AEROSPACE SYSTEMS FOR MONITORING AND CONTROL

UDC 621.396:621.396.933:629.783:621.396.946

Volodymyr Kharchenko[1]
Yuri Barabanov[2]
Andrii Grekhov[3]
Mykola Bogunenko[4]
Julia Rudnyk[5]

PERFORMANCE ANALYSIS OF "AIRCRAFT-TO-SATELLITE-TO-GROUND" LINK USING FORWARD ERROR CORRECTION

National Aviation University
Kosmonavta Komarova avenue 1, 03680, Kyiv, Ukraine
E-mails: [1]kharch@nau.edu.ua; [2]brbnv@i.ua; [3]grekhovam@ukr.net; [4]l-39@ukr.net; [5]rudnykjj@ukr.net

Abstract. *This paper focuses on the performance analysis of aeronautical satellite baseband link including Aircraft Transmitter, Uplink (AWGN channel), Satellite Transponder, Downlink (AWGN channel), and Ground Earth Station (GES) Receiver. Impact of a modulation type (BPSK, QPSK, 8PSK, 16QAM),* E_b/N_0*, satellite transponder amplifier gain without and with coding on Binary Error Rate (BER) was investigated. Effectiveness of error detection and correction for "Aircraft-to-Satellite-to-Ground" link was analyzed using classic linear block codes, like Hamming's (7, 4) code.*

Keywords: aeronautical satellite link, Airborne Transmitter, AWGN channel, BER, Ground Station Receiver, Hamming's code, modulation type, Satellite Transponder.

1. Introduction

The aeronautical telecommunication network (ATN) has been designed to provide data communications services to Air Traffic Service provider organizations for air traffic services communication, aeronautical operational control, administrative communication; and aeronautical passenger communication. The ATN comprises application entities and communication services which allow ground-ground, air-to-ground and air-to-air data subnetworks to interoperate using satellite subnetwork (Manual…2010).

Satellite communication systems are used for sending data from aircraft to a ground stations accessible to aeronautical operation control, air traffic management and air traffic control (Roddy 2006). Wide application of satellites in aviation is connected with the possibility of communication with a considerable amount of planes irrespective of a distance, with independence of expenses on a distance between planes, with insignificant influence of atmosphere and sites of land stations on reliability of communication (The Satellite…2012).

A satellite tracking of aircraft is a technology available to aircraft operators which has huge benefits and relatively low costs (An Introduction…2009). An aircraft can report its position via an aircraft/satellite data link. ADS-B (Automatic Dependent Surveillance - Broadcast) – is a technology which allows pilots and air traffic controllers to track aircrafts with high accuracy (EUROCONTROL…2012). ADS-B can make flight safe and allows using of air space more effective.

An aircraft equipped with ADS-B avionics transmit their exact position in space by means of digital communication channels. The digital code which contains this information is updated several times per second and transmitted by aircraft on discrete frequencies.

ADS-B systems based on Low Earth Orbit (LEO) satellites are of special interest (Osborne, Xie 1999).

It was found (Aircraft-to-Satellite…2003) that the most critical factors for all systems using aircraft are the transmitting antenna and the data rate that the communications system is required to carry. The maximum rate for any system in use today is set by the transmit power available from the ground (or aircraft) transmitter and the sensitivity of the satellite receiver. It is therefore necessary to determine the amount of data that must be transmitted and the time period in which the transmission must occur.

Problems connected with the performance of satellite aeronautical communication channel are very important. Even small degradation of communication channel parameters influences a rate of data transmission, a time delay and coverage.

These factors at once impact on safety of flights and operational expenses. It is necessary to have the system parameters optimized before implementation (Elbert, Elanix 2003) and when things go wrong a simulation model can be used to track down the offending element. The imitation modeling also may be useful for pre-testing any corrective action before attempting it either in space or on the ground.

To answer the question how it is possible to keep constantly communication channel parameters optimal we need to work out realistic models of satellite aeronautical communication channels and research their behavior. A communication channel can corrupt information sent over it (Huffman, Pless 2003).

An overview of the many practical applications of channel coding theory was presented in (Costello et al. 1998) and included: deep space communication, satellite communication, data transmission, data storage, mobile communication, file transfer, and digital audio/video transmission.

In most papers the power of coding was demonstrated on the base of the memoryless Additive white Gaussian noise (AWGN) channel that formed the basis for Shannon's noisy channel coding theorem (Shannon 1948).

At the same time the role of a satellite transponder as a part of the microwave repeater and antenna system that is housed onboard the operating satellite is significant (Elbert, Elanix 2003). A transponder is used to amplify carriers on the downlink side of a communications satellite. Each transponder is amplified by either a traveling wave tube amplifier or a solid state power amplifier. Satellite transponders can deliver data rates in the range of 50 to 150 Mbps and achieving these high data rates requires careful consideration of the design and performance of the transponder.

This paper is devoted to the performance analysis of aeronautical satellite baseband link on the basis of original model including Aircraft Transmitter, Uplink (AWGN channel), Satellite Transponder, Downlink (AWGN channel), and Ground Earth Station (GES) Receiver. Then influence of a modulation type (BPSK, QPSK, 8PSK, 16QAM), ratio E_b/N_0, and satellite transponder amplifier gain without and with coding on Binary Error Rate (BER) was investigated.

2. Error detection and correction analysis

The most significant question about effectiveness of error detection and correction for "Aircraft-to-Satellite-to-Ground" link was analyzed using classic linear block codes, like Hamming's (7, 4) code. This code is a linear error-correcting code that encodes 4 bits of data into 7 bits by adding 3 parity bits and can correct any single-bit error, or detect all single-bit and two-bit errors. Hamming's (7, 4) code is effective if transmission medium is not extremely noisy and burst errors do not occur.

Hamming's (7, 4) code can be computed in linear algebra terms through matrices – the code generator matrix **G** and the parity-check matrix **H** (Huffman, Pless 2003):

$$\mathbf{G} = \begin{bmatrix} 1101 \\ 1011 \\ 1000 \\ 0111 \\ 0100 \\ 0010 \\ 0001 \end{bmatrix} \quad \text{and} \quad \mathbf{H} = \begin{bmatrix} 1010101 \\ 0110011 \\ 0001111 \end{bmatrix}$$

A generator matrix generates all possible codewords

$$w = c\mathbf{G},$$

where w is a codeword of the linear code c, c is a row vector, and a bijection exists between w and c. A generator matrix can be used to construct the parity check matrix for a code (and vice-versa).

The rows of a parity check matrix are parity checks on the codewords of a code. That is, they show how linear combinations of certain digits of each codeword equal zero. Rows of the parity-check matrix **H** are used to compute the syndrome vector at the receiving end and if the syndrome vector is the null vector (all zeros) then the received word is error-free; if non-zero then the value indicates which bit has been flipped.

In MATLAB Simulink (Communications…2012) the Hamming Encoder block creates a Hamming code with message length K and codeword length N. The number N must have the form 2^M-1, where M is an integer greater than or equal to 3, then K equals N-M. The input must contain exactly K elements and if it is frame-based, then it must be a column vector. The output is a vector of length N. The Hamming Decoder block recovers a binary message vector from a binary Hamming codeword vector. For proper decoding, the parameter values in this block should match those in the corresponding Hamming Encoder block.

3. Aeronautical satellite channel simulation

For more realistic modeling of satellite communication link we have included in our model a satellite transponder and two AWGN channels for uplink and downlink. MATLAB simulation model is shown in Fig. 1 and consists of a source of information (Bernoulli Binary block), an aircraft transmitter (Hamming Encoder block, Modulator Baseband block), an uplink (AWGN channel), a satellite transponder (Receiver Dish Antenna Gain, Complex Baseband Amplifier with Noise, Transmitter Dish Antenna Gain), ground Earth station receiver (Demodulator Baseband block, Hamming Decoder block), and Error Rate Calculation block.

Complex Baseband Amplifier block in satellite transponder generates a complex baseband model of an amplifier with thermal noise. It simulates linear amplifier and allows to specify noise (noise temperature – specifies the noise in Kelvin; noise factor – specifies the noise by the following equation:

Noise factor = 1 + Noise temperature/290).

In Fig. 1 BPSK Modulator/Demodulator is shown. During a simulation QPSK, 8PSK, and 16QAM modulation schemes were considered also.

For each of these modulations Bit Error Rate (BER) was calculated without and with coding as function of a ratio E_b/N_0. The value of a ratio E_b/N_0 was changed symmetrically in uplink AWGN and downlink AWGN channels.

All calculations were done when receiver/transmitter dish antenna gain was equal to unit. Noise factor in complex baseband amplifier was taken as 2 (290 K – typical noise level). When investigating effect of coding for different modulation types we took satellite linear amplifier gain equal to unit.

This model also allows investigating a dependence of BER on satellite transponder amplifier gain without and with coding and such dependencies were obtained and analyzed for BPSK, QPSK, 8PSK, and 16QAM.

Results of simulations are shown in Figs 2–8. First, it is interesting to compare a value of BER for different modulation types without coding. From Figs 2–4 (solid lines) follows that the lowest BER has BPSK and the highest – 16QAM. For example, at $E_b/N_0 = 8$ dB:

$BER_{BPSK} = 5.8 \cdot 10^{-3}$,
$BER_{QPSK} = 6.0 \cdot 10^{-2}$,
$BER_{8PSK} = 3.1 \cdot 10^{-1}$,
$BER_{16QAM} = 4.1 \cdot 10^{-1}$.

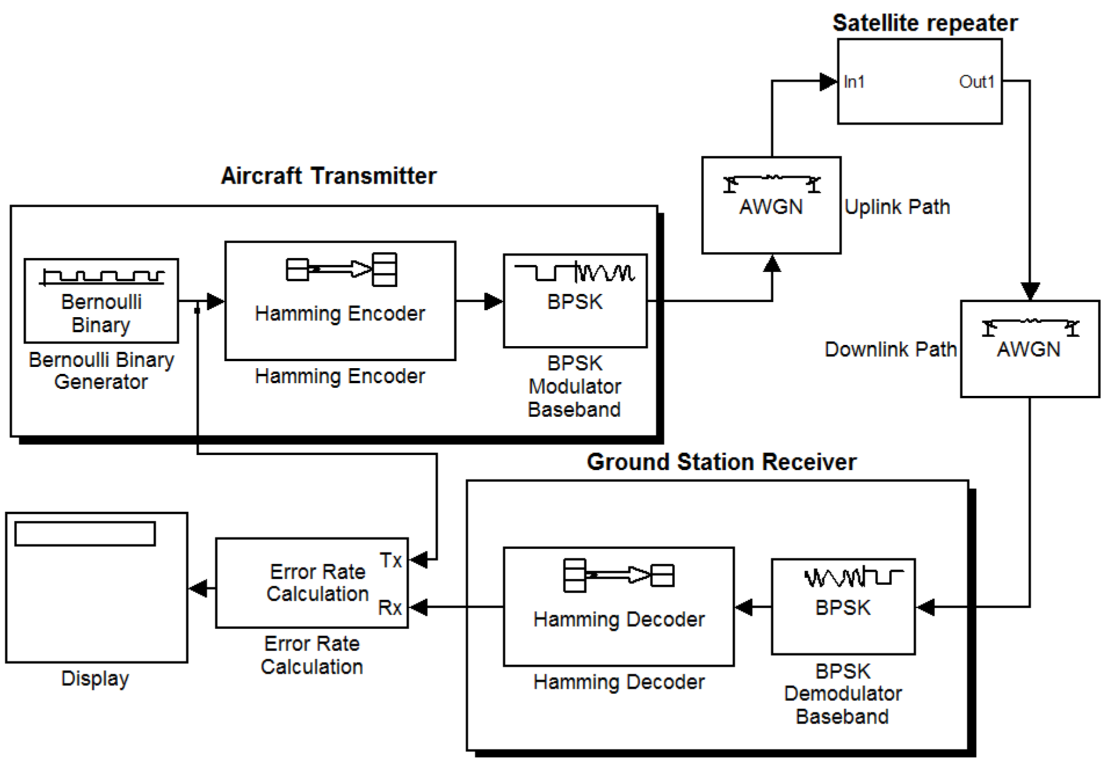

Fig. 1. "Aircraft-to-Satellite-to-Ground Earth Station" Link

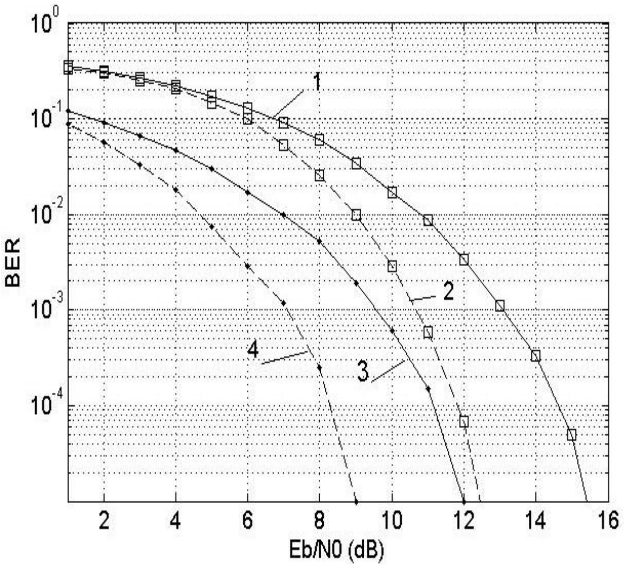

Fig. 2. Effect of coding on QPSK (1, 2) and BPSK (*3*, *4*):
1, *3* without coding;
2, *4* –with Hamming code (7, 4), *t*=1

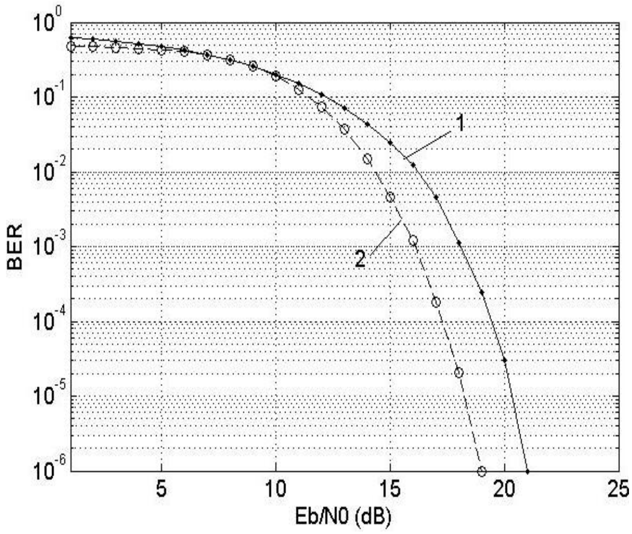

Fig. 3. Effect of coding on 8PSK:
1 – without coding;
2 – with Hamming code (7, 4), *t*=1

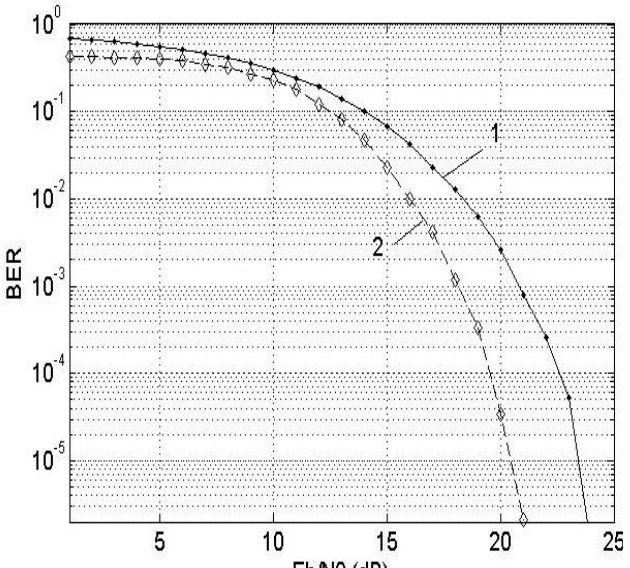

Fig. 4. Effect of coding on 16QAM:
1 –without coding;
2 –with Hamming code (7, 4), *t*=1

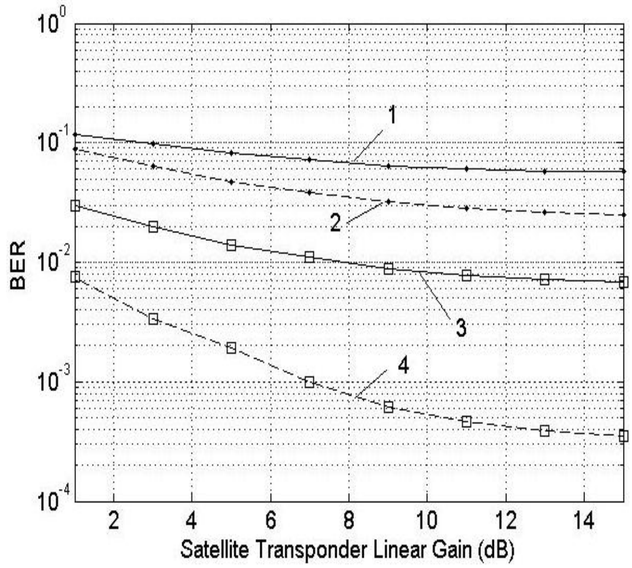

Fig. 5. Impact of Satellite Transponder Amplifier Gain on BPSK:
1 – E_b/N_0 = 1 dB, without coding;
2 – E_b/N_0 = 1 dB, Hamming code (7, 4) *t*=1;
3 – E_b/N_0 = 5 dB, without coding;
4 – E_b/N_0 = 5 dB, Hamming code (7, 4) *t*=1

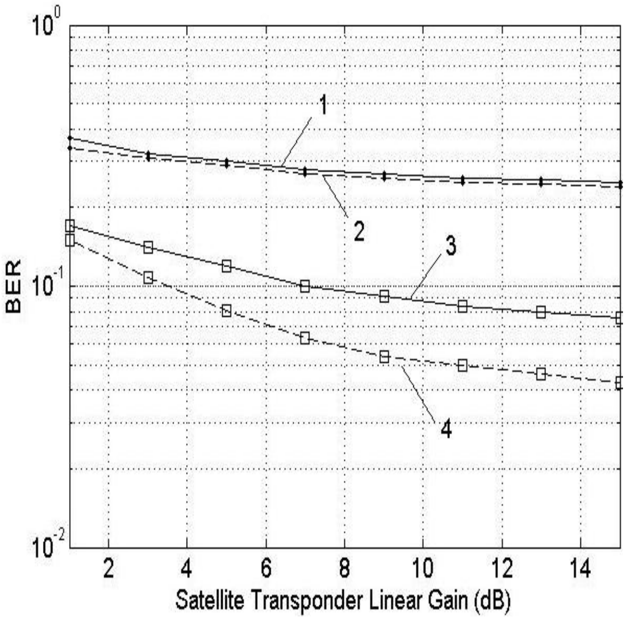

Fig. 6. Effect of Satellite Transponder Amplifier Gain on QPSK:

1 – E_b/N_0 = 1 dB, without coding;

2 – E_b/N_0 = 1 dB, Hamming code (7, 4) *t*=1;

3 – E_b/N_0 = 5 dB, without coding;

4 – E_b/N_0 = 5 dB, Hamming code (7, 4) *t*=1

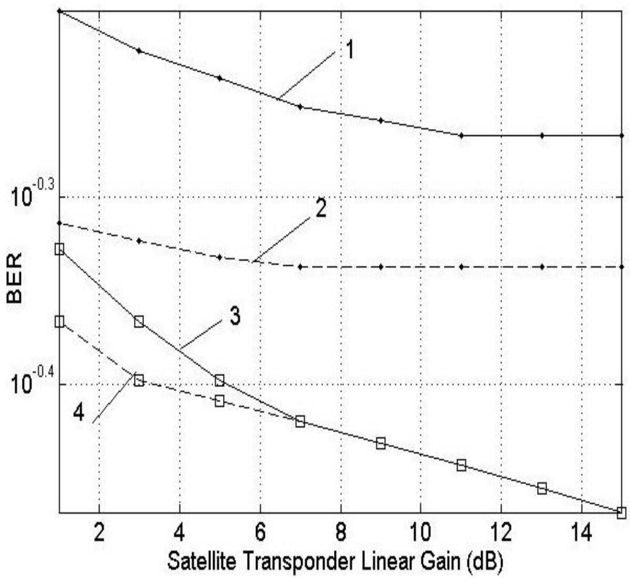

Fig. 7. Effect of Satellite Transponder Amplifier Gain on 8PSK

1 – E_b/N_0 = 1 dB, without coding;

2 – E_b/N_0 = 1 dB, Hamming code (7, 4) *t*=1;

3 – E_b/N_0 = 5 dB, without coding;

4 – E_b/N_0 = 5 dB, Hamming code (7, 4) *t*=1

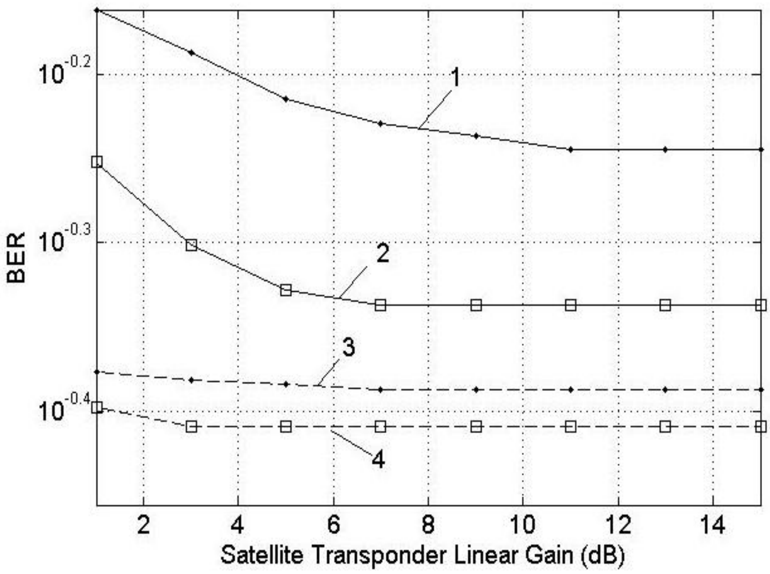

Fig. 8. Effect of Satellite Transponder Amplifier Gain on 16QAM:

1 – E_b/N_0 = 1 dB, without coding;

2 – E_b/N_0 = 1 dB, Hamming code (7, 4) *t*=1;

3 – E_b/N_0 = 5 dB, without coding;

4 – E_b/N_0 = 5 dB, Hamming code (7, 4) *t*=1

The higher amount of alternative modulation symbols – the closer plots are arranged. For example, at $E_b/N_0 = 8$ dB:

$BER_{QPSK} / BER_{BPSK} \approx 10.3$,

$BER_{8PSK} / BER_{QPSK} \approx 5.2$,

$BER_{16QAM} / BER_{8PSK} \approx 1.3$.

Secondly, a coding with Hamming code (7, 4), t=1 shows that the effect of BER decreasing is maximal for BPSK. For example, at $E_b/N_0 = 8$ dB:

$(BER_{BPSK} - BER_{codedBPSK}) / BER_{BPSK} \approx 96\%$,

$(BER_{QPSK} - BER_{codedQPSK}) / BER_{QPSK} \approx 57\%$,

$(BER_{8PSK} - BER_{coded8PSK}) / BER_{8PSK} \approx 0\%$,

$(BER_{16QAM} - BER_{coded16QAM}) / BER_{16QAM} \approx 2\%$.

Notice, that in the range 5 dB $\leq E_b/N_0 \leq$ 10 dB an effectiveness of coding for 8PSK is lower than for 16QAM (compare Figs 3 and 4).

An investigation of BER dependence on satellite transponder amplifier gain without and with coding was provided for two meanings of a ratio E_b/N_0 (1 dB and 5 dB) in uplink and downlink when receiver/transmitter dish antenna gain was equal to unit, noise factor in complex baseband amplifier was taken as 2 (Figs 5–8).

The most significant influence satellite transponder amplifier gain has on BPSK (Fig. 5). The nature of coding effect on BER decreasing is similar for BPSK and QPSK but for QPSK the effect is less (compare Figs 5 and 6).

For BPSK and QPSK decreasing of BER is bigger for higher ratio E_b/N_0 (compare upper plot for E_b/N_0 = 1 dB and lower plot for E_b/N_0 = 5 dB correspondingly in Figs 5 and 6).

Quite different impact satellite transponder amplifier gain has on 8PSK and 16QAM (Figs 7 and 8). For E_b/N_0 = 1 dB BER decreasing after coding is bigger than for E_b/N_0 = 5 dB – a converse effect than for BPSK and QPSK.

Another interesting feature is that the higher amount of alternative modulation symbols is – the less is impact of transponder amplifier gain increasing on decreasing of BER (plots in Figs 7 and 8 when gain is more than 6 dB).

4. Conclusions

Satellite communications are very important and there exist international competition in space industry. European R&D in satellite communications has encompassed a large number of activities spanning many programs and organizations. In overview (Castanet 2011) it was pointed out: "Optimization of satellite systems requires taking into account propagation information early in system design. The propagation channel has a strong impact on system performances and relevant channel models should be available to assess by simulation the end-to-end quality of service and the satellite system performances. Propagation impairments may be mitigated by specific techniques. To design and optimize such techniques, it is necessary to simulate or emulate the dynamic behavior of the propagation channel".

Our results of simulations presented here can help to understand and solve mentioned above problems. This paper deals with the performance analysis of aeronautical satellite baseband link.

Original model includes aircraft transmitter, uplink/downlink (AWGN channels), satellite transponder, and ground Earth station receiver. Impact of a modulation type (BPSK, QPSK, 8PSK, 16QAM) and satellite transponder amplifier gain without and with coding on Binary Error Rate (BER) was investigated. Effectiveness of error detection and correction for "Aircraft-to-Satellite-to-Ground" link was analyzed using Hamming's (7, 4) code.

The most important results for our model with two AWGN channels and satellite transponder are the following:

a) the lowest BER has BPSK and the highest – 16QAM;

b) the higher amount of alternative modulation symbols is – the closer plots of BER as function of E_b/N_0 are arranged in the sequence BPSK, QPSK, 8PSK, and 16QAM;

c) a coding with Hamming code (7, 4) shows that the effect of BER decreasing is maximal for BPSK;

d) in the range 5 dB $\leq E_b/N_0 \leq$ 10 dB an effectiveness of coding for 8PSK is lower than for 16QAM;

e) the most significant influence satellite transponder amplifier gain has on BPSK;

f) the nature of coding effect on BER decreasing is similar for BPSK and QPSK but for QPSK the effect is less;

g) quite different impact satellite transponder amplifier gain has on 8PSK and 16QAM – the higher is amount of alternative modulation symbols the less is impact of transponder amplifier gain increasing on decreasing of BER.

References

Aircraft-to-Satellite Links Suitable for Transmitting USDA Forest Service Infrared Forest Fire Data. 2003. Available from Internet: <http://nirops.fs.fed.us/docs/upload/USFS_satcom_report.pdf>.

An Introduction to Aircraft Satellite Tracking. 2009. Available from Internet: <http://www.indigosat.com/marketing/Aboutsatellitetracking.pdf/>.

Castanet, L. 2011. *Special issue on 'Channel modeling and propagation impairment simulation activities within the SatNEx project'*. International Journal of Satellite Communication Network. 29: 1–6.

Communications Blockset, Hamming Encoder/Decoder. 2012. Available from Internet: <http:www.mathworks.com/access/helpdesk/help/toolbox/commblks>.

Costello, D.; Hagenauer, J.; Imai, H.; Wicker, S. 1998. *Applications of Error-Control Coding*. IEEE Transactions on Information Theory 44: 2531–2560.

Elbert, B.; Elanix, M. 2003. *Simulating the Performance of Communication Links with Satellite Transponders*. Available from Internet: <http://www.applicationstrategy.com/Communications_simulation.htm>.

EUROCONTROL. ADS-B Sites. 2012. Available from Internet: <http://www.eurocontrol.int/ads_b_sites/>.

Huffman, W.; Pless, V. 2003. *Fundamentals of Error-Correcting Codes*. Cambridge. 202 p.

Manual on detailed technical specifications for the Aeronautical Telecommunication Network (ATN). 2010. ICAO. Doc. 9880-AN/466. Available from Internet: <http://portal.aerocivil.gov.co/>.

Osborne, W.P.; Xie, Y. 1999. *Propagation Characterization of LEO/MEO Satellite Systems at 900-2100 MHz*. Conference Proceedings. Available from Internet: <http://opensiuc.lib.siu.edu/ece_confs/52>.

Roddy, D. 2006. *Satellite Communications*. The McGraw Hill Companies, Inc, Fourth Edition. 656 p.

Shannon, C.E. 1948. *A mathematical theory of communication*. Bell Syst. Tech. J. 27: 379–423.

The Satellite Industry Association. 2012. Available from Internet: <http://www.sia.org/>.

Received 8 November 2012.

В.П. Харченко[1], Ю.М. Барабанов[2], А.М. Грехов[3], М.М. Богуненко[4], Ю.І. Рудник[5]. Аналіз роботи каналу зв'язку «літак–супутник–наземна станція» з використанням завадостійкого кодування
Національний авіаційний університет, проспект Космонавта Комарова, 1, Київ, Україна, 03680
E-mails: [1]kharch@nau.edu.ua; [2]brbnv@i.ua; [3]grekhovam@ukr.net; [4]l-39@ukr.net; [5]rudnykjj@ukr.net

Виконано аналіз роботи авіаційного супутникового каналу зв'язку, який включає бортовий передавач, AWGN канал догори, супутниковий транспондер, AWGN канал донизу та приймач наземної станції. Досліджено вплив коефіцієнта підсилення супутникового транспондера без завадостійкого кодування та з ним на коефіцієнт двійкових помилок BER типу модуляції (BPSK, QPSK, 8PSK, 16QAM), співвідношення E_b/N_0. Показано ефективність кодування при передачі повідомлень по каналу «літак–супутник–Земля», що досліджувалася з використанням лінійних блочних кодів Хеммінга (7,4).

Ключові слова: AWGN канал, бортовий передавач, код Хеммінга, коефіцієнт двійкових помилок (BER), приймач наземної станції, супутниковий канал зв'язку, супутниковий транспондер, тип модуляції.

В.П. Харченко[1], Ю.Н. Барабанов[2], А.М. Грехов[3], Н.Н. Богуненко[4], Ю.И. Рудник[5]. Анализ работы канала связи «самолет–спутник–наземная станция» с использованием помехоустойчивого кодирования
Национальный авиационный университет, проспект Космонавта Комарова, 1, Киев, Украина, 03680
E-mails: [1]kharch@nau.edu.ua; [2]brbnv@i.ua; [3]grekhovam@ukr.net; [4]l-39@ukr.net; [5]rudnykjj@ukr.net

Проведен анализ работы авиационного спутникового канала связи, включающего бортовой передатчик, AWGN канал наверх, спутниковый транспондер, AWGN канал вниз и приёмник наземной станции. Исследовано влияние коэффициента усиления спутникового транспондера без помехоустойчивого кодирования и с ним на коэффициент двоичных ошибок BER типа модуляции (BPSK, QPSK, 8PSK, 16QAM), соотношения Eb/N0. Показана эффективность кодирования при передаче сообщений по каналу «самолёт–спутник–Земля», исследованная с использованием линейных блочных кодов Хемминга (7,4).

Ключевые слова: AWGN канал, бортовой передатчик, код Хемминга, коэффициент двоичных ошибок (BER), приёмник наземной станции, спутниковый канал связи, спутниковый транспондер, тип модуляции.

Kharchenko Volodymyr (1946). Doctor of Engineering. Professor. Holder of a State Award in Science and Engineering of Ukraine. Winner of a State Prize of Ukraine in Science and Engineering.
Vice-Rector for Scientific-Research Work at the National Aviation University, Kyiv, Ukraine. Head of the Department of Air Navigation Systems, National Aviation University, Kyiv, Ukraine.
Education: Kyiv Civil Aviation Engineers Institute with a Degree in Radio Engineering, Kyiv, Ukraine (1967).
Research area: management of complex socio-technical systems, air navigation systems and automatic decision-making systems aimed at avoidance conflict situations, space information technology design, air navigation services in Ukraine provided by CNS/ATM systems.
Publications: 400.
E-mail: knarch@nau.edu.ua

Barabanov Yuri (1951). Candidate of Engineering (1996). Associate Professor at the Department of Air Navigation Systems, National Aviation University, Kyiv, Ukraine.
Education: Dipl.-Military Radio Engineering Degree from High Military Engineering Aviation Institute, Kyiv, Ukraine (1973).
Research area: computer modeling of antennas, wireless and satellite communication networks, telecommunications, ADS-B systems.
Publications: 50.
E-mail: brbnv@i.ua

Grekhov Andrii (1951). Doctor of Physics and Mathematics (1990). Professor (1991). Expert of EUROCONTROL for ADS-B systems.
Department of Air Navigation Systems, National Aviation University, Kyiv, Ukraine.
Education: Physical Department of the Kyiv State Taras Shevchenko University, Ukraine (1973), M.Sc. Degree with Honors confirming qualification of Physicist Theorist.
Research area: air satellite communications and information channels, computer modeling of information flows transmission in airborne collision avoidance systems, ADS-B systems, onboard recorder and communication channels, surveillance processes and modern signal processing, expansion of terrestrial surveillance systems for ADS-B using satellite system IRIDIUM, noise resistant codind and forward error correction, aviation security assessment based on simulation.
Publications: 150.
E-mail: grekhovam@ukr.net

Bogunenko Mykola (1957). Associate Professor.
Air Navigation Systems Department, National Aviation University, Kyiv, Ukraine.
Education: Kharkov High Military School of pilots, Kharkov, Ukraine (1978), Air-Force Academy (1991).
Research area: navigation and management; aviation safety provision; air traffic control intelligence systems; flight safe services; vortex wake detection systems; geoinformation systems for aviation.
Publications: 10.
E-mail: l-39@ukr.net

Rudnyk Julia (1990). Student of the National Aviation University, Kyiv, Ukraine.
Research area: surveillance, ADS-B systems, telecommunications.
Publications: 3.
E-mail: rudnykjj@ukr.net