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INFLUENCE OF NONLINEARITY ON AVIATION SATELLITE COMMUNICATION CHANNEL PARAMETERS

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Abstract. *For an investigation of satellite amplifier nonlinearity impact on aviation OFDM communication channel parameters the original model of a link "Aircraft-Satellite-Ground Station" was built using MATLAB Simulink software. The model with adaptive modulation consists of a source of information, aircraft transmitter, uplink/downlink path, satellite transponder, and ground station receiver. The dependencies of a signal to noise ratio on free space path loss for different types of amplifier nonlinearity, signals modulation (BPSK, QPSK, 16QAM, 64QAM), noise temperatures were received. The spectrums and signals constellations of received signals were compared for different types of amplifier nonlinearity. Developed model allows predicting spectral regrowth of digitally modulated OFDM signals due to amplifier nonlinearity.*

Key words: amplifier nonlinearity; aviation satellite communication; convolutional coding; free space loss; noise temperature; OFDM channel; satellite transponder.

1. Problem statement

Nowadays worldwide communications are available for aviation through communication satellites [1]. Satellite networks play an important role for the purpose of data delivery over large distances, and are an effective means for reaching remote locations lacking in communication infrastructure [2]. Aviation satellite telecommunication channels play a critical role in providing a rapidly deployable, reliable, and affordable communications [3].

The goal for the aeronautical satellite mobile communications system is to integrate a variety of communication services (voice signals, high speed data, video and multimedia traffic). One of the promising approaches is adaptive Orthogonal Frequency Division Multiplexing (OFDM). The interest in adaptive coding and modulation techniques is increased in recent years [4].

Data traffic for satellite networks must be designed to take into account characteristics of satellite systems: propagation delays, limited energy and power, relatively high channel error rates, and time-varying channel conditions [5].

The signal transmitted via satellite is affected by many factors: a free path loss, a frequency offset, a phase noise, nonlinearities, a noise temperature, amplifier nonlinearity. Therefore the main task is successful and reliable data message transmission in spite of these adverse conditions.

The information transmitting by means of OFDM signals became the standard for many modern radio systems in connection with a number of advantages - high spectral efficiency, low level of an intersymbol interference, high quality of transmitting in the conditions of frequency-selective fading.

At the same time OFDM systems are sensitive to phase and frequency instability of carriers. It is especially important to provide power efficiency for an information transmitting in aviation complexes with rigid restriction of spatially-frequency parametres for onboard radio-electronic equipment.

For this simulations are mandatory to infer the performance of mobile satellite communication systems.

Nevertheless issues related to the satellite channel nonlinearities still are not investigated in detail.

2. Analysis of researches and publications

Digital multi-carrier modulation technique OFDM has been adopted as physical layer scheme of broadband wireless air interface standards.

Nonlinear distortion is a source of major degradation of modulation fidelity in multicarrier systems with OFDM signals. Compared with conventional single carrier communication systems, OFDM signals significantly improve spectrum efficiency and reduce frequency selective fading problems. However their consisting of large numbers of independent QAM subcarriers, means the composite signal's peak to average power ratio (PAPR) can be significant. This makes them sensitive to nonlinear distortion [6].

The primary source of this nonlinear distortion is the radio frequency transmitter power amplifier. Nonlinear power amplifiers for wireless communications were modeled [7] and nonlinear power amplifier effects in multi-antenna OFDM systems were analyzed [8]. Modulation schemes effect on radio frequency power amplifier nonlinearity were considered in paper [9]. A new PAPR reduction technique of OFDM system with nonlinear high power amplifier was proposed [10]. The use of OFDM radio interface for satellite digital multimedia broadcasting systems [11], a BER for MIMO-OFDM systems [12], performances of weighted cyclic prefix OFDM with equalization [13] were studied.

3. Aim of the work

Channel nonlinearity is critical for wireless communications systems. Therefore the aim of this paper is: 1) to design model of aeronautical satellite OFDM communication channel "Aircraft–Satellite–Ground Station" with adaptive modulation using MATLAB Simulink software; 2) to calculate parameters of a channel with different types of nonlinearities; 3) to analyze the impact of nonlinearities on parameters of satellite communication channel.

4. Model for "Aircraft-Satellite-Ground Station" channel

Satellite communication channel was analyzed using original model designed on a basis of IEEE 802.11a standard and MATLAB Simulink demo model *commwman80211a*.

The model (Fig. 1) consists of "Uplink / Downlink" (Fig. 2), "Aircraft Transmitter" (Fig 3), "Satellite Transponder" (Fig 4), "Ground Station" (Fig. 5) and "Adaptive Modulation Control" (Fig. 6). Different types of "Uplink / Downlink" were considered: "Multipath", "Rayleigh Fading", "Rician Fading", "Free Path Loss with Phase/Frequency Offset" and AWGN channels. This paper is devoted to consideration of "Free Path Loss with Phase / Frequency Offset" type of a link.

Parameter settings for the model are the following: Viterbi traceback depth is 34, hysteresis factor for adaptive modulation (dB) is 3, numbers of OFDM symbols per transmit block are 20, 200, 400 and 1000, number of OFDM symbols in training sequence is 4, Low-SNR thresholds (dB) vector is [10 11 14 18 22 26 28], where less than 10 dB is for BPSK ½, between 10 dB and 11 dB - for BPSK ¾, between 11 dB and 14 dB - for QPSK ½, between 14 dB and 18 dB - for QPSK ¾, between 18 dB and 22 dB - for 16-QAM ½, between 22 dB and 26 dB - for 16-QAM ¾, between 26 dB and 28 dB – for QAM 2/3 and more than 28 dB - for 64-QAM ¾

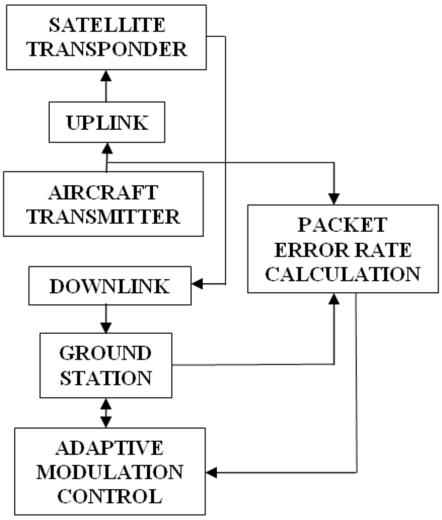

Fig. 1. "Aircraft-Satellite-Ground Station" channel

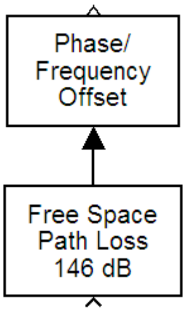

Fig. 2. "Uplink / Downlink"

Low-SNR thresholds parameter is a seven-element vector that indicates how the simulation should choose a data rate based on the Signal-Noise Rate (SNR) estimation. The model has eight modes, each associated with a particular modulation scheme and convolutional code. The seven thresholds are the boundaries between eight adjacent regions that correspond to the eight modes. Ideally, the simulation should use the highest-throughput mode that achieves a desired (zero) packet error rate. Determining appropriate thresholds often involves running the simulation multiple times, varying the values of the Low-SNR thresholds parameter.

The communication system in this model performs such tasks as: generation of random data at a bit rate that varies during the simulation; coding, interleaving, and modulation using one of eight schemes specified in the standard; OFDM transmission using 52 subcarriers, 4 pilots, 64-point FFTs (Fast Fourier Transform), and a 16- sample cyclic prefix; physical layer convergence protocol preamble modeled as four long training sequences.

Packet Error Rate Calculation block shows the packet error rate as a percentage and should always be zero during investigations.

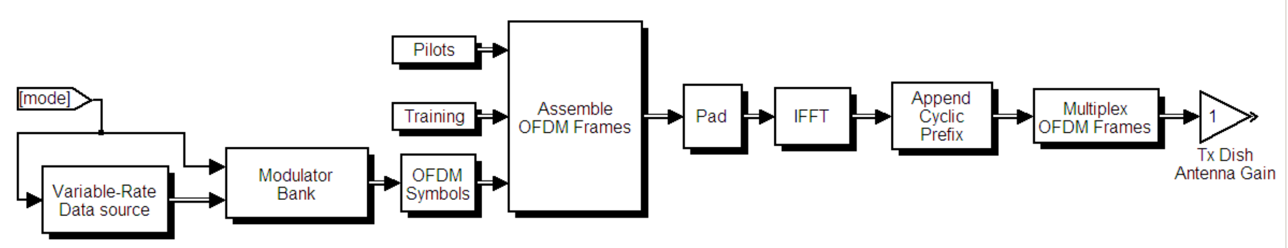

Fig. 3. “Aircraft Transmitter”

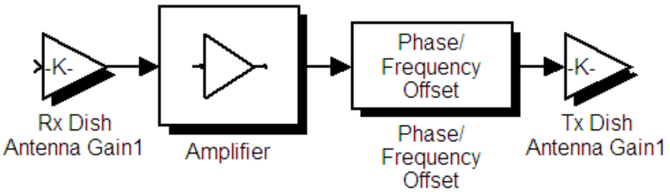

Fig. 4. “Satellite Transponder”

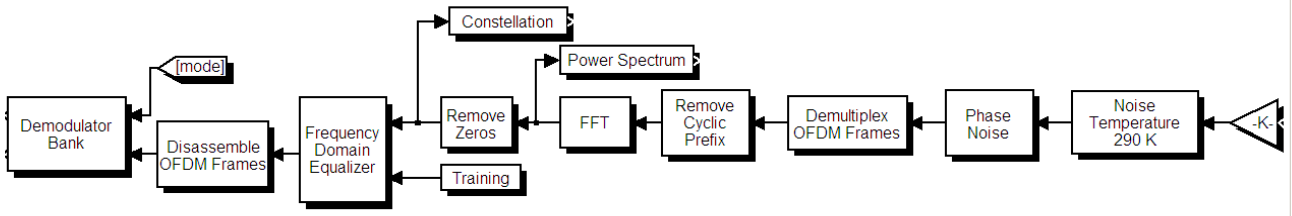

Fig. 5. “Ground Station”

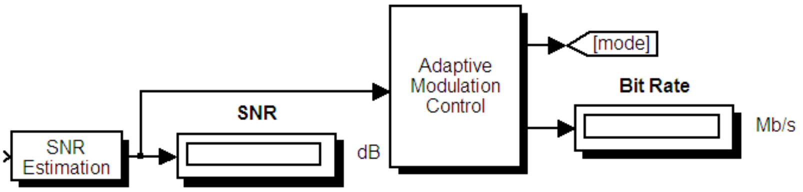

Fig. 6. “Adaptive Modulation Control”

5. Aeronautical Satellite Communication Channel Nonlinearity Simulation

For calculations the following parameters in the model (Fig.1) were set up: phase/frequency offsets in uplink/downlink and a satellite transponder are equal to zero; aircraft antenna gain (Fig. 3) was taken 12.4 (an antenna diameter ≈ 0.4 m at 4 GHz), satellite antennas gain (Fig. 4) – 31.1 (an antenna diameter ≈ 1.0 m at 4 GHz), ground station antenna gain (Fig. 5) – 62.2 (an antenna diameter ≈ 2.0 m at 4 GHz).

Dependencies of a SNR on free path losses for different models of nonlinearity, modulation modes, noise temperatures and 20 OFDM symbols per transmitting block are given on Fig. 7–12. During modeling the value of a packet error rate was kept at zero by changing the type of modulation (using a SNR estimation and adaptive rate control). In accordance with this a SNR was changed. Free space path loss values were changed simultaneously in a uplink and a downlink.

The options for the method for modeling amplifier nonlinearity are Linear, Cubic Polynomial [3], Hyperbolic Tangent, Saleh model [14], Ghorbani model [15], and Rapp model [16].

The **linear method** is implemented by a Gain block (with a linear gain 10 dB). All five subsystems for the **nonlinear method** options apply a memoryless nonlinearity to the complex baseband input signal. Each one multiplies the signal by a gain factor; splits the complex signal into its magnitude and angle components; applies an AM/AM conversion to the magnitude of the signal, according to the selected nonlinearity method, to produce the magnitude of the output signal; applies an AM/PM conversion to the phase of the signal, according to the selected nonlinearity method, and adds the result to the angle of the signal to produce the angle of the output signal; combines the new magnitude and angle components into a complex signal and multiplies the result by a gain factor, which is controlled by the Linear gain parameter.

For **Cubic Polynomial Model** the Amplifier block models the AM/AM nonlinearity by:

– using the third-order input intercept point *IIP3*= 30 dBm parameter to compute the factor *f,* which scales the input signal before the Amplifier block applies the nonlinearity:

$$f=\sqrt{\frac{3}{IIP3\left(W_{atts}\right)}}=\sqrt{\frac{3}{10^{\left(IIP3(dBm)-30\right)/10}}};$$

– computing the scaled input signal by multiplying the amplifier input signal by *f*;

– limiting the scaled input signal to a maximum value of 1;

– applying an AM/AM conversion to the amplifier gain, according to the following cubic polynomial equation:

$$F_{AM/AM}\left(u\right)=u-\frac{u^{3}}{3};$$

where u is the magnitude of the scaled input signal, which is a unitless normalized input voltage.

The Amplifier block uses the AM/PM conversion (10 degrees per dB) parameter, which specifies the linear phase change, to add the AM/PM nonlinearity within the power limits specified by the Lower input power limit for AM/PM conversion (10 dBm) parameter and the Upper input power limit for AM/PM conversion (infinite dBm) parameter. Outside those limits, the phase change is constant at the values corresponding to the lower and upper input power limits. The Linear gain (10 dB) parameter scales the output signal.

In **Hyperbolic Tangent Model** data are processed as in Cubic Polinomial Model with the exception of applying an AM/AM conversion to the amplifier gain, according to the following equation:

$$F_{AM/AM}\left(u\right)=\tanh\left(u\right).$$

For **Saleh Model** with a negligible nonlinearity the Input scaling (-21.5957 dB) parameter scales the input signal before the nonlinearity is applied. The block multiplies the input signal by the parameter value, converted from decibels to linear units.

The AM/AM parameters [alpha=2.1587 beta=1.1517] are used to compute the amplitude gain for an input signal using the following function

$$F_{AM/PM}\left(u\right)=\frac{au}{1+\beta u^{2}}.$$

The AM/PM parameters [alpha=4.0033 beta=9.1040] are used to compute the phase change for an input signal using the following function

$$F_{AM/PM}\left(u\right)=\frac{au^{2}}{1-\beta u^{2}},$$

where u is the magnitude of the input signal.

The Output scaling (32.9118 dB) parameter scales the output signal.

For **Ghorbani Model** the Input scaling (-1.5957 dB) parameter scales the input signal before the nonlinearity is applied. The block multiplies the input signal by the parameter value, converted from decibels to linear units.

The AM/AM parameters [x_1 = 8.1081 x_2 = 1.5413 x_3 = 6.5202 x_4 = -0.0718] are used to compute the amplitude gain for an input signal using the following function

$$F_{AM/AM}\left(u\right)=u-\frac{x_{1}u^{x_{2}}}{1+x_{3}u^{x_{2}}}+x_{4}u.$$

The AM/PM parameters [y_1 = 4.6645 y_2 = 2.0965 y_3 = 10.88 y_4 = –0.003] are used to compute the phase change for an input signal using the following function

$$F_{AM/PM}\left(u\right)=\frac{y_{1}u^{y_{2}}}{1+y_{3}u^{y_{2}}}+y_{4}u,$$

where u is the magnitude of the scaled signal.

The Output scaling (32.9118 dB) parameter scales the output signal.

For **Rapp Model** the amplitude gain for an input signal is computed by the following function

$$F_{AM/AM}\left(u\right)=\frac{u}{\left(1+\left(\frac{u}{Q_{sat}}\right)^{2S}\right)\frac{1}{2S}},$$

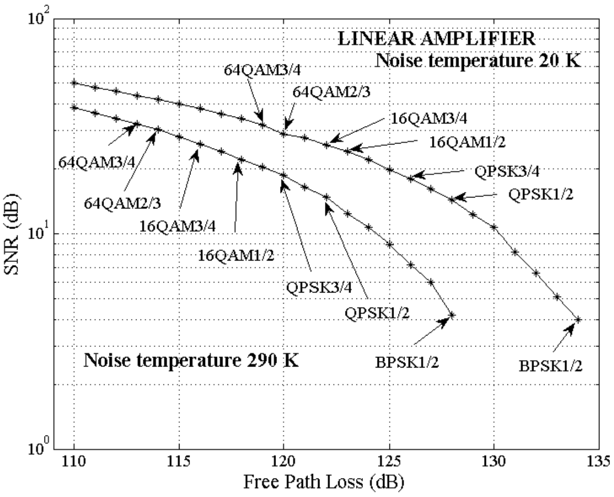

Fig. 7

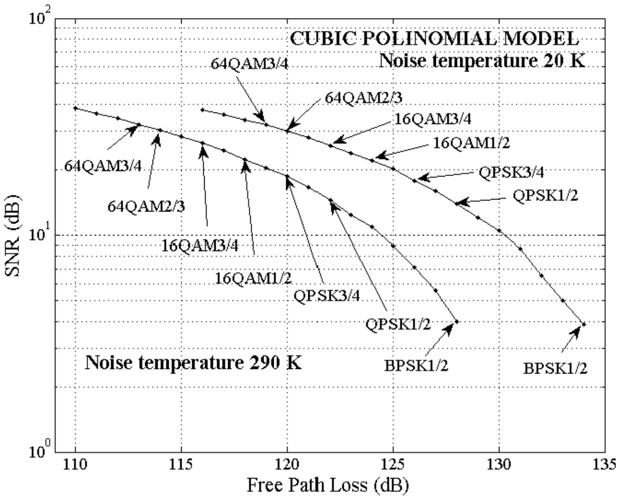

Fig. 8

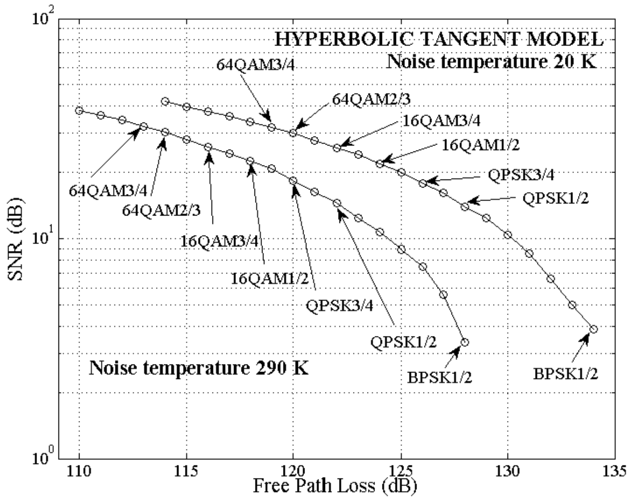

Fig. 9

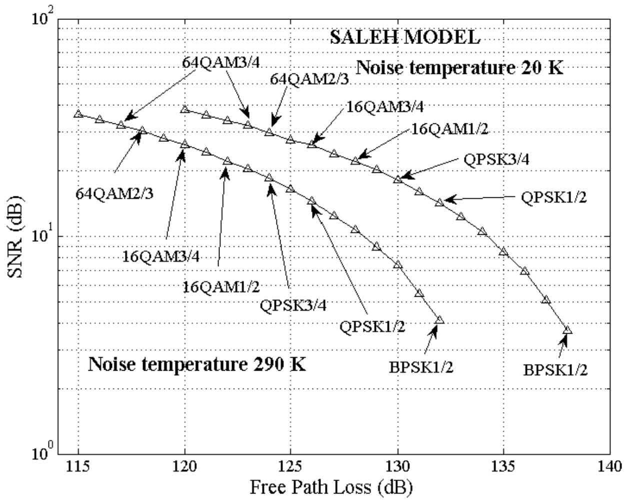

Fig. 10 (negligible nonlinearity)

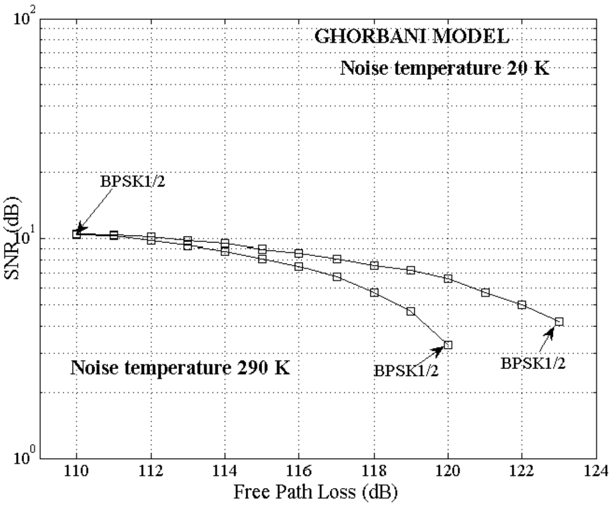

Fig. 11

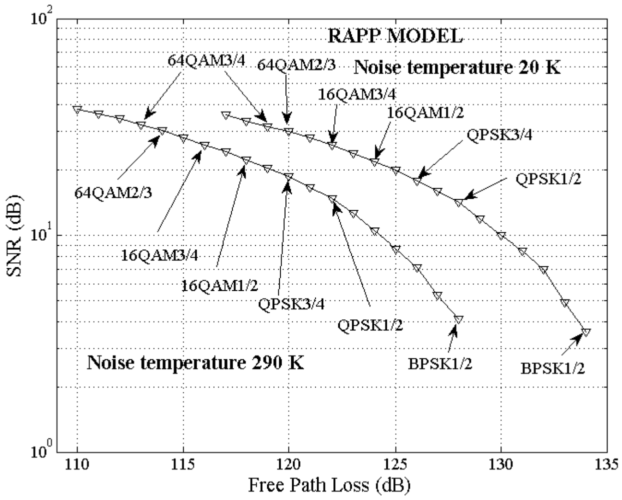

Fig. 12

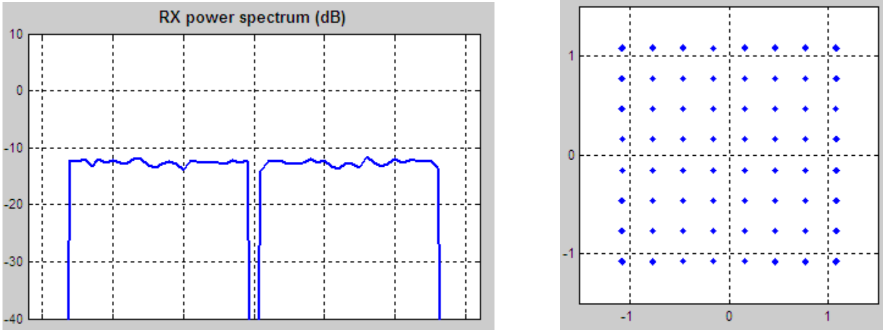

Fig. 13. Power spectrum and signal constellation for the Linear Amplifier (SNR = 66.7 dB, bit rate = 54 Mb/s, free path loss in uplink/downlink 70 dB, T=20 K)

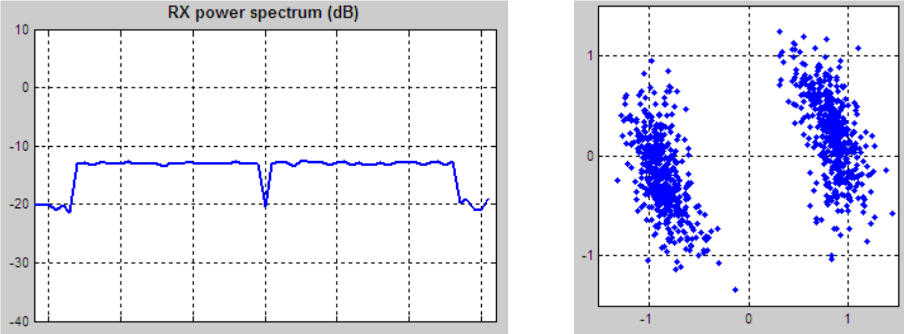

Fig. 14. Power spectrum and signal constellation for the Cubic Polinomial Model (SNR = 5.2 dB, bit rate = 6 Mb/s, free path loss in uplink/downlink 70 dB, T=20 K)

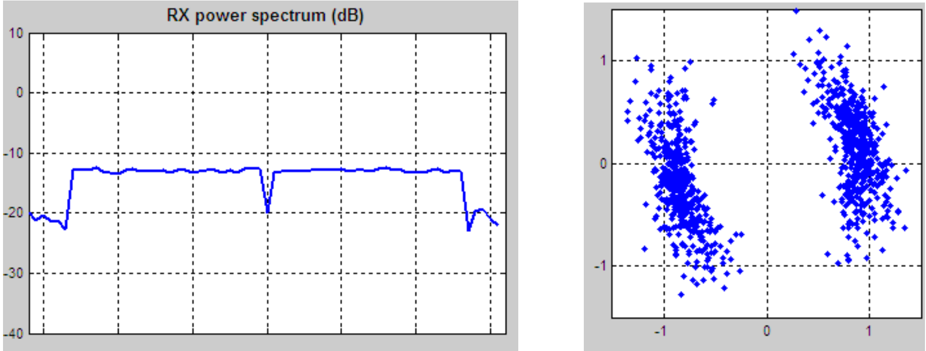

Fig. 15. Power spectrum and signal constellation for the Hyperbolic Tangent Model (SNR = 5.7 dB, bit rate = 6 Mb/s, free path loss in uplink/downlink 70 dB, T=20 K)

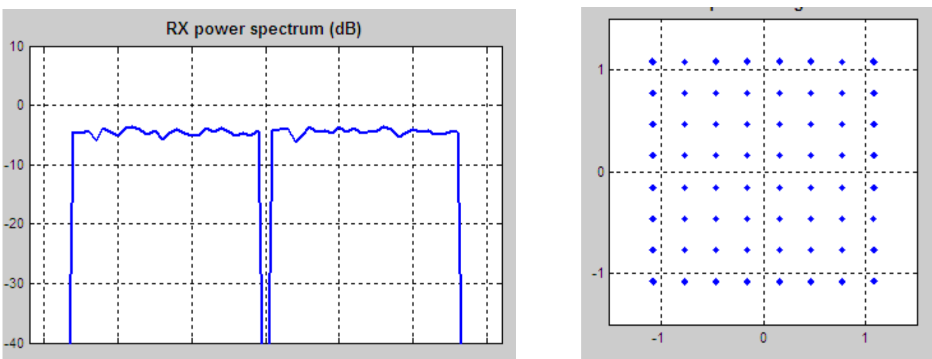

Fig. 16. Power spectrum and signal constellation for the Saleh Model with negligible nonlinearity (SNR = 63.2 dB, bit rate = 54 Mb/s, free path loss in uplink/downlink 70 dB, T=20 K)

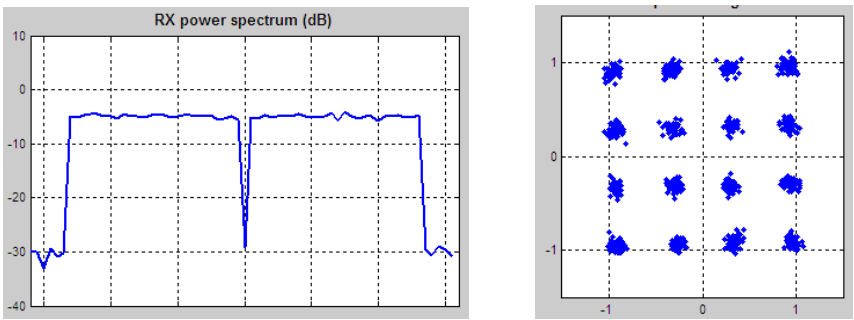

Fig. 17. Power spectrum and signal constellation for the Saleh Model with moderate nonlinearity (SNR = 23.1 dB, bit rate = 24 Mb/s, free path loss in uplink/downlink 70 dB, T=20 K)

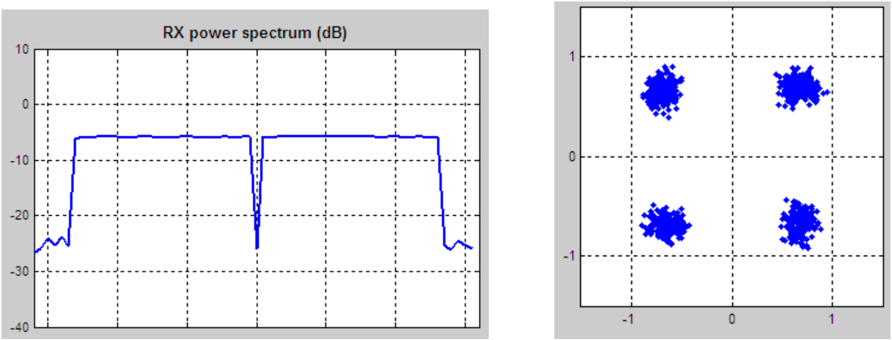

Fig. 18. Power spectrum and signal constellation for the Saleh Model with severe nonlinearity (SNR = 17.9 dB, bit rate = 18 Mb/s, free path loss in uplink/downlink 70 dB, T=20 K)

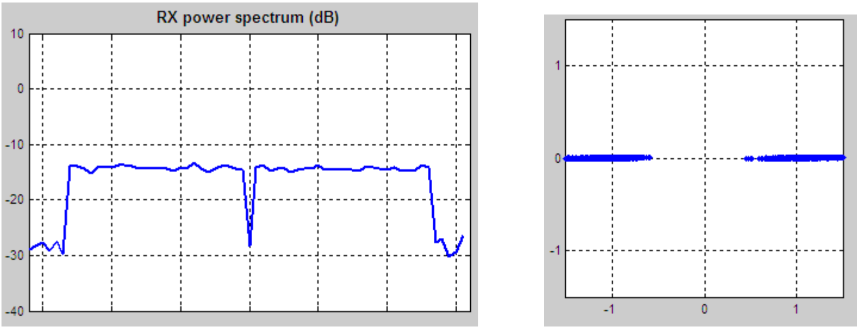

Fig. 19. Power spectrum and signal constellation for the Ghorbani Model with severe nonlinearity (SNR = 11.3 dB, bit rate = 6 Mb/s, free path loss in uplink/downlink 70 dB, T=20 K)

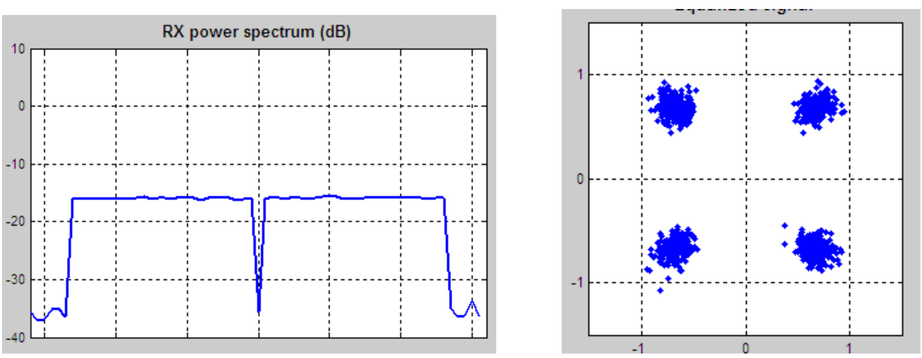

Fig. 20. Power spectrum and signal constellation for the Rapp Model (SNR = 18.0 dB, bit rate = 18 Mb/s, free path loss in uplink/downlink 70 dB, T=20 K)

where u is the magnitude of the scaled signal, S=0.5 is the Smoothness factor and O_{sat} = 1 is the Output saturation level. The Rapp model does not apply a phase change to the input signal.

Data for Fig. 7–12 were obtained with models parameters described above and show how big a SNR ratio should be and what type of a modulation to be used for data transmission without errors for given free space path losses and a noise temperature.

At values of free path losses marked by arrows the modulation type is changed and the data rate increases for the lower values of free path losses: BPSK ½ (6 Mb/s), QPSK1/2 (12 Mb/s), QPSK3/4 (18 Mb/s), 16QAM1/2 (24 Mb/s), 16QAM3/4 (36 Mb/s), 64QAM2/3 (48 Mb/s) and 64QAM3/4 (54 Mb/s).

As seen from figures a noise temperature essentially impacts the results.

Satellite OFDM communication channels cease to work at different values of free path losses for different nonlinearity models. For example, at noise temperature T = 20 K (290 K) channels are “closed”: for the Linear Model (Fig. 7) - when free path losses are 134 dB (128 dB); for the Cubic Polinomial Model (Fig. 8) – at 134 dB (128 dB); for the Hyperbolic Tangent Model (Fig. 9) – at 134 dB (128 dB); for the Saleh Model with a negligible nonlinearity (Fig. 10) – at 138 dB (132 dB); for the Ghorbani Model (Fig. 11) – at 123 dB (120 dB); and for the Rapp Model (Fig. 12) – at 134 dB (128 dB).

According to calculations all the models of non-linear amplifiers (except the Ghorbani model) gave similar curves for the dependence of a SNR on the free path loss in OFDM satellite communication channel. The best from the point of view of the channel "closing" is the Saleh model.

At different values of free path losses OFDM satellite communication channels operate at different types of a modulation. For example, at a noise temperature T = 290 K and free path losses 120 dB (115 dB): for the Linear Model – it occurs QPSK3/4 (16QAM3/4); for the Cubic Polinomial Model – QPSK3/4 (16QAM3/4); for the Hyperbolic Tangent Model – QPSK3/4 (16QAM3/4); for the Saleh Model – 16QAM3/4 (64QAM3/4); for the Ghorbani Model – BPSK1/2 (BPSK1/2); and for the Rapp Model – QPSK3/4 (16QAM3/4).

Data for power spectra and signal constellations (Fig. 13-20) were received with models parameters described above but the lower value of free path losses. It allows revealing the effect of nonlinear amplifiers. A signal with a bigger power and amplitude shifts the transponder amplifier in a region of nonlinearity (Fig. 14, 15, 17-20) and the chosen parameters for AM/AM and AM/PM distortions worsen data transmission conditions.

For example, comparing the spectrums of received signals for the linear amplifier model (Fig. 13) and the Saleh model (Fig. 16) we can see the spectrum power growth in the latter case. This growth is due to the nonlinearity of the amplifier. When digitally modulated signals go through a nonlinear amplifier, spectral regrowth (broadening) appears in the output for the Cubic Polinomial Model (Fig. 14), the Hyperbolic Tangent Model (Fig. 15), the Saleh Model with moderate (Fig. 17) and severe (Fig. 18) nonlinearities, the Ghorbani Model (Fig. 19) and the Rapp Model (Fig. 20)

Comparing the constellations of received signals for the Saleh model (Fig. 16-18) with different levels of nonlinearity we can see the signal distortion at the received signal. This distortion is due to the nonlinearity of the amplifier.

6. Conclusions

For investigation the influence of satellite amplifier nonlinearity the model was developed with adaptive modulation for satellite OFDM communication channel.

Dependencies were received of a SNR ratio on the type of a modulation (BPSK, QPSK, 16QAM, 64QAM), a bit rate, free space path losses, noise temperatures for different models of memoryless nonlinear satellite amplifiers (the Cubic Polinomial Model, the Hyperbolic Tangent Model, the Saleh Model, the Ghorbani Model and the Rapp Model).

On the basis of received is this paper data (under the given conditions: a type of nonlinearity, a number of OFDM symbols, noise temperatures, gains of antenna dishes and the satellite transponder amplifier nonlinearity type) the channel parameters were estimated: the level of free space loss, for which the satellite communication channel is "open"; the type of a modulation and data transfer rate, which are possible under the given conditions.

Developed model allows predicting spectral regrowth of digitally modulated OFDM signals due to amplifier nonlinearity. Prediction of spectral regrowth for a prescribed level of amplifier nonlinearity can be very helpful for designing communication systems.

References

[1] *Rumanek J., Šebesta J.* New Channel Coding Methods for Satellite Communication. – Radioengineering. – 2010. – v. 19. – N 1. – P. 155–161.

[2] *Modiano E.* Satellite Data Networks. Journal of Aerospace Computing, Information, and Communication. – 2004. – v.1. – P. 395–398.

[3] Global Air Navigation Plan for CNS/ATM Systems. ICAO, 1998. Doc. 9750. Available from Internet: <http://www.icao.int/publications/Documents/9750_2ed_en.pdf>.

[4] *Faezah J., Sabira K.* Adaptive Modulation for OFDM Systems. International Journal of Communication Networks and Information Security. 2009. – v.1. – N2. – P. 1–8.

[5] *Sharma D., Srivastava P.* OFDM Simulator Using MATLAB. International Journal of Emerging Technology and Advanced Engineering. – 2013. – v. 3. – N 9. – P. 493-496.

[6] *O'Droma M., Mgebrishvili N., Goacher A.* Theoretical analysis of intermodulation distortion in OFDM signals in the presence of nonlinear RF high power amplifiers. IEEE 59th VTC, 2004. – 17–19 May. – v.3, P. 1295 – 1299.

[7] *Jantunen P.* Modeling of Nonlinear Power Amplifiers for Wireless Communications. The thesis for the degree of Master of Science. Esp[oo, Finland. – 2004. – 138 p. Available from the Internet: <http://www.researchgate.net/publication/224263342_Nonlinear_RF_power_amplifier_behavioural_analysis_of_wireless_OFDM_systems>.

[8] *Gregorio F.H.* Analysis and Compensation of Nonlinear Power Amplifier Effects in Multi-Antenna OFDM Systems. Dissertation for the degree of Doctor of Science in Technology. – 2007. – 133 p. Available from Internet:

[9] http://lib.tkk.fi/Diss/2007/isbn9789512290017.

[10] *El-Khatib Z., MacEachern, Mahmoud S.A.* Distributed CMOS Bidirectional Amplifiers: Broadbanding and Linearization Techniques. Chapter 2 Modulation Schemes Effect on RF Power Amplifier Nonlinearity and RFPA Linearization Techniques. Analog Circuits and Signal Processing. Springer. – 2012. – 134 p.

[11] *Park D., Song H.* A new PAPR reduction technique of OFDM system with nonlinear high power amplifier. IEEE Trans. CE. 2007. – v.53. – N2. – P. 327 – 332.

[12] *Cioni S., Corazza G. E., Neri M.,* Vanelli-Coralli A. On the use of OFDM radio interface for satellite digital multimedia broadcasting systems. International Journal of Satellite Communications and Networking. – 2006. – v.24. – N2. – P. 153–167.

[13] *Varade S., Kulat K.* BER Comparison of Rayleigh Fading, Rician Fading and AWGN Channel using Chaotic Communication based MIMO-OFDM System. International Journal of Soft Computing and Engineering. – 2012. – v.1. – N6. – P. 2231–2307.

[14] *Roque D., Siclet C.* Performances of Weighted Cyclic Prefix OFDM with Low-Complexity Equalization. IEEE Communications Letters. 2013. – v.17. – N3. – P. 439–442.

[15] *Saleh A.A.M.* Frequency-independent and frequency-dependent nonlinear models of TWT amplifiers. IEEE Trans. Communications. 1981. – v.COM-29. – P. 1715–1720.

[16] *Ghorbani A., Sheikhan M.* The Effect of Solid State Power Amplifiers (SSPAs) Nonlinearities on MPSK and M-QAM Signal Transmission. Sixth Int. Conference on Digital Processing of Signals in Comm., 1991, pp. 193–197.

[17] Rapp C. Effects of HPA-Nonlinearity on a 4-DPSK/OFDM-Signal for a Digital Sound Broadcasting System. Proceedings of the Second European Conference on Satellite Communications, Liege, Belgium. 1991. – P. 179–184.

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В.П. Харченко[1], А.М. Грехов[2], І.М. Алі[3]. Вплив нелінійності на параметри авіаційного супутникового канала зв'язку

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Для дослідження впливу нелінійності супутникового підсилювача на параметри авіаційного супутникового комунікаційного OFDM канала розроблено оригінальну модель каналу зв'язку "Літак-Супутник-Наземна Станція" з використанням програмного комплексу MATLAB Simulink. Модель канала з адаптивною модуляцією складається із джерела інформації, передавача літака, каналу нагору/униз, супутникового транспондера, приймача наземної станції. Отримано залежності співвідношення сигнал-шум від втрат у вільному просторі для різних типів нелінійності підсилювача, різних модуляцій (BPSK, QPSK, 16QAM, 64QAM), різних температур шуму. Порівняно спетри та сигнальні сузір'я прийнятих сигналів для різних типів нелінійності підсилювача. Розроблена модель дозволяє визначати уширення спектру цифрового модульованого OFDM сигнала завдяки нелінійності підсилювача.

Ключові слова: адаптивна модуляція; втрати у вільному просторі; згортальне кодування; нелінійність підсилювача; супутниковий зв'язок; супутниковий транспондер; шумова температура; OFDM канал.

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Для исследования влияния нелинейности спутникового усилителя на параметры авиационного спутникового коммуникационного OFDM канала разработана оригинальная модель канала связи "Самолет-Спутник-Наземная Станция" с использованием программного комплекса MATLAB Simulink. Модель канала с адаптивной модуляцией состоит из источника информации, передатчика самолета, канала вверх/вниз, спутникового транспондера, приемника наземной станции. Получены зависимости соотношения сигнал-шум от потерь в свободном просторанстве для разных типов нелинейности усилителя, разных модуляций (BPSK, QPSK, 16QAM, 64QAM), разных температур шума. Спектры и сигнальные созвездия принятых сигналов сравнивались для разных типов нелинейности усилителя. Разработанная модель разрешает определять уширенне спектра цифрового модулированного OFDM сигнала, вызванное нелинейностью усилителя.

Ключевые слова: адаптивная модуляция; нелинейность усилителя; потери в свободном пространстве; свёрточное кодирование; спутниковая связь; спутниковый транспондер; шумовая температура; OFDM канал.

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