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Features of Calculation and Design of High-Speed Radio Links for Earth Remote Sensing Spacecraft

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Abstract. The paper discusses the issues of selecting the parameters of the fine structure of modulated signals to optimize frequency-energy resources when designing a high-speed (hundreds and thousands Mbit/s) radio links for data transfer. Their features is application of signal-code constructs with the kinds of a high-order modulation and coding methods with high code rates.

Based on the analysis of a model of a radio link with nonlinearity, which limits a peak power in the output of the power cascade of the transmitter and a modulating signal with a nonzero value of a peak factor, the estimations of the main characteristics of a radio link are made.

It is noted that when realizing the set value of a signal-to-noise ratio, the fulfilment of the norms on providing the ratio of the values of the radiating powers in the main and adjacent channels can be limited.

The reasons of the spread in the estimations of the radio link parameters given in domestic and foreign publications on the question under consideration are analyzed.

It is marked, that the results received in the paper, are expedient to use during designing, tests, measurements, and optimization of the parameters of onboard and ground complexes of the radio lines of high-speed data transmission aimed to operate in Earth remote sensing (ERS) systems.

Keywords: high-speed radio links, modulated signals, signal-code constructs, frequency-energy resources, Nyquist filter, peak factor

The main feature of high-speed radio links (with transmission speeds from several hundred Mbit/s to several Gbit/s) is the need to use high modulation rate (m≥3) and code rate (R≥0.8), which is determined by strict requirements imposed by limitations in the availability of frequency resources. The modulation multiplicity with the value m>3 determines the use of a multilevel amplitude-phase structure, since for m>3 this structure, compared with a single-level (phase only structure), provides a maximum of the minimum Euclidean distance between the points of the equivalent "signal constellation".

In this case, the amplitude-phase structure implies two types of signal constellation: in the form of a rectangular lattice (QAM) and in the form of points located on a series of concentric circles (APSK).

The quantitative energy characteristics corresponding to these types of modulation are determined by two parameters:

- the minimum Euclidean distance between the points of the signal constellation;

- peak factor of the modulated signal (in a nonlinear channel with limited peak power).

The experience of design of complexes and equipment of high-speed radio links shows that these features are not always taken into account by developers of technical requirement specifications for both systems and instruments.

For the APSK, the error probability is determined by averaging the probability integral based on a search for all Euclidean distances of the signal constellation:

$$P_{\mathrm{e}} \leqslant \frac{1}{M} \sum_{x \in X} \sum_{\substack{x' \in X \\ x' \neq x}} Q\left(\sqrt{\frac{\mathrm{E}_s |x - x'|^2}{2N_o}}\right)$$

$\mathrm{E}_s = |x - x'| = d'$ is the Euclidean distance $\left(d'_{ij} = \right.$ $\left. = \sqrt{(r^2_{p(i)} + r^2_{q(j)} - 2 \cdot r_{p(i)} \cdot r^2_{q(j)} \cdot \cos(\beta)_{ij})}\right)$, ß is the angle between the points of the constellation [1]).

For QAM, the error probability is determined by the following formula [2, p. 586]:

$$P_{\mathrm{e}} \approx \frac{2(1 - L^{-1})}{\log_2 L} Q\left[\sqrt{\left(\frac{3\log_2 L}{L^2 - 1}\right)\frac{2Eb}{N_o}}\right].$$

In both formulas, $Q(x) = 1/\sqrt{2\pi} \times \int\limits_x^\infty e^{-\left(\frac{t^2}{2}\right)} dt$ is the probability integral, for small error probabilities replaced by the approximation [2]: $Q(x) \approx \exp(-0{,}5x^2)/(x\sqrt{2\pi})$.

Peak-factor PARP (pick / average ratio power) is the ratio of the peak power P_{peak} to the average power of $P_{av:}$

PARP = $P_{peak}/P_{av} = (U_{peak}/U_{rms})^2$.

For a signal at period 0,T [6]:

$$\mathrm{PARP} = \frac{\max_{t \in [0,T]} |s(t)|^2}{\frac{1}{T}\int_0^T |s(t)|^2\, dt}.$$

Or the same in terms of discrete components [3]:

$$\mathrm{PARP} = \frac{\max_{n=0,1,\ldots,N-1} |x_n|^2}{\frac{1}{N}\sum_{n=0}^{N-1} |x_n|^2}.$$

The value of PARP in actual transmission systems depends on two parameters:

- the multiplicity of the modulation type;

- the rounding factor of the matched Nyquist filter, which determines the bandwidth of the emitted signal on air.

Table 1 lists the main parameters for several types of modulation that are currently in use or are expected to be used in the satellite systems of high-speed information transmission in the foreseeable future. The complex of these parameters is partially calculated by the above formulas and partially borrowed from these sources [3, 4, 5, 7].

Table 2 shows the PARP values of the digital filter (DF), depending on the selected rounding factor α [8].

Since the bandwidth occupied by the spectrum of the modulated signal is defined as Δf≈ (1 + α) × fc (where fc is the character frequency of the signal on air), the desire to save frequency resources (choosing a smaller value of α) calls for a larger extension between the operating point of the nonlinear amplifier and the point of its saturation and, consequently, leads to losses of energy resources.

The resulting peak-factor is formed by summing the data by the peak factor, given in Table 1 and Table 2.

For example, Table 3 gives comparative data on the total PARP value for a DF with different rounding and modulation coefficients of type 16APSK and 16QAM.

According to the data in Table 3, two conclusions can be drawn:

1. Since the resulting peak factor (PARP) of APSK is less than that of QAM, this makes it possible (in the case of peak power limitation) to use the power of the output stage of the transmitter more efficiently and, for this reason, APSK is used in space transmission systems

Table 1

Modulation type	BPSK, QPSK	8PSK	16 PSK	16QAM	16APSK (4+16)	32 QAM	32 APSK (4+12+16)	64QAM	64APSK (4+12+16+32)
Peak factor [db]	0	0	0	2.56	1.065, (R=4/5), γ*=2.75	2.3	2.06	3.68	2.62
E_{bit}/N_o [db] at $P_{er}=10^{-6}$	10.6	13.8	18	14.4	15.5	16	17.4	18.8	19.5

Note: γ* is the ratio of the diameters of the outer and inner rings of the signal constellation for the code rate (R = 4/5).

Table 2

α	0.15	0.2	0.3	0.4	0.5
PARP [dB]	6.3	5.6	4.5	3.5	2.8

Table 3

α	0.15	0.2	0.3	0.4	0.5
PARP Σ APSK [db]	7.36	6.66	5.56	4.66	3.86
PARP Σ QAM [dB]	8.86	8.16	7.06	6.06	5.36

in an overwhelming number of cases, despite the fact that QAM has a minimal Euclidean distance slightly larger than that of APSK.

2. These tables make it possible to estimate the required OBO (Output Back Of) value, the linearity margin from the saturation point of the PA and the corresponding change in the average output power of the transmitter and, accordingly, the efficiency.

Figure 1 shows the corresponding schemes of a real X-band transmitter with an average output power $P_{out.\ av}$ = 8 watts.

The graph in Figure 1 shows that in this particular case, the presence of a peak factor in the modulating signal requires a margin of linearity of the power amplifier stage of about 4.6 dB.

Simultaneously with the requirement to provide the required transmitter power in order to realize the required signal-to-noise ratio, there is a requirement not to exceed the specified level of radiation in the adjacent channel.

In this case, the ACPR (Adjacent Channel Power Ratio) parameter is used as a measure of the linearity of systems operating using multi-position modulation signals, which is determined by the following relation [9]:

$$ACPR=10lg(P_{mc}/P_{ac})$$

where R_{mc} is the average signal power in the main channel, and P_{ac} is the average signal power in the adjacent channel, as shown in Fig. 2.

A mode with a given level of radiation power in an adjacent channel is provided by a simulation or experimentally by changing the load level.

The effect of channel nonlinearity on the transmission quality can be estimated from the curves in Fig. 3, which show the dependence of the error probabilities on the energy of the radio link - $P_{er}=f(E_{bit}/N_o)$ for 16QAM and 16APSK for α = 0.35.

The meaning of these curves is that in the case of 16APSK, the achievable average power (and, hence, E_{bit}/N_{er}) for a certain dependence of the nonlinearity of the PA is about 1 – 2 dB more. This leads to the possibility of realizing the magnitude of the error probability by about 1 – 2 orders of magnitude less than in the case of using QAM.

It should be noted that in the sources cited in the literature, there is a certain variation in the absolute and relative noise immunity of different types of signals. This fact is due to the multi-vector nature and some uncertainty in setting the initial data for the calculation.

The total ambiguity and error of calculations consists of the following components:

- errors in the computation of the probability integral and its approximations for small error probabilities;
- an ambiguous choice of the value of the rounding factor from the possible range (usually ~ 0.2 – 0.5);
- some heuristics when selecting the required value of the OBO;

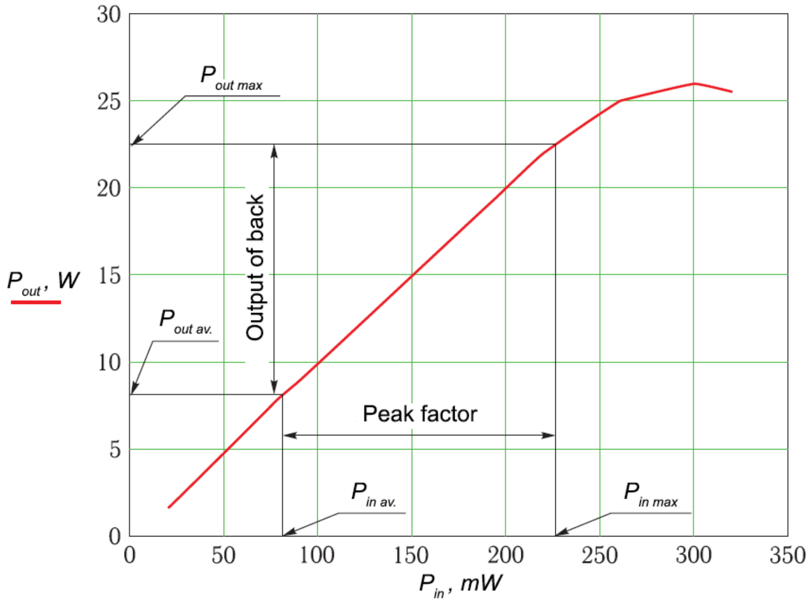

Fig. 1. Influence of the peak factor on the output parameters of the PA

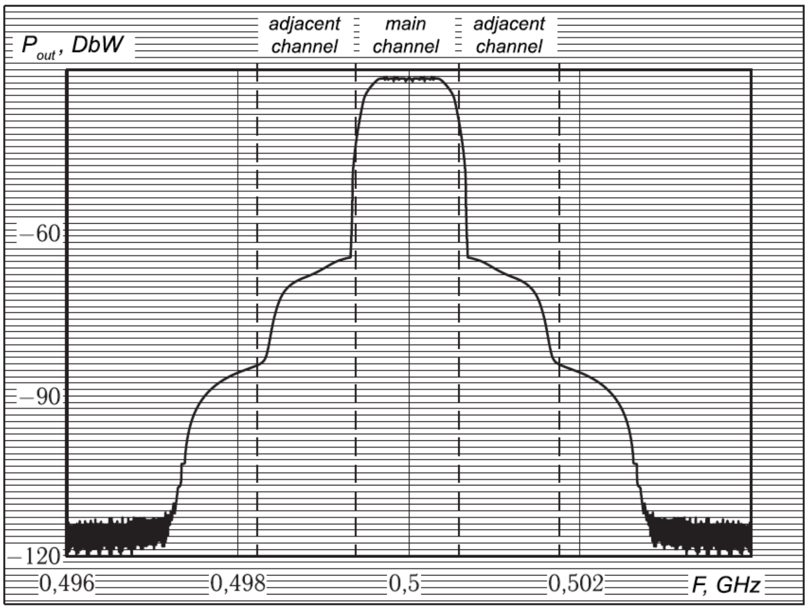

Fig. 2. Typical distortions of the signal spectrum due to the nonlinearity of the transmitter

- the use in the calculation of the value of the Euclidean distance either minimum or averaged (sometimes truncated) by the signal constellation;

- the use of various methods for approximating the parameters of the nonlinearity of output power stages (including taking into account the nonlinearity of the AGC of the transmitter);

- the use of slightly different relationships between the radii of circles of the signal constellation, which are usually chosen different for different code rates.

Conclusion

In the article the questions concerning the choice of parameters of the transmission path of the high-speed radio link are considered when using the Nyquist filter in the transmitter modulator.

It is shown that in the case of limiting the peak power of the transmitter and the requirement to save frequency resources by reducing the rounding factor and selecting an APSK of higher multiplicity, it is necessary to take

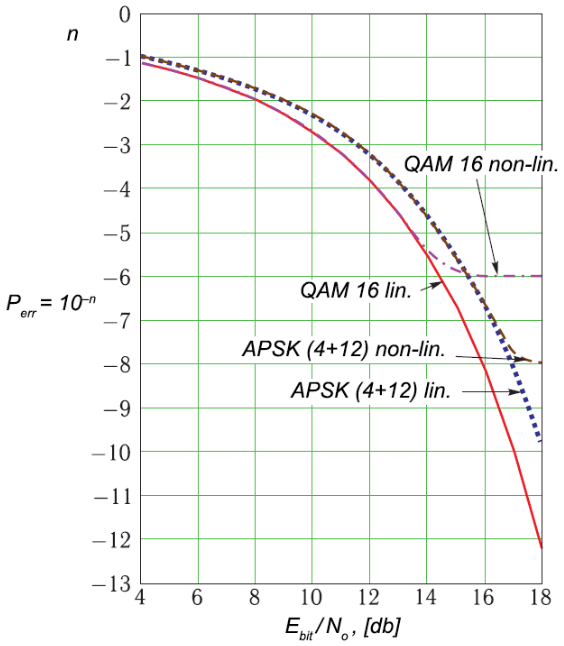

Fig. 3 Comparative dependences $P_{er}=f(E_{bit}/N_o)$ for 16QAM and 16APSK in a linear and nonlinear channel

into account the increase in the magnitude of the peak factor of the transmitter signal, which leads to a decrease in the emitted average power and the efficiency of the transmitter.

It is noted that in the process of increasing the power of the emitted signal, norms should be provided for the signal-interference ratio in the main and adjacent channels.

The reasons for the variation in radio link parameter estimates, which are presented in Russian and foreign papers, are analyzed, and corresponding quantitative estimates are made.

References

1. Jordanova L., Laskov L., Dobrev D. Constellation and Mapping Optimization of APSK Modulations used in DVB-S2. *Engineering, Technology & Applied Science Research*. 2014, Vol. 4, No. 5, pp. 690–695. Available at: https://zenodo.org/record/14687#.WXHwmS7WgeE (accessed 30 October 2017).
2. Sklar B. *Tsifrovaya svyaz'. Teoreticheskie osnovy i prakticheskoe primenenie* [Digital Communications: Fundamentals and Applications]. Moscow, Vil'yams. 2nd edition, revised. 2007, 586 p. (translated from English).
3. Chayratsami P., Thuaykaew S. *The Optimum Ring Ratio of 16-APSK in LTE Uplink over Nonlinear System*. Available at: http://www.icact.org/upload/2013/0554/20130554_Journal_B.pdf (accessed 30 October 2017).
4. Gaudenzi R., Fabregas A., Martinez A. Turbo-Coded APSK Modulations Design for Satellite Broadband Communications. *International Journal of Satellite Communications and Networking*. Published online 19 May 2006 in Wiley InterScience (www.interscience.wiley.com). Available at: http://www.dtic.upf.edu/~amartinez/publications/apsk_ijsc_published.pdf (accessed 30 October 2017).
5. Lottici V., Luise M., Reggiannini R. *Adaptive Nonlinear Compensation of Satellite Transponder Distortion for High-Level Data Modulations*. Available at: https://www.researchgate.net/publication/228600391_APSK_Coded_Modulation_Schemes_for_Nonlinear_Satellite_Channels_with_High_Power_and_Spectral_Efficiency (accessed 30 October 2017).
6. Baldi M. A comparison between APSK and QAM in wireless tactical scenarios for land mobile systems. *Journal on Wireless Communications and Networking*. Published October 19, 2012. Available at: http://jwcn-eurasipjournals.springeropen.com/articles/10.1186/1687-1499-2012-317 (accessed 30 October 2017).
7. John S. Seybold. *Crest Factors for QAM Signals*. Available at: http://mathscinotes.com/2012/11/crest-factors-for-qam-signals/ (accessed 30 October 2017).
8. *RF signal processing. June 2002. Output Back-Off Requirements For Root-Raised, Cosine-Filtered Digital Signals*. Available at: http://defenseelectronicsmag.com/site-files/defenseelectronicsmag.com/files/archive/rfdesign.com/images/archive/0602Seybold50.pdf
9. Malev A.S., Solov'ev A.M., Shutov V.D. Podkhody k optimizatsii metodov formirovaniya signalov s mnogopozitsionnoy modulyatsiey po minimumu pik-faktora [Optimization of signal's parameters with multiway modulation for the purpose of crest factor minimization]. *Teoriya i tekhnika radiosvyazi*

[Radio communication theory and equipment]. Voronezh, OAO “Kontsern “Sozvezdie”, 2012, No. 2, pp. 50–56. (in Russian)

10. Pedro E. Santacruz. *Analysis of the effects of nonlinear amplification on turbo Coding*. Thesis Presented to the Faculty of the Graduate School of The University of Texas at El Paso in Partial Fulfillment of the Requirements for the Degree of Master of Science. Available at: http://mpc.ece.utexas.edu/users/pesantacruz/files/thesis.pdf (accessed 30 October 2017).
11. Ershov A.N., Petrov S.V., Berezkin V.V., Petrov A.V., Pochivalin D.A. Metody proektirovaniya i apparatnoy realizatsii tsifrovykh fil’trov dlya vysokoskorostnoy radiolinii v sistemakh DZZ [Methods of Design and Hardware Implementation of Digital Filters for High-Speed Radio Link in Earth Remote Sensing Systems]. *Raketno-kosmicheskoe priborostroenie i informatsionnye sistemy* [Rocket-Space Device Engineering and Information Systems]. Moscow, FIZMATLIT, 2017, Vol. 4, No. 1, pp. 25–31. (in Russian)