Coherent demodulation of the two-level APSK signals with the symbol amplitude estimation

O V Chernoyarov¹,²,³, A N Glushkov⁴, V P Litvinenko⁵, V A Mironov⁴ and A V Salnikova³

¹ Department of Mathematics, Physics and System Analysis, Maikop State Technological University, 191, Pervomayskaya, Maikop, 385000, Russia
² International Laboratory of Statistics of Stochastic Processes and Quantitative Finance, National Research Tomsk State University, 36, Lenin Avenue, Tomsk, 634050, Russia
³ Department of Electronics and Nanoelectronics, National Research University “MPEI”, 14, Krasnokazarmennaya, Moscow, 111250, Russia
⁴ Zhukovsky-Gagarin Air Force Academy, 133, Marshal Nedelin, Voronezh, 394052, Russia
⁵ Department of Radio Engineering, Voronezh State Technical University, 14, Moscow Avenue, Voronezh, 394026, Russia

E-mail: chernoyarovov@mpei.ru

Abstract. The study focuses on the algorithms for the coherent demodulation of the two-level amplitude phase-shift keyed signals with an estimate of the received symbol amplitude carried out by its relative comparison with the preceding symbol amplitude. Determining calibrated values of the symbol amplitudes in order to compare them with the preset threshold values is considered unnecessary in this case. Phase demodulation is implemented based on the phase detector of the multi-level phase-shift keyed signals. Symbol amplitudes are determined by the quadrature channels responses. Both analog and digital demodulation algorithms are considered. Simulation of the demodulation algorithm is carried out.

1. Introduction
The amplitude phase-shift keyed (APSK) signals [1] are widely used in mobile radio networks [2], in digital TV [3] and in optical cable communication lines [4], [5]. They are characterized by a high noise immunity and information delivery speed, but they also require a demodulator phase locking and a strict control of the received signal amplitude in order to be able to compare it with the preset threshold values. Signal positions are presented as the “constellation” in the form of the concentric circles where the dots are the images of the initial phases of the received symbols, while the circle radius corresponds to their amplitude. In the case of the two-level amplitude phase-shift keying, the constellation is composed of the two circles. On the first of them with the amplitude (radius) \( U_1 \), \( M_1 \) signal positions are situated, while on the second, with the greater amplitude - \( U_2 > U_1 \) - one finds \( M_2 \) signal positions, so that the general number of the signal positions is expressed as

\[
M = M_1 + M_2.
\]
To describe the signal, one uses the following notations: MAPSK (8APSK, 16APSK) or $M_1 + M_2$ APSK (that are 4+4APSK, 8+8APSK, 4+12APSK). The choice of the constellation is made in terms of noise immunity, power efficiency and signal modulation/demodulation comfort. The 4+12APSK signal is utilized in digital TV [3], while the 4+4APSK and 8+8APSK signals are very suitable for use in optic cable communication lines [4, 5]. The different corresponding constellation choices possible are discussed in [6-8]. The symbol amplitude ratio in the two-level APSK is $U_2/U_1 \approx 3$, and it depends on the internal coding speed [9].

APSK signal demodulation presupposes determining the normalized amplitude and phase of the received signal and their comparison with the coordinates of the decision making regions for the corresponding constellation, see, for example, [10-11]. In the simpler case [6, 8], when one deals with the 8+8APSK signal, one should separately compare the two possible values of the symbol amplitude with the threshold value, and only then the signal phase is determined. For this purpose, the received signal level should be normalized using the automatic gain control of the receiver. If the noise is present, symbol amplitude determination errors may result in decreasing noise immunity.

In practice, when determining symbol amplitude, one should find out, if it belongs to the lower or the upper level of the APSK signal (the numerical values of these levels are then neglected). In this case, precise normalization of the received signal gain is not required.

2. Amplitude phase-shift keyed signal

The received element of two-level APSK signal can be presented as

$$s(t) = S_m \cos(2\pi f_0 t + \psi_{mn} + \psi_0).$$

In (2), the notations are the following: $S_m$ is the amplitude ($m = 1$ or $m = 2$ – these are the numbers of the signal gains) which can take on the values $S_1$ or $S_2$ (for example, $S_2 = 3S_1$). $f_0$ is the carrying frequency, $\psi_0$ is the initial phase and

$$\psi_{mn} = a_{mn} 2\pi / M_m$$

is the signal phase while $a_{mn} = 0, 1, \ldots, (M - 1)$, $n$ is the number of the signal value of the phase for the $m$-th level, and the general number of signal positions is determined according to (1).

Under the coherent demodulation, the phase-locking device in an operation mode provides the condition $\psi_0 = 0$.

3. Demodulation algorithms

For the demodulation of the APSK signal, it is necessary to determine the amplitude $S_k$ and the initial phase $\psi_k$ of the received $k$-th symbol and to compare them with the decision making regions of the preset constellation. In figure 1a, one can see the 4+12APSK signal constellation ($M_1 = 4$, $M_2 = 12$), while in figure 1b the 8+8APSK signal constellation is shown ($M_1 = M_2 = 8$). In both cases, $U_1$ and $U_2$ are the normalized symbol amplitudes and $U_0$ is the threshold level. Signal positions are presented as dots; the thickening lines stand for the decision making regions for the received positions that can be described within the quadrature coordinates $I, Q$ or by polar coordinates $U, \psi$ for which the amplitudes of the received symbols of the APSK signals should be normalized.

APSK signal demodulator is designed based on the phase and amplitude detectors [1], and its block diagram is demonstrated in figure 2. The input signal $s(t)$ arrives to the quadrature processing unit (QPU) [10], by the signal synchronous with $s(t)$ that is $s_0(t) = S_0 \cos(2\pi f_0 t)$ coming from the reference generator (RG) and, with the help of 90 degrees phase shifter (PS), the multipliers and the integrators, the responses $y_0(t)$ and $y_1(t)$ are calculated at the $T$ symbol length interval as follows:

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Figure 1. The signal constellations: (a) 4+12APSK; (b) 8+8APSK.

Figure 2. The block diagram of the demodulator.

\[ y_0(t) = \int_{t-T}^{t} S_m \cos(2\pi f_0 t' + \psi_{m}) S_0 \cos(2\pi f_0 t') \, dt', \quad (3) \]

\[ y_1(t) = \int_{t-T}^{t} S_m \cos(2\pi f_0 t' + \psi_{m}) S_0 \sin(2\pi f_0 t') \, dt'. \quad (4) \]

These responses arrive to the phase detector (PD), generating the value of the initial phase \( \psi \) of the APSK signal input symbol according to rule:

\[ \psi_i = \begin{cases} -\arctan(y_1/y_0), & \text{if } y_0 \geq 0, \\ \pi - \arctan(y_1/y_0), & \text{if } y_0 < 0. \end{cases} \]
Then the symbol amplitude $S$ is determined in the amplitude detector (AD) by the quadrature responses

$$S = \sqrt{y_0^2 + y_1^2}$$

and it must be normalized in terms of the threshold level $U_0$ of the constellation (figure 1).

The values of $S$ and $\psi$ produced at the end of the symbol reception determine the point on the constellation and the decision concerning the received position is made regarding the constellation element closest to this point.

The algorithm of decision making concerning the level of the received symbol is proposed, and it does not require normalization of such symbol and its comparison with the threshold but uses the ratio between the amplitudes of the received and the preceding symbols instead. These amplitudes are presented as $S_1$ and $S_2$, respectively. Here

- if under $a_1 \approx 2$ the inequality
  $$\frac{S_1}{S_2} \geq a_1$$
  holds, then the received signal belongs to the level $U_2$ (figure 1);

- if under $a_2 \approx 1/2$ the inequality
  $$\frac{S_1}{S_2} \leq a_2$$
  holds, then the received signal belongs to the level $U_1$;

- if the inequality
  $$a_2 < \frac{S_1}{S_2} < a_1$$
  holds, then the level of the received signal coincides with the level of the preceding signal.

The values of the coefficients $a_1$ and $a_2$ can undergo optimization in the vicinity of the specified values according the recommendations specified in [9].

Thus, it is practical to rewrite the conditions (5)- (7) in the following way:

$$S_1 - a_1 S_2 \geq 0, \quad S_1 - a_2 S_2 \leq 0, \quad S_1 - a_1 S_2 < 0 \text{ and } S_1 - a_2 S_2 > 0,$$

(8)

while, in the digital devices, the multiplication by $a_1 = 2$ and $a_2 = 1/2$ is carried out be the shift in word size of the binary codes.

To implement the algorithm (8), one should write down the preceding value of the amplitude $S_2$ into the delay unit (DU) (figure 2), and the values of $S_1$ and $S_2$ together with the value of $\psi$ should be transferred to the resolver (RS) which applying (8) generates the code $D$ for the received symbol.

The demodulator presented in figure 2 can be implemented as digital unit (algorithm) based on the amplitude detector [12] and phase detector [13].

4. **Demodulator operation**

After the reception of the current symbol is completed, the responses (3) and (4) of the quadrature processing unit undergoing integration at the interval $T = N T_0$ (there $T_0 = 1/f_0$ is the carrier period) are equal to

$$y_0(t) = S_m S_0 \cos \psi_{mn}/2, \quad y_0(t) = S_m S_0 \sin \psi_{mn}/2.$$
Under the digital demodulation implementation, according to [12], [13], the corresponding responses of the quadrature channels are equal to

\[ y_0(t) = 2NS_m \cos \psi_{mn}, \quad y_1(t) = 2NS_m \sin \psi_{mn}. \]

The realizations of the normalized responses of the quadrature channels for the constellation depicted in figure 1b are exemplified in figure 3, where \( i \) is the number of the current processed period and the integer values \( i/N \) corresponds to the moments of the symbol ending when the decisions are made concerning the amplitude and the phase.

The signal phase is determined in the phase detector according to (3) and it does not depend upon the received signal amplitude. As for the symbol amplitude, it is determined based on (4), and the example of the time diagram \( S_i/S_1 \) under \( S_2/S_1 = 3 \) and precise normalizing of the signal gain for the constellation depicted on figure 1b is presented in figure 4.

![Figure 3. The quadrature channel responses.](image1)

![Figure 4. The symbol amplitude.](image2)

If the normalization of the signal gain in the demodulator is distorted, as, for example, in the case when the signal fading occurs, then the errors of the symbol amplitude estimation may take place. It leads to the decreased noise immunity. It should be noted that, in accordance with (8), the relative estimate of the received symbol amplitude does not require its normalization, and thus the demodulator implementation is simplified considerably.
5. Conclusion
The two fast processing algorithms are introduced. The first helps to demodulate the two-level APSK signals accompanied with the relative estimate of the symbol amplitude. The advantage of this algorithm is that it does not require normalization of the received signal in terms of its constellation. The second allows making decision on the received symbol amplitude while the minimum number of operations is required for this. The operation of the demodulator and the timing diagrams of its responses are studied. It is demonstrated that the proposed algorithm for the relative determination of the received symbol amplitude is efficient and can significantly simplify the hardware implementation of the demodulator.

Acknowledgments
This study was financially supported by the Ministry of Science and Higher Education of the Russian Federation (research project No. FSWF-2020-0022).

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