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**MODELING OF “SATELLITE-TO-AIRCRAFT” LINKFOR SELF-SEPARATION**

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**Abstract.**For modelling of data transmissionfrom low-orbit satellite constellation Іrіdіum the original model of a communication channel "Satellite-to-Aircraft" was built using MATLABSіmulіnk.The model comprises “Satellite Downlink Transmitter” (Bernoulli Random Binary Generator, Convolutional Encoder, BPSK Baseband Modulator, High Power Amplifier with a memoryless nonlinearity, Satellite Phase Noise, Transmitter Dish Antenna Gain), “Downlink Path” (Free Space Path Loss, Phase/Frequency Offset), “Aircraft Downlink Receiver” (Receiver Dish Antenna Gain, Aircraft Receiver System Temperature, Viterbi Decoder), “Error Rate Calculation” block and “Display”.Modeling was realized without and with convolutional coding (r=3/4, K=7) at different noise temperatures and free space losses. Dependencies of a Bit Error Rate on free space path losses, antennas diameter, phase/frequency offsets, satellite high power amplifier backoff level, and phase noise were received and analyzed.

**Key words**:free-flight, self-separation, ADS-B, BER,communication channel, aircraft, satellite, convolutional encoder, BPSK, free space loss, phase/frequency offset, memoryless nonlinearity, phase noise, Viterbi decoder, amplifier backoff level, noise temperature, antenna diameter.

**1. Introduction**

Self-separation is an operational concept within the [Free Flight](http://en.wikipedia.org/wiki/Free_flight_%28air_traffic_control%29) initiative (RTCA 1995)and involves rules of the air, communication technologies, protocols, [air traffic management](http://en.wikipedia.org/wiki/Air_traffic_management) and others (ICAO 2011).

Key technological aspect of self-separation isAutomatic Dependent Surveillance-Broadcast (ADS-B), in which aircraft transmit periodic position and state reports(Minimum 2002,EUROCONTROL 2012). “ADS–B In refers to an appropriately equipped aircraft’s ability to receive and display another aircraft’s ADS–B Out information as well as the ADS–B In services provided by ground systems, including Automatic Dependent Surveillance–Rebroadcast (ADS–R), Traffic Information Service–Broadcast (TIS–B), and, if so equipped, Flight Information Service–Broadcast (FIS–B). When displayed in the cockpit, this information greatly improves the pilot’s situational awareness in aircraft not equipped with a traffic alert and collision avoidance system (TCAS)/ airborne collision avoidance system (ACAS)” (Federal 2010).

ACAS is designed to work both autonomously and independently of the aircraft navigation equipment and autopilot systems as well as any ground systems used for the provision of air traffic services. Through antennas, ACAS interrogates the ICAO standard compliant transponders of aircraft in the vicinity. Based upon the replies received, the system tracks the slant range, altitude (when it is included in the reply message) and bearing of surrounding traffic (ACAS 2012).TCAS is intended only for collision avoidance, butself-separation requires complex processing logic, time anticipation and procedure changes. Self-separation feasibility is dependent on confidence in automation and its co-existence with the human role in the cockpit.

Another technical concept for the association between self-separation and [ADS-B](http://en.wikipedia.org/wiki/Automatic_dependent_surveillance-broadcast)was called Airborne Separation Assistance System (ASAS) which performs the core logic of self-separation and other related applications (CARE-ASAS 2004).

The safe integration of Unmanned Aircraft Systems (UAS)into non-segregated airspace will be impossible without new technologies for detect and avoid systems and frequency spectrum protection from unintentional or unlawful interference (Third 2011, Towards 2012).Remotely Piloted Aircraft (RPA) canbe integrated inthe international civilaviation in theforeseeable future. The Remotely Piloted Aircraft Systems (RPAS) Roadmap will provide a strategy for achieving RPAS integration into the European air system from 2016 (Remotely 2012).Problems caused by UAS flights in thecommon airspace are connected with the necessity of reliable real time control duringthe flight.Communication links for RPA are shown in Fig. 1.

UAS flightsin thecommon airspacefrom our point of viewglobally can beprovidedby ADS-B Out / In, TIS-B, FIS-B using low Earth orbit satellite constellations for self-separation data transition.



**Fig. 1.** Communication links (Figure 5-3 from (ICAO 2011))

One of such constellation is global satellite communication service Iridium (Manual2007), which allows aviation users to send and receive voice, messaging and data regardless of their positions on or above the earth: air-to-land, land-to-air and air-to-air.

On 20 June 2012 satellite operator Iridium has decided that from 2015 they will be putting ADS-B receivers on its next-generation satellite constellation, aimed at bringing global, real-time aircraft surveillance for air navigation service providers (Iridium-Adds-ADS-B2012).

Telecommunications satellite systems are widely used in aviationdue toadvantagesof satellite communication whichis connected with possibility of operation with many airplanes at long distances and with independence of communication expenses on distances to airplanes (An Introduction2009, ManualDoc9880, Roddy2006, Woolner2003).

Modeling of ADS-B messages transmission withouterror-control coding was realized previously in our papers (Kharchenko2012a, 2012b, 2012c).

The aim of this paper is: 1) to design the model of communication channel "Satellite-to-Aircraft" with error-control coding for Iridium system using MATLAB Simulink software; 2) on the base of this model investigate a channel integrity and receive dependences of a bit-error rate (BER) on a free space path loss, a phase/frequency offset, a satellite transponderhigh power amplifiers backoff level, antennas diameter, a phase noise and a noise temperature, a bit rate; 3) to analyze the end-to-end signal constellations.

**2. Model for “Satellite-to-Aircraft” Link**

The Iridium system includes 66 low-orbit satellites at an altitude of 780 km and equally divided into 6 orbital planes (Iridium 2008).Each satellite can communicate with the Airborne Earth Station.Each satellite uses three phased-array antennas for the user links.These arrays are designed to provide user-link service by communicating within the 1616-1626.5 MHz band. The gateway serves as a gateway to the Aviation Telecommunication Network for forwarding messages from the aircraft to the required Air Traffic Command or Aircraft Operational Communication unit.

Channels are implemented in the Iridium Satellite Network using a hybrid Time Division Multiple Access/Frequency Division Multiple Access architecture based on Time Division Duplex using a 90 millisecond frame and a Binary Phase-Shift Keyed (BPSK) modulation scheme (or DE-QPSK differential encoding).

A model for satellite communication channel "Satellite-to-Aircraft"was builtusing MATLAB Sіmulіnk software and demo model “RF Satellite Link”. The original model, shown in Fig. 2comprises “SatelliteDownlink Transmitter” (Bernoulli Random Binary Generator, Convolutional Encoder, BPSK Baseband Modulator, High Power Amplifier(HPA) with a memoryless nonlinearity, Phase Noise,Transmitter Dish Antenna Gain), “Downlink Path” (Free Space Path Loss, Phase/Frequency Offset), “Aircraft Downlink Receiver”(Receiver Dish Antenna Gain,Ground Receiver System Temperature, Viterbi Decoder), “Error Rate Calculation block” and “Display”.

In the“SatelliteDownlink Transmitter”the Bernoulli Binary Generator block generates random binary numbers using a Bernoulli distribution with parameter p, produces “zero” with probability p and“one” with probability 1-p (the value p=0,5 is used). The output signal is a frame-based matrix.The Bernoulli Binary Generator block generates adiscrete signal and updates the signal at integer multiplesof a fixed time interval, called the sample time. The length ofthis time interval has the value 1 second. The output data type is “double”.

Iridium system employs aBPSK modulation and forward error correction coding in the form of convolutional encoding with Viterbi decoding (Viterbi1971). Iridium uses a rate 3/4, constraint length 7, (r=3/4; K=7) convolutional code on both transmission and reception (Costello1998).The Convolutional Encoder block is using the poly2trellis(7,[171 133],171)function with a constraint length of 7, code generator polynomials of 171 and 133 (in octal numbers), and a feedback connection of 171 (in octal). The puncture vector is [1; 1; 0; 1; 1; 0].

The BPSK Baseband Modulator block modulates a signal using the binary phase shift keying method. The output is a baseband representation of the modulated signal.

The High Power Amplifier block applies memoryless nonlinearity to complex baseband signal andprovides five different methods for modeling the nonlinearity. In this paper results only forSaleh model with standard AM/AM and AM/PM parameters are given(Saleh1981). A HPA backoff level is used to determine how close the satellite high power amplifier is driven to saturation. The following selected backoff is used to set the input and output gain of the Memoryless Nonlinearity block: 30 dB - the average input power is 30 decibels below the input power that causes amplifier saturation(in



**Fig. 2.** “Satellite-to-Aircraft ion” Link

this case AM/AM and AM/PM conversion is negligible); 7 dB - moderate nonlinearity; and 1 dB - severe nonlinearity.

The Phase Noise block adds receiver phase noise to a complex baseband signal. The block applies the phase noise as follows: generates additive white Gaussian noise and filters it with a digital filter; adds the resulting noise to the angle component of the input signal. The level of the spectrum is specified by the noise power contained in a one hertz bandwidth offset from a carrier by a certain frequency. Modeling was provided for three levels: negligible (phase noise level: -100dBc/Hz, frequency offset: 100 Hz), low (-55 dBc/Hz, frequency offset: 100 Hz), high (-48 dBc/Hz, frequency offset: 100 Hz).

The Transmitter (Receiver) Dish Antenna Gainblock multiplies the input by a constant value (gain).Dependencies of a BER on transmitting and receiving antennas diameter were obtained using vectors [d1, d2] for each pair “transmitter-receiver”. The first element in the vector [d1, d2] represents the transmitting antenna diameter (in meters) and is used to calculate the gain in the Transmitter Dish Antenna Gain block. The second element represents the receiving antenna diameter and is used to calculate the gain in the Receiver Dish Antenna Gain block. The default setting is [1.0,1.0] (an antenna gain is 12,4) and diameters of all antennas (transmitting antenna on a satellite and receiving antenna on an aircraft) were changed simultaneously.

In the “Downlink Path”the Free Space Path Lossblock simulates the loss of signal power due to the distance between theaircraft uplink transmitter and thesatellite transponder receiver. The block reduces the amplitude of the input signal by an amount that is determined by the Loss (dB) parameter.

The Phase/Frequency Offsetblock applies phase and frequency offsets to an incoming signal.

In the “Aircraft Downlink Receiver”the Viterbi Decoderblock decodes input symbols to produce binary output symbols. Unquantized decision type parameter was used.

Comparing scatter plots of the signal after BPSK modulation and before demodulation allows viewing the impact of all impairments on the received signal.

**3. Aeronautical Satellite Channel Simulation**

For computer modeling a distance between the Iridium satellite and the aircraft (satellite altitude) 780 km and an operational frequency 1616 MHzwere taken.Changing acarrier frequency of the link updates the Free Space Path Loss block.

Free-space path loss is the loss in [signal strength](http://en.wikipedia.org/wiki/Signal_strength) that results from a [line-of-sight](http://en.wikipedia.org/wiki/Line-of-sight_propagation) path through free space, does not include the [gain](http://en.wikipedia.org/wiki/Antenna_gain) of the [antennas](http://en.wikipedia.org/wiki/Antenna_%28radio%29) used at the [transmitter](http://en.wikipedia.org/wiki/Transmitter) and [receiver](http://en.wikipedia.org/wiki/Receiver_%28radio%29), is [proportional](http://en.wikipedia.org/wiki/Proportionality_%28mathematics%29) to the [square](http://en.wikipedia.org/wiki/Square_%28algebra%29) of the distance between the transmitter and receiver, and also proportional to the square of Iridiumoperational [frequency](http://en.wikipedia.org/wiki/Frequency). A dependence of a BER on free space path loss for different noise temperatures without coding and with convolutional coding is shown in Fig. 3. Convolutional coding considerably decreases errors probability and a BER is vanishingfor free space path loss in the range from 0 dB to 221 dB (in case of very low noise temperature 20 K) and from 0 dB to 208 dB (in case of typical noise temperature 290 K). For low-orbital satellites such losses are realistic and for geostationary satellites they can achieve 200 dB (Osborne1999, Sclar2001).

Changing of all antennas diameter has significant

influence on errors probability shown in Fig. 4 – themore antennas diameter, the less is an error probability. In this simulation free space path loss was fixed, HPA nonlinearity – moderate, and two noise temperatures were considered.

Convolutional coding essentially reduces the error probability that leads to a BER vanishing for antennas with diameter more than 1,2 m. Iridium satellite has three Main Mission Antennas (each of 0,86 m wide and 1,86 m high) (Iridium2008). The same area has a circle with diameter ≈1,4 m. Apparently, results of our modeling are in the good consent with these data.



**Fig. 3.**Dependence of an error probability for a BPSK modulation scheme on free space path loss:

dots – without coding, circles – with convolutional coding (rate ¾, constraint length K=7);receiver noise temperatureis 20 K

(dashed lines) and 290 K (solid lines);HPA backoff level is 7 dB;phase and frequency offsets are equal to zero;

antennas gain G=1;satellite phase noise is negligible



**Fig. 4.**Dependence of error probability for a BPSK modulation scheme on satellite and aircraft antennas diameter:

circles – with convolutional coding (rate ¾, constraint length K=7);receiver noise temperatureis 20 K

(dashed lines) and 290 K (solid lines); phase and frequency offsets are equal to zero; HPA backoff level is7 dB;

free space path loss is250 dB;satellite phase noise is negligible



**Fig. 5.** Dependence of error probability for BPSK modulation scheme on phase offset in the downlink:

dots – without coding, circles – with convolutional coding(rate ¾, constraint length K=7);receiver

noise temperatures 290 K, free space path loss 250 dB; HPA backoff level7 dB; frequency offset is equaled to zero;

antennas gain G=10;satellite phase noise is negligible

In the presence of an arbitrary phase offset introduced by the uplink and the downlink, the demodulator is unable to tell which constellation point is which. A dependence of a BER on phase offset in the uplink and the downlink is shown in Fig. 5 for two noise temperatures without convolutional coding and with it.At usingconvolutional coding a BER is vanishing for phase shifts up to 7oat uplink and downlink losses in free space 157 dB and a noise temperature of a satellite transponder and a ground receiver 290 K.Signal constellations for BPSK modulation scheme at the phase offset 20oin thedownlink is shown in Fig. 6.

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**Fig. 6.**End signal constellation for BPSK modulation scheme for phase offset 20oin the downlink:

with convolutional coding (rate ¾, constraint length K=7); satellite and aircraft receivers noise temperatures 0 K;

free space path loss 160 dB; HPAs backoff level 7 dB; frequency offset is equal to zero; d1 = d2=1,0 m;

satellite transponder phase noise is negligible

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**Fig. 7.**Signal constellation for BPSK modulation scheme for the high level ofphase noise (-48 dBc/Hz, frequency offset: 100 Hz):with convolutional coding (rate ¾, constraint length K=7);satellite and ground receivers noise temperatures 0 K; free space path loss 160 dB; HPAs backoff level 7 dB;phase offset is equal tozero; d1 = d2= 1,0 m

Setting the Phase Noise parameter to thehigh level (-48 dBc/Hz, frequency offset: 100 Hz) leads to the increased variance in the tangential direction in the received signal scatter plot shown in Fig. 7. Setting the Phase Noise to the low level (-55 dBc/Hz, frequency offset: 100 Hz)leads to a situation when the variance in the tangential direction has decreased somewhat. This level of phase noise is not sufficient to cause errors.

In proposed model aircraft uplink transmitter amplifier and the satellite transponder are amplifyinga signal on the uplink and the downlink sides of Iridium communications satelliteby themodel of a traveling wave tube amplifier (TWTA) using the Saleh model.For an input sine wave of frequency *f* and amplitude *r*, the TWTA is characterized by the relationship (Elbert 2003):

$y\left(t\right)=A\left[r\left(t\right)\right]sin⁡(2πft+φ\left[r\left(t\right)\right])$ ,

wherethe empirical relations

$$A\left(r\right)=\frac{a\_{r}r}{1+b\_{r}r^{2}}, φ\left(r\right)=\frac{a\_{φ}r^{2}}{1+b\_{φ}r^{2}}$$

describe *A(r)* and *φ(r)*. The first term is called AM/AM conversion, and the second is AM/PM conversion (the four constants:  $a\_{r}=2,1587; b\_{r}=1,1517; a\_{φ}=4,0330; b\_{φ}=9,1040)$ .

Nonlinear method options in the block apply a memoryless nonlinearity to the complex baseband inputsignal in the following manner: 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 Saleh nonlinearity method, to produce the magnitude of the output signal; applies an AM/PM conversion to the phase of the signal, according to the Saleh 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. A dependence of a BER onnonlinearities of satellite transponder and aircraft uplink transmitter amplifiers is shown in Table 1.

Table 1. Dependence of Error Probability for BPSK Modulation Scheme on Satellite HPA Nonlinearity

|  |  |  |
| --- | --- | --- |
| HPA backoff level | BER (Aircraft Receiver Noise Temperatures T=20K) | BER (Aircraft Receiver Noise Temperatures T=290K) |
| Free Space Path Loss  | Free Space Path Loss  |
| 210 dB | 214 dB | 225 dB | 203 dB | 206 dB | 212 dB |
| 30 dB (negligiblenonlinearity) | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 |
| 7 dB (moderate nonlinearity) | 0,0 | 0,0 | 2,78·10-1 | 0,0 | 0,0 | 5,43·10-2 |
| 1 dB (severe nonlinearity) | 0,0 | 1,89·10-2 | 4,93·10-1 | 5,98·10-2 | 4,26·10-1 | 4,980·10-1 |
| *Note:*  Antennas gain G=1; with convolutional coding (rate ¾, constraint length K=7); without phase and frequency offsets. |

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**Fig. 8.**Dependence of error probability for a BPSK modulation scheme on data transmission rate:

free space path loss 180 dB (dots), 150 dB (circles), 100 dB (diamonds); with convolutional coding (rate ¾, constraint length K=7);receiver noise temperature is 290 K; phase and frequency offsets are equal to zero; HPA backoff level is 7 dB;

satellite phase noise is negligible; antennas gain G=1

For modeling a data transmission with different rates it is possible to change sample time in the Bernoulli Binary Generator block.The sample time is a parameter that indicates when, during simulation, the block produces outputs. So, a value inversely proportional to a sample time will give a number of samples per second and can be considered as equivalent of a bit rate. In Fig. 8 a dependence of a BER on a bit rate for different free space path lossesis shown.

**4. Conclusions**

For modelling of ADS-B messages transmiton on the base of low-orbit satellite constellation Іrіdіum the original model of a communication channel "Satellite-to-Aircraft" with error-control codingwas built using MATLAB Sіmulіnk software.

For studying of a signal transmission through a communication channel without coding and with convolutional coding the following parameters were changed: losses in a free space from 0 dB to 225 dB (Fig. 3); noise temperature of an aircraft receiver (20 K, 290 K); symmetrically antennas diameter that increased or reduced a power of the received signal (Fig. 4); phase offsets from 0o to 20o (Fig. 5, 6); nonlinearity of HPAs on an airplane and a satellite (Table 1); satellite phase noise (Fig. 7); and data bit rate (Fig. 8).

Signal changes were analyzed by means of active windows-indicators which allowed defining a BER and constellations of the transmitted and received signals Fig. 6, 7).

Dependencies shown in Fig. 3-8 were obtained for “standard parameters”: without coding and with convolutional coding (rate ¾, constraint length K=7); noise temperatures 20 K and 290 K; negligible HPA; and negligible phase noise. Values of free space path losses,phase and frequency offsets, antennas diameter were specified in each special case.

For “standard parameters” a BER is vanishing for free space path losses changing from 0 dB to 221 dB at use of convolutional coding and a noise temperature 20К (Fig. 3) .This result is in good agreement with a satellite communication channel budget (Sklar2001).

Antennas diameter essentially influence on a BERwhat is shown in (Fig. 4).The probability of errors for “standard parameters” is vanishing for diameters of all antennas more than 1,2 m. This result is in good agreement with the size of Iridium satellite antennas (Iridium2008).

Influence of convolutional coding on dependence of a BER on phase offsets in thelink is critical and changes character of this dependence (Fig. 5), essentially reducing a level of errors. Under "standard parameters" and noise temperature 20 Ka BER is vanishing at phase shifts up to 14o. The signal constellation (Fig. 6) shows a presence of strong distortions during signal transmission.

Satellite transponder is the central element of a considered communication channel and transponder linear gain along with a choice of a working point (level of TWTA nonlinearity)make strong impact on quantity of errors at data transmission. Under “standard parameters”, noise temperature 290 K and free spacelosses 157 dB in the uplink and 157 dB in the downlink a BER vanishes when transponder linear gain is not less than 8 dB (Fig. 7). At a noise temperature 20 K and free spacelosses 160 dB in the uplink and 160 dB in the downlink a BER vanish when transponder linear gain is not less than 6 dB.

Influence of HPA backoff parameter on a BER was studied for different free space losses and noise temperatures (Table 1). In this case a gain of all four antennaswas equal to unit to exclude effect of preamplifying in front of satellitetransponder HPA. Nevertheless, results of modelling have shown that defining influence on a BER has backoff parameterof the aircraft (compare cases 2, 5, 8 and 3,6, 9 in Table 1). It is possible to explain this by entering ofpredistortions byaircraft HPA which then are partially compensated by the transponder HPA.

The impact of phase noise on a transmitted signal is shown in Fig. 8.

Proposed model can be used as basic model for investigation of communication between two airplanes and ground stations using several satellites.

Developed model can also be used for finding optimal methods of error-correcting coding.

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