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RESEARCH ARTICLE

Effect of synchronization system errors on the reception noise immunity of amplitude-phase shift keyed signals

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Abstract
Objectives. An urgent task in the context of modern radio and television systems is to improve the quality and quantity of transmitted information. For example, the use of multiple amplitude-phase shift keyed (APSK) signals—16-APSK and 32-APSK—in digital satellite television systems of the Digital Video Broadcasting–Satellite2 (DVB-S2) standard made it possible to transmit 30% more data in the same frequency bands in comparison with the previous DVB-S standard. Such increases in information transmission rates impose more stringent requirements on hardware. An important role in the reception of APSK signals, as well as the signals of other coherent signal processing systems, is played by the stability of synchronization systems. The presence of operational errors can significantly reduce the quality of information reception. The aim of the present work was to analyze the effect of phase and clock synchronization errors on the reception noise immunity of APSK signals with a ring signal constellation structure.
Methods. The study used statistical radio engineering methods informed by optimal signal reception theory.
Results. The effect of phase and clock synchronization errors on the reception noise immunity of APSK signals having a signal constellation ring structure is analyzed. The dependencies of the bit error probability on the magnitude of the phase shift and the clock offset were characterized. The effect of synchronization errors on reception quality were compared with the known results for quadrature amplitude modulation (QAM) signals.
Conclusions. At an acceptable energy loss of no more than 1 dB, the critical phase error can be considered as 2°–3°, while the critical clock error is 3–4%. A coherent receiver of APSK signals is more sensitive to the phase error of reference oscillations than a similar receiver of QAM signals, whereas clock errors have the same effect on the reception quality of these signals.

Keywords: amplitude-phase shift keying, synchronization, phase error, clock error, noise immunity

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НАУЧНАЯ СТАТЬЯ

Влияние погрешностей системы синхронизации на помехоустойчивость приема сигналов с амплитудно-фазовой манипуляцией

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Резюме
Цели. Актуальной задачей современных систем радиосвязи и телевидения является повышение качества и количества передаваемой информации. Применение многопозиционных сигналов с амплитудно-фазовой манипуляцией (АФМ) 16-АФМ и 32-АФМ в системах цифрового спутникового телевидения стандарта DVB-S2 обеспечило возможность передачи на 30% больше данных в тех же полосах частот по сравнению с предыдущим стандартом DVB-S. Такое увеличение скорости передачи информации определило более жесткие требования к аппаратному обеспечению этих систем. Для приема сигналов АФМ, как и для многих других систем, использующих когерентную обработку сигналов, важную роль играет стабильность работы систем синхронизации. Наличие погрешностей в их работе может значительно снизить качество приема информации. Цель работы – анализ влияния погрешностей фазовой и тактовой синхронизации на помехоустойчивость приема сигналов с амплитудно-фазовой манипуляцией с кольцевой структурой сигнального созвездия.
Методы. Использованы методы статистической радиотехники и теории оптимального приема сигналов.
Результаты. Проведен анализ влияния погрешностей фазовой и тактовой синхронизации на помехоустойчивость приема сигналов с амплитудно-фазовой манипуляцией с кольцевой структурой сигнального созвездия. Получены зависимости вероятности битовой ошибки от величины фазового сдвига и смещения тактовых моментов. Проведено сравнение влияния погрешностей синхронизации на качество приема с известными результатами для сигналов с квадратурной амплитудной модуляцией (КАМ).
Выводы. Установлено, что при допустимых энергетических потерях не более 1 дБ критической фазовой погрешностью можно считать величину 2–3 градуса, а критическая тактовая погрешность составляет 3–4%. Когерентный приемник сигналов АФМ более чувствителен к фазовой погрешности опорных колебаний, чем аналогичный приемник сигналов КАМ, а тактовые погрешности одинаково сказываются на качестве приема этих сигналов.

Ключевые слова: амплитудно-фазовая манипуляция, синхронизация, фазовая погрешность, тактовая погрешность, помехоустойчивость

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INTRODUCTION

A remaining challenge in contemporary radio and television systems consists in improving the quality and quantity of transmitted information. For example, multiple amplitude-phase shift keyed (APSK) 16-APSK and 32-APSK signals in the new-generation DVB-S2 digital satellite television systems can be used to transmit 30% more data than the previous DVB-S standard within the same frequency bands[1] [1]. Such increases in the information transmission rate have imposed additional requirements on the hardware used in these systems. As with other coherent signal processing systems, the stability of synchronization systems plays an important role is played in the reception of APSK signals. The presence of errors in their operation can significantly reduce the quality of information reception. The effect of synchronization errors on the reception noise immunity of multiple quadrature amplitude modulation (QAM) signals has been analyzed in previously published works [2–12]. In the present work, a study was made of the effect of phase and clock synchronization errors on the reception noise immunity of APSK signals having a ring signal constellation structure.

CALCULATION PROCEDURE

Let us write a model of an APSK signal in clock cycle time T_s in the form

$$s_i(t) = A_{av} r_i \cos(\omega_0 t + \varphi_i),\ t \in (0, T_s],\ i = \overline{0, M-1}, \quad (1)$$

where A_{av} is the average signal amplitude; ω_0 is the carrier frequency; r_i and φ_i are quantities determining the amplitude and phase of the signal, respectively; and M is the number of the constellation points.

Let us consider the operation of a multichannel coherent receiver of APSK signals (Fig. 1) [13, 14] in the presence of white Gaussian noise $n(t)$ with parameters

$$< n(t) > = 0; < n(t_1) n(t_2) > = \frac{N_0}{2} \delta(t_2 - t_1),$$

where N_0 is the one-sided noise power spectral density, δ is the delta function, and t_1 and t_2 are moments of time.

The receiver correlators calculate the convolution integrals

$$J_i = \frac{2}{N_0} \int_0^{T_s} x(t) s_{refi}(t) dt,\ i = \overline{0, M-1} \quad (2)$$

[1] DVB. https://www.dvb.org/standards/dvb-s2x. Accessed December 20, 2022.

of the received process $x(t) = s_i(t) + n(t)$ with reference signals $s_{refi}(t)$. Comparison of the received J_i values and their combinations with the thresholds set in the solver (maximum selection unit) allows one to determine the transmitted channel symbol.

The probability of erroneous reception of any (mth) channel symbol is found under the condition $J_m > \{J_i + \delta_{mi}\};\ i \neq m;\ i, m = \overline{0, M-1}$, namely,

$$P_{es\,m} = 1 - \prod_{\substack{i=0 \\ m \neq i}}^{M-1} p(J_m - J_i > \delta_{mi})\big|_m, \quad (3)$$

where $p(J_m - J_i > \delta_{mi})|_m$ is the probability that the output value of the mth correlator is higher than the output value of any other (ith) correlator, provided that the mth symbol was transmitted; $\delta_{mi} = \frac{E_{s_m} - E_{s_i}}{N_0} = \frac{E_{s\,av}}{N_0}(r_m^2 - r_i^2) = \frac{E_b \log_2 M}{N_0}(r_m^2 - r_i^2)$ is the decision threshold; E_b is the average signal energy per 1 bit of information; and E_{s_m} and E_{s_i} are the energies of the mth and ith signal transmissions, respectively; $E_{s\,av}$ is the average energy of signal transmissions.

The probabilities $p(J_m - J_i > \delta_{mi})|_m$ can be calculated by determining the statistical characteristics J_i of the distributions of random processes and their linear combinations—means m_{mi} and variances D_{mi} [15]:

$$p(I_m - I_i > \delta_i)\big|_m = 1 - Q\left(\frac{m_{mi}}{\sqrt{D_{mi}}}\right),$$

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^{\infty} e^{-t^2/2} dt, \quad (4)$$

where $Q(x)$ is the Q-function.

The bit error probability using the Gray code can be found from the relation [13]

$$P_{eb} = \frac{P_{es}}{\log_2 M}. \quad (5)$$

The presence of errors in the generation of reference signals $s_{refi}(t)$ causes errors in the calculation of correlation integrals (2) and, as a result, an increase in error probabilities (3) and (5).

EFFECT OF THE PHASE ERROR IN THE REFERENCE OSCILLATION GENERATION UNIT

The phase error $s_{refi}(t)$ of the reference oscillation generation unit is caused by additional phase shift ϕ,

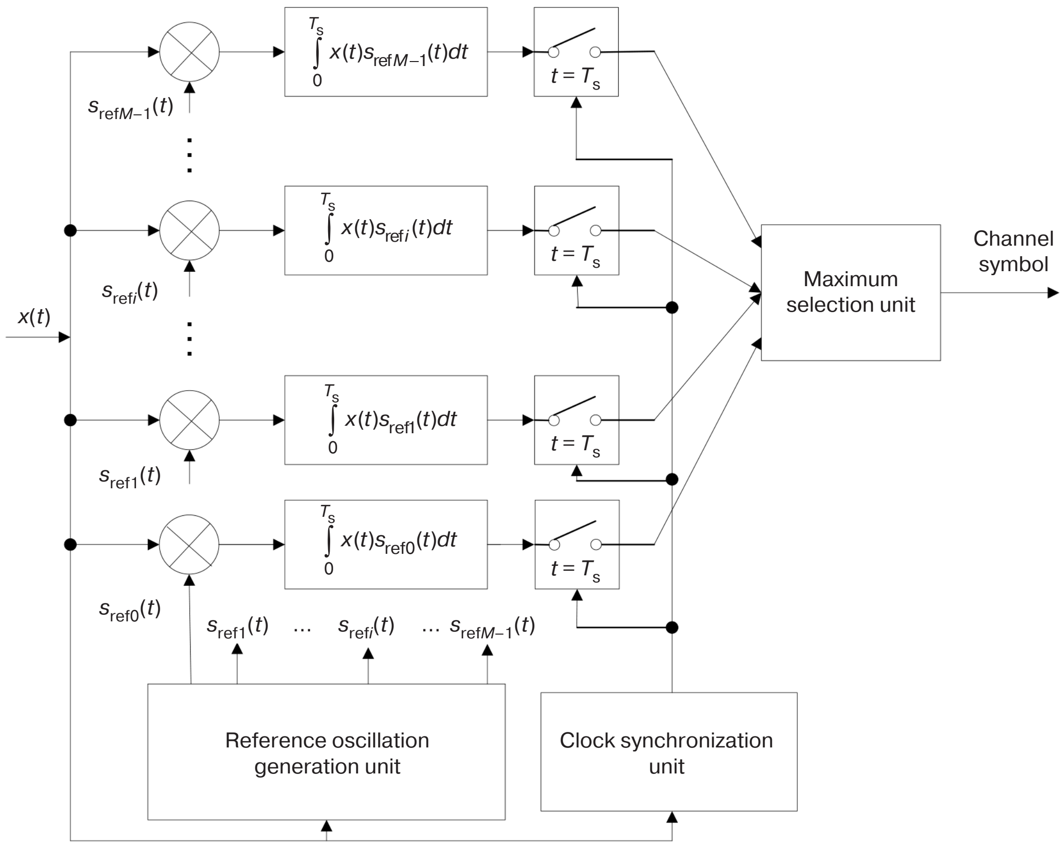


Fig. 1. Flowchart of a multichannel coherent receiver of APSK signals

e.g., due to the nonideality of the characteristics of the phase-locked loop system:

$$s_{\text{ref}i}(t) = A_{\text{av}} r_i \cos(\omega_0 t + \varphi_i + \phi),\ i = \overline{0, M-1}.$$

Figure 2 presents an example of the effect of such a shift on the shape of the signal constellation of a 16-APSK signal.

In this case, the means m_{mi} and variances D_{mi} in expression (4) have the form

$$m_{mi} = \frac{E_{\text{s av}}}{N_0}(2r_m{}^2\cos\phi - 2r_m r_i \cos(\varphi_m - \varphi_i - \phi) - r_m^2 + r_i^2),$$

$$D_{mi} = \frac{2E_{\text{s av}}}{N_0}(r_m{}^2 + r_i^2 - 2r_m r_i \cos(\varphi_m - \varphi_i)).$$

Calculation of the bit error probability from formulas (3)–(5) for signals 16-APSK and 32-APSK gives the following results (Figs. 3 and 4).

It can be seen that, at a small phase shift of $\phi < \pi/90$ (2°), the bit error probability decreases insignificantly, but with an increase in the phase shift, the noise immunity noticeably deteriorates, and at $\phi > \pi/45 = 4°$, the P_{eb} value can increase by an order of magnitude. Calculations show that, for $P_{\text{eb}} = 10^{-4}$ at $\phi = \pi/36 = 5°$, this is equivalent to energy losses of about 2.5 and 3.0 dB at $M = 16$ and 32, respectively.

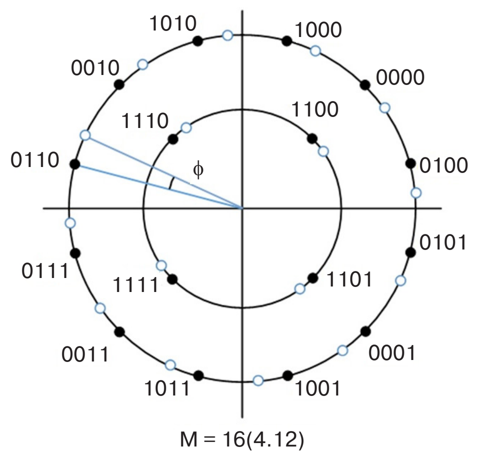
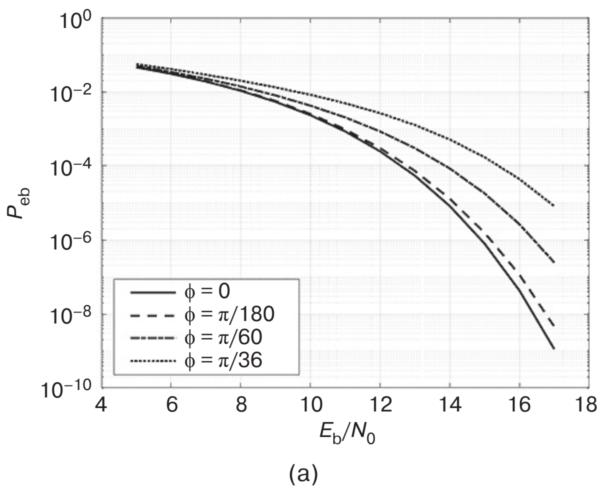


Fig. 2. Change in the signal constellation of a 16-APSK signal in the presence of phase shift ϕ

A comparison of the results of this work with the published results [5, 9] for QAM signals shows that, at the same M, the coherent reception of signals with the square shape of the signal constellation is somewhat more resistant to phase errors in reference oscillations than that of signals with the ring shape of the signal constellation. For example, at $\phi = \pi/60 = 3°$ and $P_{\text{eb}} = 10^{-4}$, the energy losses are 1.0 dB and 1.2 dB, respectively.



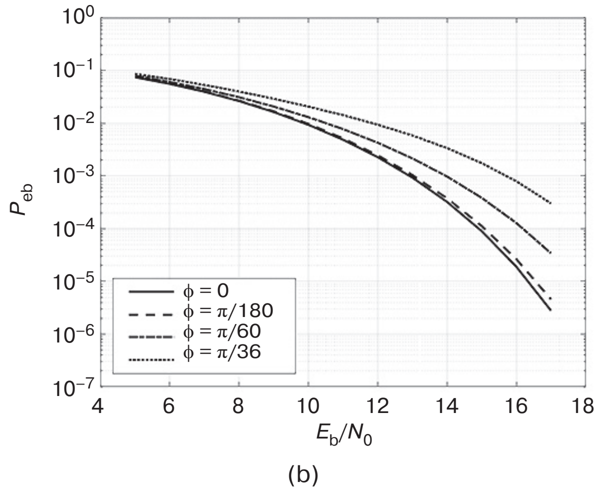


Fig. 3. Dependence of the bit error probability on the signal-to-noise ratio at phase shift ϕ of reference oscillations for (a) 16-APSK and (b) 32-APSK signals

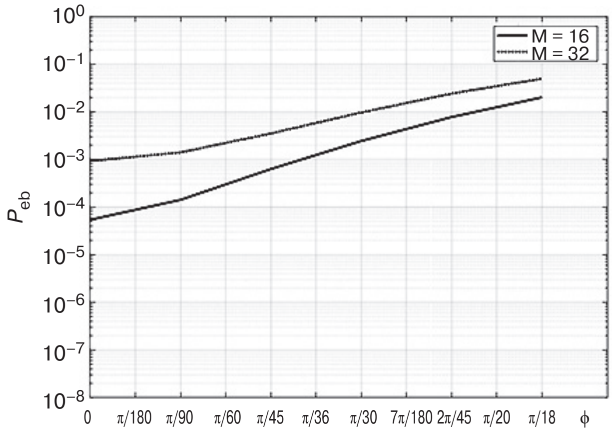


Fig. 4. Dependence of the bit error probability on the phase shift ϕ of reference oscillations at E_b/N_0 = 13 dB

EFFECT OF THE CLOCK OFFSET IN THE CLOCK SYNCHRONIZATION UNIT

Errors in the clock synchronization unit can lead to certain clock offset ξ in the clock cycle time T_s, which determines the limits of integration in expression (2).

In this case, the convolution integrals

$$J_i = \frac{2A_{av}}{N_0}\int_{\xi}^{T_s+\xi} x(t) r_i \cos(\omega_0 t + \varphi_i)dt$$

are calculated at the following parameters of the received and reference signals:

$$s(t) = \begin{cases} A_{av} r_i \cos(\omega_0 t + \varphi_i),\ t \in (\xi, T_s), \\ A_{av} r_j \cos(\omega_0 t + \varphi_j),\ t \in [T_s, T_s + \xi), \end{cases}$$

$$s_{refi}(t) = A_{av} r_i \cos(\omega_0 t + \varphi_i), t \in (\xi, T_s + \xi),$$

where the subscript j refers to the next channel symbol.

In this case, the means m_{mi} and variances D_{mi} in expression (4) take the form

$$m_{mi} = \frac{2E_{s\ av}}{N_0} r_m \left(1 - \frac{\xi}{T_s}\right)(r_m - r_i \cos(\varphi_m - \varphi_i)) +$$
$$+ \frac{2E_{s\ av}}{N_0} r_j \frac{\xi}{T_s}(r_m \cos(\varphi_j - \varphi_m) -$$
$$- r_i \cos(\varphi_j - \varphi_i)) - \frac{E_{s\ av}}{N_0}(r_m^2 - r_i^2),$$

$$D_{mi} = \frac{2E_{s\ av}}{N_0}(r_m{}^2 + r_i^2 - 2r_m r_i \cos(\varphi_m - \varphi_i)).$$

Figures 5 and 6 illustrate the dependences of the bit error probability at various clock offsets.

One can see that a large error in the clock synchronization system significantly reduces the noise immunity of reception of APSK signals. For example, for

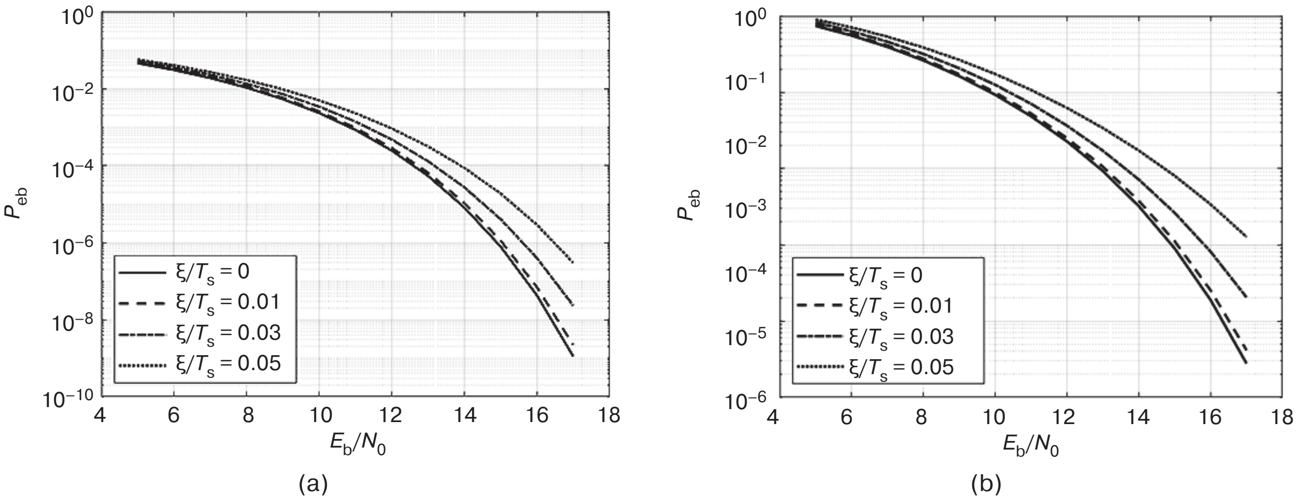


Fig. 5. Dependence of the bit error probability on the signal-to-noise ratio at various clock offsets ξ/T_s for (a) 16-APSK and (b) 32-APSK signals

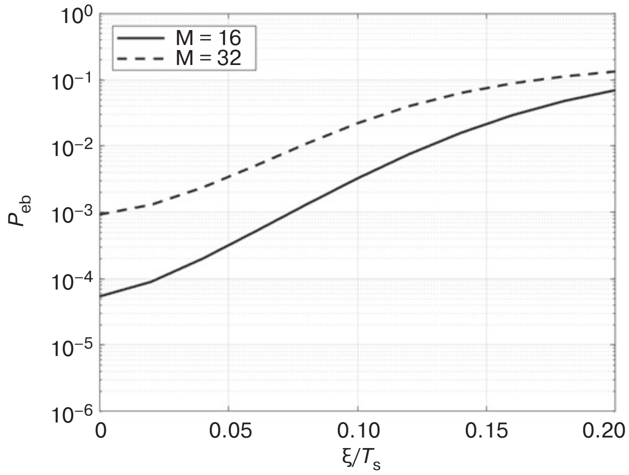


Fig. 6. Dependence of the bit error probability on the clock offset ξ/T_s at E_b/N_0 = 13 dB

$P_{eb} = 10^{-4}$ already at $\xi/T_s = 0.05$ (or 5%), the equivalent energy loss is about 1.5 and 2.0 dB at M = 16 and 32, respectively.

A previous similar analysis of QAM signals [5, 9] showed that clock errors have the same effect on the reception quality of QAM and APSK signals.

CONCLUSIONS

From the obtained results, the following conclusions can be drawn.

1) The presence of a phase shift of reference oscillations during the coherent reception of APSK signals can noticeably deteriorate the noise immunity. At an acceptable energy loss of no more than 1 dB, the critical phase error can be considered as around 2°–3°.
2) The presence of an error in the clock synchronization unit during the coherent reception of APSK signals can also significantly reduce the noise immunity. At an acceptable energy loss of no more than 1 dB, the critical clock error can be considered to be 3–4%.
3) Although a coherent receiver of APSK signals is more sensitive to phase errors of reference oscillations than a similar receiver of QAM signals, clock errors affect the reception quality of these signals in the same way.

Authors' contribution. All authors equally contributed to the research work.

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