

## **Analysis of the Raman spectrum of high-power amplifiers of wireless communication systems**

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At present, the transfer of information is an integral part of technologies that are actively developing in the framework of the process called the Fourth Industrial Revolution. In this, space-satellite, satellite and other mobile wireless communication systems play an increasingly important role. Almost all of them include multiple access, which means a method of common resource division of the communication channel between subscribers (each mobile station has the ability to use a satellite retransmitter or the base station of a mobile wireless communication system to transmit its signals regardless of the operation of another station). Multiple-access communication systems are used for digital radio and television broadcasting in high-speed communication lines, in wireless local area networks, for data transmission in the microwave range, and also for communication with various mobile partners. In the radio transmitting and receiving paths of communication systems with multiple access, multiple signals are used (the sum of the power of the subscriber signals) with very complex types of digital envelope modulation, so they use wide working bands. With an increase in the quality of information transmission in mobile wireless communication systems, there are special requirements for powerful amplification systems (PAS) of receiving-transmitting tracts, which must have high efficiency and high output power, required bandwidth, network capacity, and linearity of message transmission channels. To achieve maximum efficiency in the PAS, the operating point of its amplifying element should be near the saturation region, on the main nonlinearity of the transfer characteristic. When multiple signals are introduced simultaneously into the PAS, it generates unfiltered intermodulation harmonics (IH). Intermodulation harmonics are formed due to the nonlinearity of the amplitude characteristics and the unevenness of phase-amplitude characteristics and due to the need to work with the highest efficiency of the PAS, which requires a shift of the operating point to the saturation thresholds of their amplifying elements. This, in turn, causes the appearance of IH. Since the harmonic oscillations IH actually represent noise for neighboring communication channels and are not theoretically filtered, an equalizer (otherwise an optimizer) of characteristics, is needed to reduce the level of these interferences in the output (Raman) spectrum of the PAS.

**Keywords:** communication systems, group signals, amplitude characteristics, adaptive mathematical models, modeling, harmonics of intermodulation, correction of nonlinear systems characteristics.

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## Анализ комбинационного спектра высокомоощных усилителей систем беспроводной коммуникации

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В настоящее время передача информации является неотъемлемой частью технологий, активно развивающихся в рамках процесса, называемого Четвертой промышленной революцией. В этом всё большую роль играют спутнико-космические, спутниковые и другие подвижные системы беспроводной коммуникации. Почти все они включают в себя множественный доступ (multiple access), под которым понимается способ разделения общего ресурса канала связи между абонентами (каждая мобильная станция имеет возможность пользоваться ретранслятором спутника или базовой станцией подвижной системы беспроводной коммуникации для передачи своих сигналов независимо от работы другой станции). Связные системы с множественным доступом используются для цифрового радио- и телевидения в высокоскоростных линиях связи, в беспроводных локальных сетях, для передачи данных в СВЧ-диапазоне, а также для связи с различными подвижными партнерами. В радиопередающих и радиоприемных трактах связных систем с множественным доступом используются множественные сигналы (сумма мощностей сигналов абонентов) с весьма сложными видами цифровой модуляции огибающей, поэтому в них применяют широкие рабочие полосы. С повышением качества передачи информации в подвижных системах беспроводной коммуникации имеют место особые требования к мощным усилительным системам (МУС) приема-передающих трактов, которые должны обладать высоким КПД и большой выходной мощностью, требуемыми широкополосностью, емкостью сети и линейностью каналов передачи сообщений. Для достижения максимальной эффективности в МУС рабочая точка его усилительного элемента должна находиться вблизи области насыщения, на основной криволинейности передаточной характеристики. Когда множественные сигналы вводятся одновременно в МУС, он генерирует нефильтруемые гармоники интермодуляции (intermodulation harmonics; англ. IH). Гармоники интермодуляции образуются вследствие нелинейности амплитудных характеристик и неравномерности фазо-амплитудных характеристик и необходимости работать с наиболее высоким КПД МУС, что и требует сдвига рабочей точки к порогам насыщения их усилительных элементов. Это в свою очередь и вызывает появление IH. Поскольку гармонические коле-

бания ИН фактически представляют собой шум для соседних каналов связи и теоретически не фильтруемы, необходим выравнитель (иначе оптимизатор) характеристик для уменьшения уровня этих помех в выходном (комбинационном) спектре МУС.

**Ключевые слова:** системы связи, групповые сигналы, амплитудные характеристики, адаптивные математические модели, моделирование, гармоники интермодуляции, коррекция характеристик нелинейных систем.

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The aim of this work is to solve the problems of increasing the output power and efficiency of powerful amplification systems (PAS), as well as increasing the capacity and expanding the bandwidth of communication systems with multiple access of mobile stations of subscribers. All this is achieved by optimizing the characteristics of the PAS, which leads to a sharp decrease in the intermodulation harmonics (IH) power, and as a result – the actual recovery (return) of useful energy.

In theory and practice, there is a statistical relationship between the parameters of the input and output multiple signals of a nonlinear dynamic system. That is why we can apply the adaptive linearization method for these non-linear microwave (UHF) power amplifiers in order to analyze and calculate the output Raman spectrum.

Nonlinear distortions (ND), including IHs, are caused by the generation of new harmonic components in the spectrum of the useful signal. The input of the PAS does not contain these components, and they are associated exclusively with the presence of curved sections “below” (noise area) and “above” (distortion area), in particular, on the amplitude characteristics (AC) (Fig. 1) [1–3].

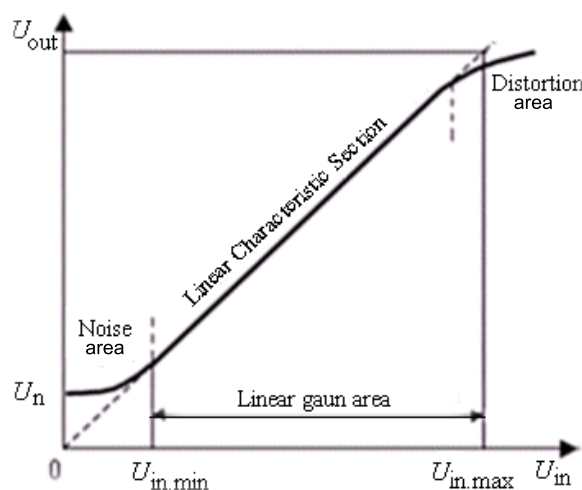


Fig 1. Real amplitude characteristic of the PAS.

The appearance of ND, and in particular IHs, in the transceiver paths of a mobile satellite, space-satellite, and terrestrial communication systems with multiple access to mobile wireless communication stations leads to a situation where, in addition to useful signal power limited due to internal relatively small noise (noise area of the actual PAS), a new threshold power level appears in the distortion area. In these areas, there is a violation of the linear dependence of the real part of the transmission coefficient, i.e., of the dependence of the output signal power on the level of the input oscillation.

The method of adaptive optimization of the characteristics of a nonlinear PAS is based on the artificial replacement of the nonlinear conversion of multiple amplified signals with equivalent linear transformations [1–3], while the nonlinear element of the PAS is replaced by a linear equivalent, and the nonlinear AC is replaced by a linear one. As a result of such a replacement, the PAS is linearized, which makes it possible to use methods of studying linear dynamic systems for it. Then, IHs are automatically compensated according to the results of calculations obtained on the basis of computer mathematics (CM) using the adaptive digital-tax equalizer of characteristics.

So, IHs arise in transceivers as a result of simultaneous action, in the simplest case, of two test harmonics with radiation frequencies  $f_1$  and  $f_2$  on its nonlinear amplifying element. IHs are in the working band of useful signals. It is theoretically and practically impossible to filter them out. Therefore, they are undesirable. Most dangerous are third-order IHs, the harmonics of intermodulation at frequencies  $(2f_1 - f_2)$  and  $(2f_2 - f_1)$ . In a real environment, it is very difficult to distinguish IHs from useful signals and interference from another, unauthorized radio station operating in a communication system [1–3].

Today, the functions of transcendental type, such as cylindrical functions of the first kind [3–6], are widely used as mathematical apparatus for calculating. They provide fast and correct convergence of the solutions of a number of mathematical, physical and technical problems describing many physical processes accompanied by constant loss of the internal energy for a nonlinear dynamical system (for example, losses in the PAS due to emerging IHs). These functions can be somehow reduced to widely known transcendental functions.

Cylindrical functions, as a class of transcendental functions, are solutions of the Bessel differential equation [3–7]:

$$x^2 \frac{d^2 y}{dx^2} + x \frac{dy}{dx} + (x^2 - \nu^2)y = 0, \quad (1)$$

where the parameter  $\nu$  is the order taking complex (arbitrary) values.

We expand equation (1) in a power series near the point  $x = 0$ :

$$J_\nu(x) = \sum_0^\infty \frac{(-1)^n (0.5x)^{2n+\nu}}{n! \Gamma(n+\nu+1)}, \quad (2)$$

where  $\Gamma(n+\nu+1)$  is the gamma function widely known in mathematics. (It was introduced by Leonard Euler, and it owes its designation to Legendre).

According to relation (2), any term of the power series expansion

$$J_{fk}(\nu, \tau, \gamma) = \frac{e^{-\gamma\tau}}{\pi} \int_0^\pi \cos \left[ \lambda_k^{(\nu)} \left( 1 - e^{-2\gamma\tau} \right) \sin \varphi - \nu \varphi \right] d\varphi. \quad (3)$$

where  $\lambda_k^{(\nu)}$  are the roots of the equation.

In accordance with formula (2), the initial term of the series expansion

$$a_0 = \left(\frac{x}{2}\right)^v \frac{1}{v!}. \quad (4)$$

Similarly, each term in the expression (2) can be calculated as

$$a_k = a_{k-1} \frac{(-1)(0.5x)^2}{k(n+k)}. \quad (5)$$

Note that compared with geometric cosine and sine functions that behave identically on the entire numerical axis and are periodic functions with a period of oscillations of  $2\pi$ , changes in functions (3) for large values of the variable  $x$  gradually degenerate and tend to zero [6–9].

It should be noted that the asymptotic period of their oscillations tends to the classical value  $2\pi$ . For example, for small values of the index  $x$  of functions (3), even for variable  $X > 8$ , the interval between roots becomes equal to  $\pi$ . For sufficiently large values of the argument  $x$ , the asymptotic expansion is used:

$$J_v(x) = \sqrt{\frac{2}{\pi x}} \cos(x - 0.25\pi - 0.5v\pi). \quad (6)$$

An important feature of expressions (6) is that they, given by the relation  $J_v(\lambda_m^{(v)}x)$ , form a complete orthogonal system of functions that allows us to represent different analytic functions in the form of infinite series of products

$$f(x) = \sum_{m=1}^{\infty} a_m J_v(\lambda_m^{(v)}x). \quad (7)$$

On the basis of the above assumptions, one can represent the orthogonal Bessel functions of the first kind in numerical form using the integrals (3) [7–9]:

$$Jf_k(v, \tau, \gamma) = \frac{e^{-\gamma\tau}}{\pi} \int_0^{\pi} \cos\left(\lambda_k^{(v)}(1 - e^{-2\gamma\tau}) \sin \varphi - v\varphi\right) d\varphi. \quad (8)$$

Nowadays, the direct application of functions (8), as well as their decomposition into orthogonal systems, is one of the promising directions in solving real practical problems and constructing reliable mathematical models of amplifying PAS included in the transceiver paths of mobile and satellite communication systems with multiple access.

**Analysis of nonlinear transformations on the basis of transcendental functions.** Let one harmonic voltage component  $u(t)$  be supplied to the input of the PAS. The relationship between the current and the acting voltage can be written as

$$i = f[u(t)]. \quad (9)$$

The input voltage  $u(t)$  usually consists of a bias voltage  $U_0$  and a harmonic  $u_{\omega} = U_{\omega} \cos \omega t$ , so, in the PAS  $i = f(U_0 + U_{\omega} \cos \omega t)$ .

Then we expand the last dependence of the output current into the Taylor series in the following form [7–9]:

$$e^{ud/dx} f(x) = \sum_{n=0}^{\infty} \frac{1}{n!} \frac{d^n f(x)}{dx^n} u^n \quad (10)$$

Substituting the values  $u_{\omega} = U_{\omega} \cos \omega t$  into (9) we have

$$i = \exp \left( U_{\omega} \cos \omega t \frac{d}{dU_0} \right) f(U_0). \quad (11)$$

Expanding expression (11) in the Laurent series, substituting functions (3) into it and bringing the function  $f(U_0)$  under the differentiation sign we obtain [10–14]:

$$i = \sum_{m=0}^{\infty} \frac{1}{2^{2m} (m!)^2} \frac{d^{2m} f(U_0)}{dU_0^{2m}} U_{\omega}^{2m} + \quad (12)$$

$$+ \sum_{p=1}^{\infty} \sum_{m=0}^{\infty} \frac{1}{2^{2m+p-1} (m+p)! m!} \frac{d^{2m+p} f(U_0)}{dU_0^{2m+p}} U_{\omega}^{2m} \cos p \omega t.$$

Relation (12) obtained as a result of simple mathematical transformations determines the complete Raman spectrum of the output current of a nonlinear element (in this case, the powerful output transistor of the PAS) and allows us to calculate almost every component of the Raman spectrum at the output of the transmitting amplifier path. Let us represent the voltage acting on the input of the PAS by the sum of the constant component and the harmonics of the group signal:

$$u = U_0 + \sum_{s=1}^K U_{\omega_s} \cos \omega_s t, \quad (13)$$

where  $s = 1, 2, \dots, K$ .

Then, in trigonometric form, expression (12) can be represented as follows [5, 6, 8–10]:

$$i = \left[ \prod_{s=1}^k I_0 \left( \frac{dU_{\omega_s}}{dU_0} \right) \right] f(U_0) + \quad (14)$$

$$+ 2 \sum_{p_1=h_1}^{\infty} \sum_{p_2=h_2}^{\infty} \sum_{p_k=h_k}^{\infty} \left[ \prod_{s=1}^k I_{P_s} \left( \frac{dU_{\omega_s}}{dU_0} \right) \right] f(U_0) \cos \left( p_1 \omega_1 + \sum_{s=2}^k \pm p_s \omega_s \right) t,$$

where the lower limits for summing indices in the sums  $h_1, h_2 \dots h_k$  are selected on the basis of the condition

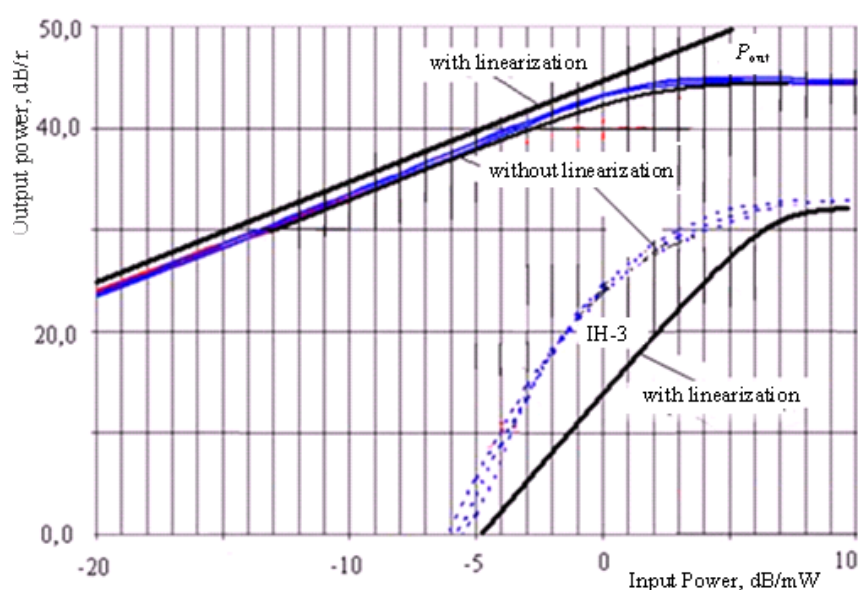
$$\sum_{s=1}^k h_s = 1.$$



Expression (14) defines all components of the output current, and each of them is easily calculated using Bessel functions of the first kind of the  $p$ -order [2, 7, 11–15]. On the basis of these results, a method for adaptive alignment of nonlinear PAS with a common envelope of amplified multiple signals was developed (Fig. 2).

Figure 2 shows that the transfer AC of the PAS in the gain range is almost linear. A similar change accompanies the IH-3 characteristic. This means that the adaptive linearization scheme sharply reduced the level of all IHs transforming their power into useful multiple signals.

So, IHs arise in transmitters as a result of simultaneous exposure to at least two signals with frequencies  $f_1$  and  $f_2$ .



**Fig. 2.** Amplitude characteristics of the PAS without linearization and with linearization.

In a real environment, it is very difficult to distinguish IH from signals from another, unauthorized station.

The object of the influence of signals with frequencies  $f_1$  and  $f_2$  is the PAS at the output of the transmitter.

IHs are in the working band. It is practically impossible to filter them out. Therefore, they are undesirable. Most dangerous are third-order IHs, the harmonics at frequencies  $(2f_1 - f_2)$  and  $(2f_2 - f_1)$ , where  $f_1$  and  $f_2$  are the two most significant spectral test components of the input signal (for example, the carrier and side harmonics, the first and second harmonics and etc.).

### Conclusion

A modern method for correcting the transfer characteristic of powerful amplification systems is analyzed. It is established that the method of approximating the transfer characteristics by Bessel functions can be quite effective for studying nonlinear PAS when amplifying multiple signals in wireless communication systems.

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