−1	IV > III > II > III
180°	1	1	1	−1	−1	−1	1	−1	I > IV > III > IV
270°	−1	1	1	1	1	−1	1	1	II > I > IV > I

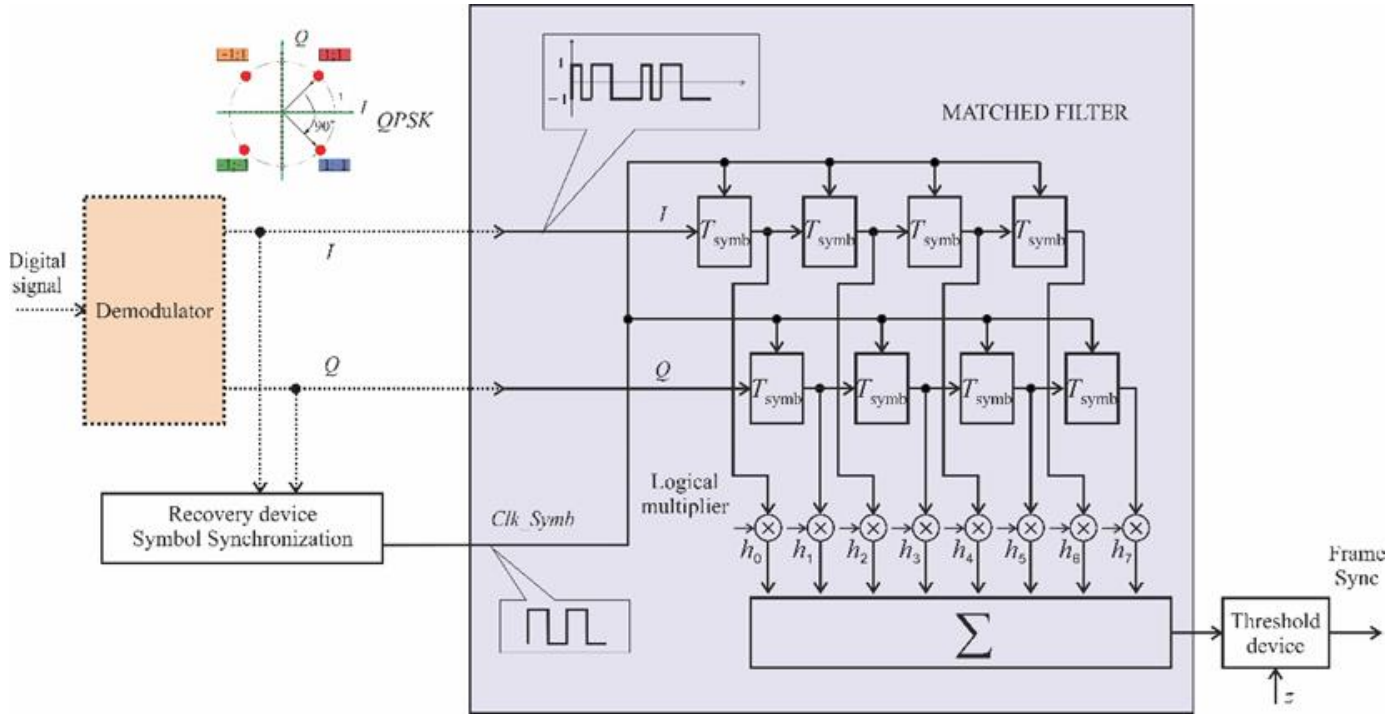

Fig. 8. Structure diagram of the synthesized matched filter.

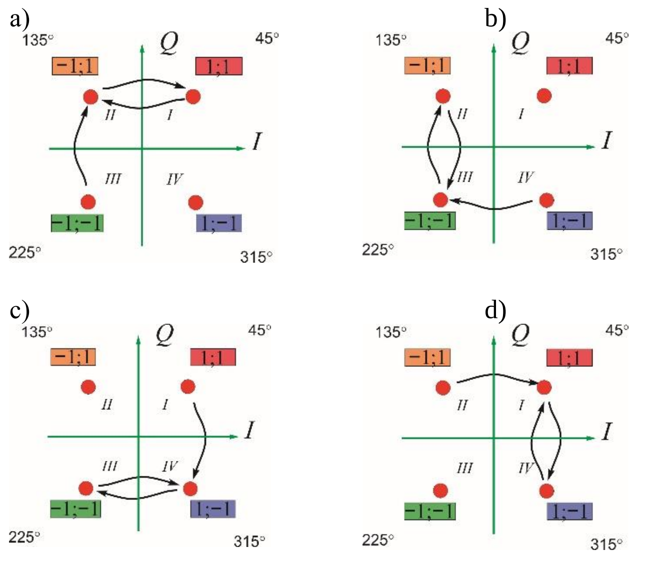

Fig. 9. Diagrams of phase-shift values of a signal with QPSK modulation and phase shifts: a) 0°, b) 90°, c) 180°, d) 270°.

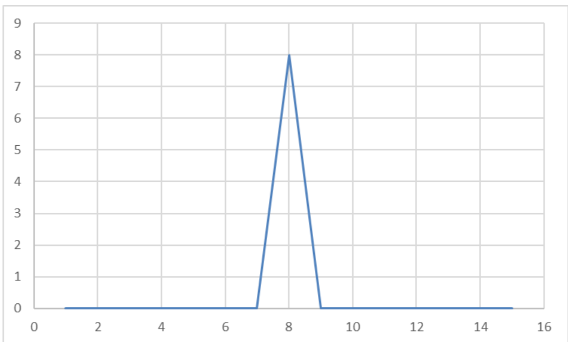

Fig. 10. NACF for a binary sequence of an even length of $N = 8$ with a section length of $i = 2$, $|R_{bmax}| = 0$ for any shift (0°, 90°, 180°, 270°).

State diagrams (Fig. 9) show that during the transmission of the synchronization sequence, the signal moves in at least three quadrants, which provides good conditions for restoring the symbolic synchronization.

Let us build the correlation functions of all possible realizations of binary sequences from Table III for a sequence of a length of $N = 8$, $S = \{-1; -1; -1; 1; 1; 1; -1; 1\}$.

The NACF type for a binary sequence of an even length of $N = 8$ with a section length of $i = 2$ is shown in Fig. 10.

The graphs of the cross-correlation functions (CCF) with a section length of $i = 2$ are shown in Fig. 11.

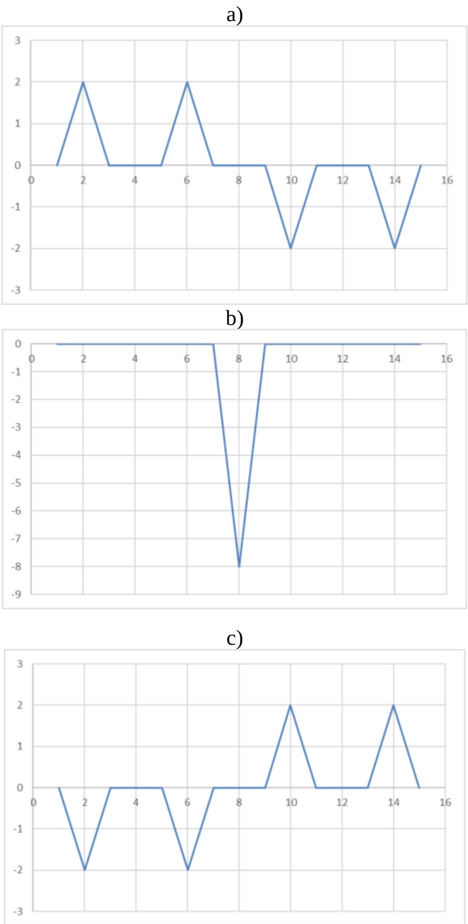

Fig. 11. CCFs with section length of $i = 2$ for the binary sequence and a sequence shifted by: a) 90°, b) 180°, c) 270°.

As seen from Fig. 10 and 11, the properties of an ideal NACF remain intact for all rotations (phase shifts), with the CCF having a small level of positive side lobes (no more than 0.25). Thus, the obtained sequences can be successfully used to solve the problem of fast synchronization of modems with QPSK modulation. It has also been established that the sequences have good cross-correlation properties and can also be used in systems based on the code division principle.

VIII. Conclusion

In this paper, the authors propose a functional circuit for phase synchronization of the carrier frequency for QPSK modulation, which provides a faster response time than the classical carrier recovery circuits such as the Costas loop, Pistolcors and Siphorov circuits.

As an alternative to differential coding, which is normally used in carrier reconstruction, we propose a solution containing four MFs with rotationally invariant (by an angle multiple of 90°) binary synchronization sequences and with an ideal NACF for character-oriented reception.

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