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ADS-B Satellite Communication Channel Based on IEEE 802.16 Standard

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***Abstract* – Original models of "Aircraft-Satellite-Ground Station" communication channel based on IEEE 802.16 standard were built by using MATLAB Simulink. The influence of aircraft transmitter nonlinearity for different types of fading in the channel (Rayleigh and Rician) was studied and the possibility of correcting nonlinearity by using pre-distortion was revealed. The impact of space-time diversity (MISO 2 × 1) for different types of fading in channels was investigated. The effect of the Doppler frequency shift on the operation of communication channels was analyzed.**

***Keywords* – ADS-B, Doppler shift, fading, MISO, nonlinearity correction, OFDM, satellite channel, space-time diversity.**

I. Introduction

On 20 June 2012, the operator of the Iridium satellite constellation decided to equip the next generation of satellites with Automatic Dependent Surveillance-Broadcast (ADS-B) transponders [1].

The authors of this article independently developed the model of Iridium satellite communication channel in 2011, and published the results of channel operation modelling in January 2012 [2]. In the next article dependencies of a Bit Error Rate (BER) on satellite transponder linear gain, antennas diameter, phase/frequency offsets, free space path losses, aircraft and satellite transponder high power amplifier back off level, and phase noise were received and analysed [3].

Instead of the planned renewal of the satellite constellation in 2015, the new 20 satellites were put into orbit only in 2017, and in total it will be necessary to put into orbit 75 more satellites [4].

With the help of the joint venture Aireon LLC, the Iridium management is going to place on all Iridium-NEXT satellites a real-time aircraft surveillance system using ADS-B signals transmitted by all commercial airplanes [5].

ADS-B signals are continuously transmitted by an aircraft's Mode-S transponder at 1090 MHz frequency and contain information about call sign, aircraft course, coordinates, speed, fuel contamination, etc. (Fig. 1) [6].

With the help of Harris Corporation, 81 receivers of ADS-B signals operating in 1090 Extended Squitter mode were manufactured for the new Iridium NEXT satellites. Such a surveillance system will be capable of tracking in real-time more than 10 000 aircraft and transmitting data to air traffic control centers with a delay of less than 1.5 seconds with an update rate of less than eight seconds [6].

ADS-B message travelling time and average downlink utilization for different Iridium link architectures were estimated in 2014 [7]. It was found that the delay is about 1.4 s to 1.5 s. The dependences of message travelling time on different number of satellites (N is 1 to 10) for several aircraft (n is 1 to 3) were obtained on the basis of original models.

The WiMAX Forum approved two IEEE 802.16d-2004 [8] and IEEE 802.16e-2005 standards [9], which are called fixed and mobile system profiles, respectively. In the IEEE 802.16 standards, a wide range of fundamentally different options is possible for developing a wireless broadband system with different physical layer implementations, media access control, frequency bands, etc. This diversity gives several possible options for the communication channel, which are all compatible with the IEEE standards [10].

The advantage of WiMAX comes from combining Orthogonal Frequency Division Multiplexing (OFDM) with smart antenna technologies [10]. Modern mobile satellite telecommunication technologies combine the spatial diversity and OFDM [11]. A comparison of Rayleigh Fading, Rician Fading and AWGN Channel using Chaotic Communication based on Multiple-Input Multiple-Output (MIMO) – OFDM System was provided in the paper [12].

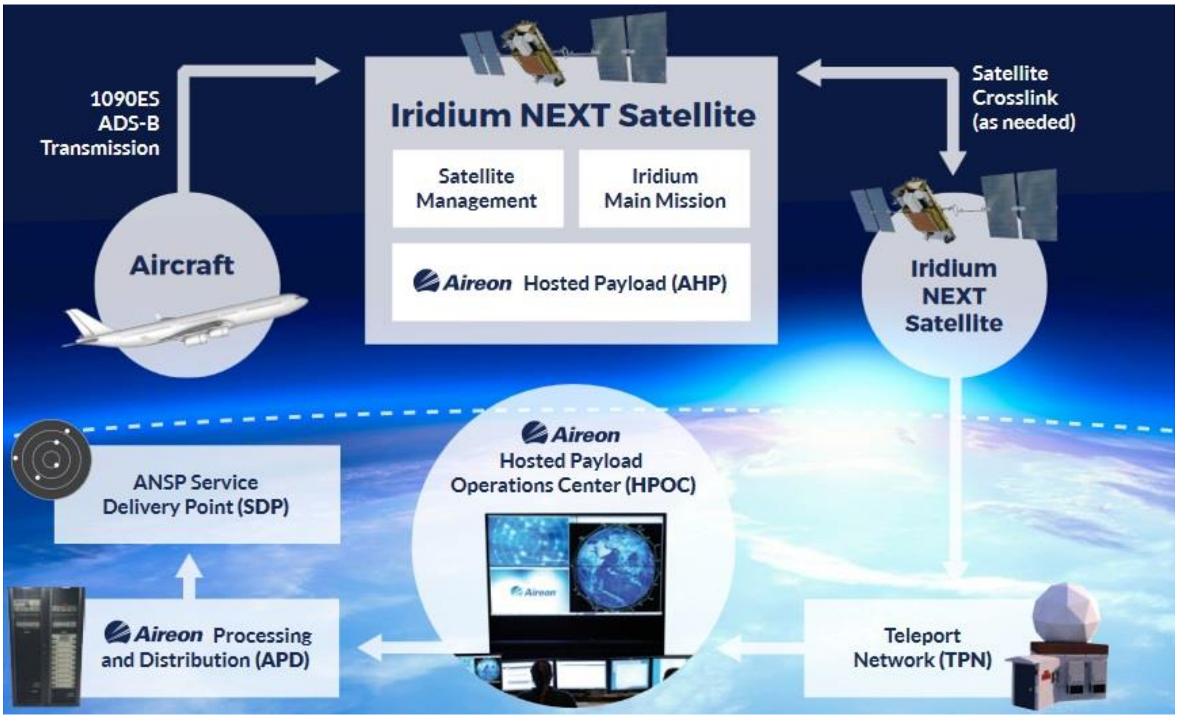


Fig. 1. Communication links [6].

This article provides an approximation for modeling, which is based on IEEE 802.16d and 802.16dstbc standards with Space-Time Block Coding (STBC).

II. Problem Statement

The aim of this paper is:

1) to simulate the operation of the aeronautical satellite channel for ADS-B data transmission on the basis of IEEE 802.16 standard;
2) to design the models of OFDM communication channel "Aircraft-Satellite-Ground Station" with adaptive modulation and error-control coding using MATLAB Simulink software;
3) to study the influence of aircraft transmitter nonlinearity for different types of fading in the channel (Rayleigh and Rician) and to reveal the possibility of correction using pre-distortion;
4) to investigate the impact of space-time diversity (MISO 2×1) for different types of fading in the channels;
5) to analyze the effect of the Doppler frequency shift on the operation of communication channels.

III. "Aircraft-Satellite-Ground Station" Link Models

The models proposed for the ADS-B satellite channel (Table I) were designed by using MATLAB demo examples *commwman80216dstbc* and *commwman80216d*.

In the channel block "Aircraft Transmitter" (Fig. 2), the following operations are performed: 1) formation of a random information stream transmitted through the satellite and consisting of bits generated in the transmitter; 2) modulation using BPSK, QPSK, 16-QAM or 64-QAM constellations; 3) forward error correction (FEC) using the Reed-Solomon (RS) code and convolutional code (CC);

4) transmission of an OFDM signal using 192 subcarriers, 8 pilot signals, 256-point fast Fourier transform (FFT); 5) space-time block coding (STBC) using the Alamouti code [13]; 6) introduction of different levels of non-linearity and 7) use of digital pre-distortion, which can correct non-linearity.

The "Ground Station Receiver" channel block (Fig. 3) performs the following operations: 1) channel estimation (determines the signal-to-noise ratio (SNR_{est}) in the received signal); 2) reception of OFDM signals and their processing by using the STBC model; 3) hard-decision demodulation with Viterbi decoding [14].

TABLE I

MODELS FOR AVIATION SATELLITE LINK BASED ON IEEE 80216 STANDARD

No.	Model	Uplink	Downlink
1	*80216dstbc Rayleigh*	MISO channel (2 × 1) uses multipath Rician fading with the same parameters for each link (Fig. 4a). *K*-factor: 0.5. Delay vector (s): [0 0.4 0.9] · 10^{-6}. Gain vector (dB): [0 –5 –10]. The channel contains three signals, the first of which is a line-of-sight component with Rician fading and given *K*-factor, and the remaining two signals are independent signals with Rayleigh fading without a line-of-sight component	Multipath Rayleigh Fading Channel (Fig. 4b). Delay vector (s): [0 0.4 0.9] · 10^{-6}. Gain vector (dB): [0 –5 –10]. Discrete paths are independent Rayleigh fading processes. Doppler spectrum type: Flat
2	*80216dstbc Rician*	The same as for Model 1 (Fig. 4a)	Multipath Rician Fading Channel (Fig. 4c). *K*-factor: 0.5. Delay vector (s): [0 0.4 0.9] · 10^{-6}. Gain vector (dB): [0 –5 –10]. The channel contains three signals, the first of which is a line-of-sight component with Rician fading and given *K*-factor, and the remaining two signals are independent signals with Rayleigh fading without a line-of-sight component. Doppler spectrum type: Flat
3	*80216d Rayleigh*	Multipath Rician fading channel. *K*-factor: 0.5. Delay vector (s): [0 0.4 0.9] · 10^{-6}. Gain vector (dB): [0 –5 –10]	The same as for Model 1 (Fig. 4b)
4	*80216d Rician*	The same as for Model 3	The same as for Model 2 (Fig. 4c)

As follows from Table I, all models are divided into several groups. For models 1 and 2 the uplink channel for data transmission from the aircraft to the satellite has space-time coding and Rice fading (Fig. 4a), and for models 3 and 4 in the uplink there is no space-time coding.

The channel for data transmission from the satellite to the ground station for models 1 and 3 is a multipath channel with Rayleigh fading (Fig. 4b), and for models 2 and 4 – a multipath channel with Rician fading (Fig. 4c).

For models 3 and 4 (Table I) it is possible to choose a non-fading, flat-fading, or dispersive uplink multipath fading channel.

All the models use adaptive modulation, which uses the SNR estimate in the receiver. This allows to dynamically change the data transfer rate depending on the conditions of the signal passage in the channel. All the models use a modulation bank with a standard set of seven modulation types, each with a specific modulation rate and RS-CC coding rate.

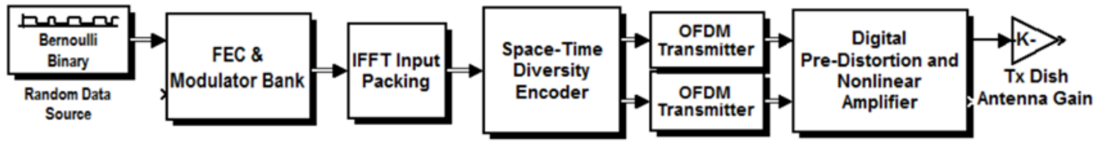


Fig. 2. “Aircraft Transmitter”.

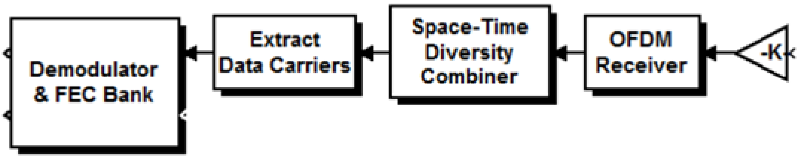


Fig. 3. “Ground Station Receiver”.

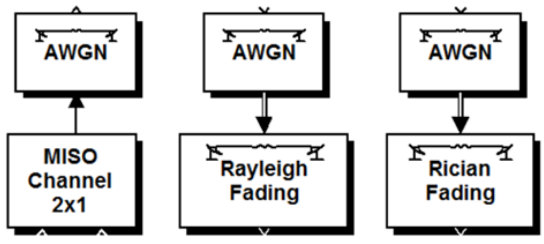


Fig. 4. MISO Uplink, Rayleigh and Rician Downlinks.

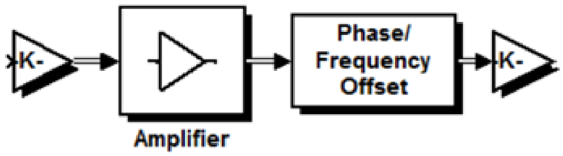


Fig. 5. “Satellite Transponder”.

Such parameters as the channel capacity, number and parameters of transmitted OFDM symbols, thresholds for transition to another type of modulation, etc. in all the models can be changed using the model parameter configuration block.

In the models under consideration, it is possible to simulate channel operation without taking into account the nonlinearity, taking into account the moderate and strong nonlinearities of the aircraft transmitter amplifier. In this case, the nonlinearity is realized with the help of the Saleh model [15] with and without the pre-distortion of the signal.

All blocks of models (Aircraft Transmitter, Satellite Transponder and Ground Station Receiver) contain antenna amplifiers, with which it is possible to set the antenna gain, taking into account the diameter of the antenna used and the operating frequency.

The numerical results of channel simulation are displayed by the block showing the BER, the number of bit errors and the total number of processed bits. With adaptive modulation, the type of modulation is selected depending on the signal level in the receiver so that the BER parameter always has to be equal to zero. Other blocks show the SNR_{est} in the receiver and the type of the corresponding modulation. The SNR in the uplink is specified during the simulation.

IV. NONLINEARITY IMPACT ON AERONAUTICAL SATELLITE CHANNELS OPERATION

For the calculations, the following parameters in the models were set up: “Aircraft Transmitter” antenna gain was taken as 3.1 (antenna diameter ≈ 0.4 m at 1 GHz), “Satellite Transponder” antenna gains were taken as 7.8 (antenna diameter ≈ 1.0 m at 1 GHz), “Ground Station Receiver” antenna gain – 15.5 (antenna diameter ≈ 2.0 m at 1 GHz).

In the Model Parameters configuration block channel bandwidth was taken as 3.5 MHz and 7 MHz, the number of OFDM symbols per burst was taken as 1, 20 and 100. The obtained results were similar and are given in figures for channel bandwidth 3.5 MHz and OFDM symbols per burst 20.

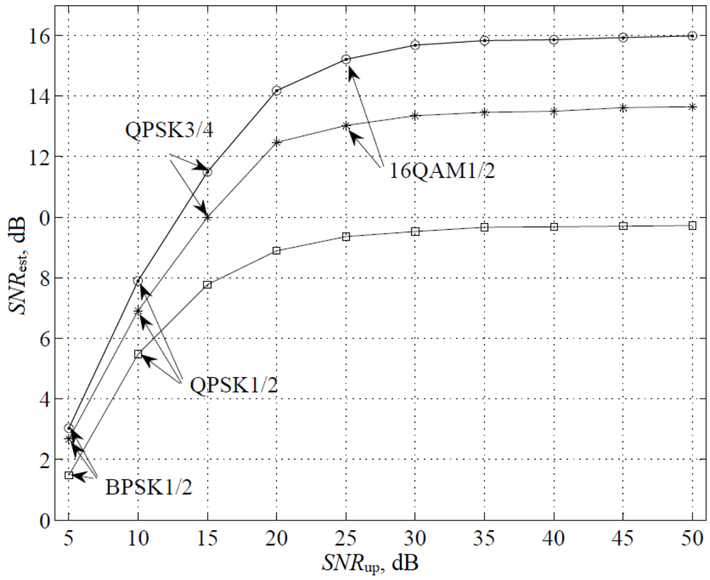


Fig. 6. Dependences of SNR_{est} in “Ground Station Receiver” on SNR_{up} in uplink when “Aircraft Transmitter” nonlinearity is: disabled (points), moderate nonlinearity (stars), moderate nonlinearity with correctible pre-distortion (circles), severe nonlinearity (squares) for *80216dstbc Rayleigh* model; Max Doppler shift is 0.5 Hz.

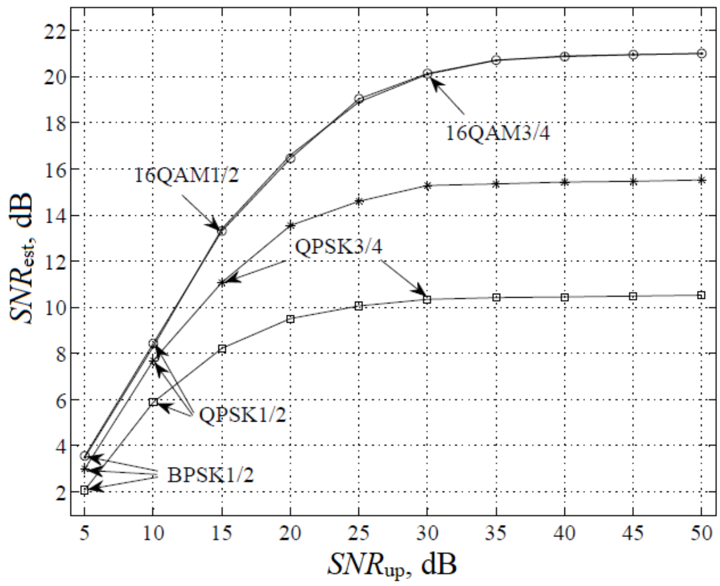


Fig. 7. Dependences of SNR_{est} in “Ground Station Receiver” on SNR_{up} in uplink when “Aircraft Transmitter” nonlinearity is: disabled (points), moderate nonlinearity (stars), moderate nonlinearity with correctible pre-distortion (circles), severe nonlinearity (squares) for *80216dstbc Rician* model; Max Doppler shift is 0.5 Hz.

The dependences of estimated SNR_{est} in "Ground Station Receiver" on SNR_{up} in uplink for different levels of "Aircraft Transmitter" nonlinearity are given in Fig. 6, Fig. 7 for models *80216dstbc Rayleigh* and *80216dstbc Rician* (Table I), respectively.

The arrows in the figures show the moment of transition to higher types of modulation. The common thing for both types of fading is the possibility of correcting the moderate nonlinearity by introducing a pre-distortion (plots for points and circles coincide).

All curves go to "saturation" but in case of disabled nonlinearity this happens for Rayleigh fading (Fig. 6) at a value of $SNR_{est} \approx 16$ dB and have the highest modulation 16QAM1/2, while for Rician fading (Fig. 7) at a value of $SNR_{est} \approx 21$ dB and have the highest modulation 16QAM3/4.

Both models operate almost identically up to values of $SNR_{up} \approx 10$ dB, but for large values of SNR_{up} the deviations increase (with the exception of the case of strong transmitter nonlinearity). In general, it should be noted that the channel with the Rician fading has better performance for data transmission.

V. Space-Time Diversity (MISO 2 × 1) for Different Types of Fading in Channels

Requirements for the throughput of satellite communication networks are very high and are constantly growing. The obvious options for increasing the bandwidth are increasing the channel width and using higher-order modulations. However, they do not completely solve the problem of providing high throughput because the frequency range is still limited.

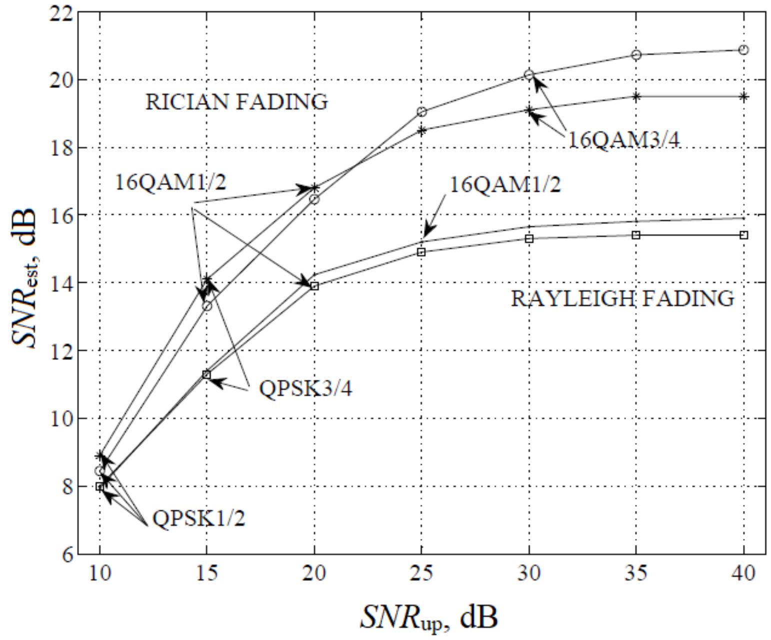


Fig. 8. The impact of space-time diversity (MISO 2 × 1) for different types of fading in the channels: *80216d Rayleigh* model (squares), *80216d Rician* model (stars), *80216dstbc Rayleigh* model (points), *80216dstbc Rician* model (circles); Max Doppler shift is 0.5 Hz.

Moreover, the use of higher order modulation implies an increase in SINR (Signal to Interference plus Noise Ratio), which also has its limit. Another way to increase the throughput of wireless systems is to use multiple transmit and receive antennas (MIMO) and special signal processing in this case.

The diversity transmission (Tx Diversity) is the case of using more antennas on the transmitting side than at the receiving end. From the point of view of MIMO, such a system is called MISO – Multiple Input Single Output. The simplest case of such a system: two transmitting antennas, and the receiving one is called MISO 2 × 1 (models *80216dstbc Rayleigh* and *80216dstbc Rician* in Table I).

MISO does not increase the bandwidth of the channel, but it increases the reliability of transmission. At the same time, the use of MISO allows to transfer the necessary additional signal processing from the receiving side (mobile station) to the transmitting (base station). Space-time coding is used to generate a reliable signal. The effect of space-time coding is demonstrated in Fig. 8, where the graphs for different types of fading are compared. Calculations were carried out for the case of moderate transmitter nonlinearity with correctible pre-distortion. The arrows in the figure show the moment of transition to higher types of modulation and demonstrate how the parameters of data transmission vary depending on the signal propagation conditions.

In the case of Rayleigh fading, the use of space-time coding (Fig. 8, points) improves the data transfer (higher values of the SNR_{est} are observed) throughout the entire range of SNR_{up}.

In the case of Rician fading, the use of space-time coding (Fig. 8, circles) gives higher values of SNR_{est} only at $SNR_{\mathrm{up}} \approx 22$ dB.

VI. The Effect of Doppler Frequency Shift on the Operation of Communication Channels

The Doppler frequency shift occurs in the case of a relative motion of the transmitter and receiver. The aircraft and the satellite move relative to each other, and the satellite moves relative to the ground station. Therefore, it is necessary to take into account the Doppler shift of the frequency both in the communication channel “Aircraft-Satellite” and in the channel “Satellite-Ground Station”.

Doppler shifts in all models were set symmetrically in the channel up and down. BER values and modulation types for different Doppler frequencies are given in Table II.

TABLE II

BER Values and Modulation Types for Different Doppler Frequencies

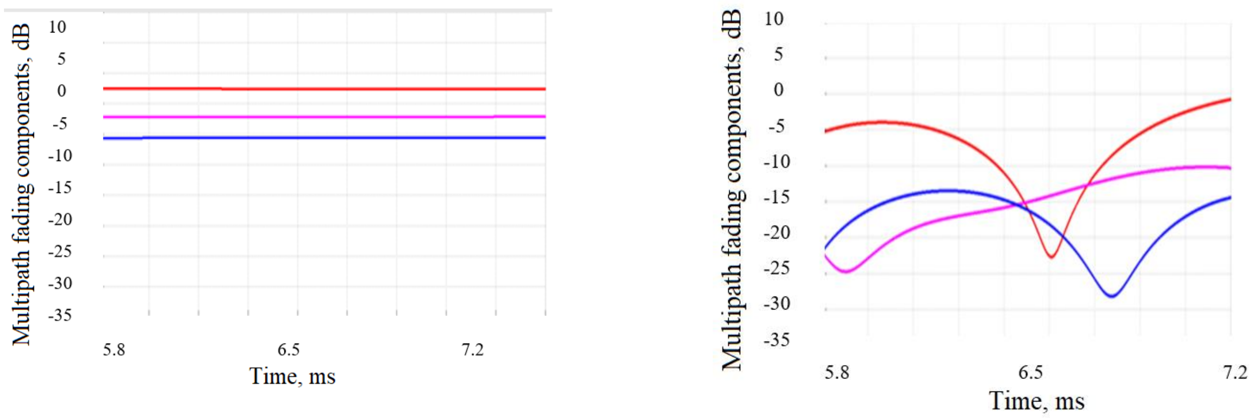
Models	**1 Hz**		**10 Hz**		**100 Hz**		**500 Hz**	
	BER	**Modulation**	**BER**	**Modulation**	**BER**	**Modulation**	**BER**	**Modulation**
80216d Rayleigh	0.0	16QAM1/2	0.00370	16QAM1/2	0.13	BPSK1/2	0.37	BPSK1/2
80216d Rician	0.0	16QAM1/2	0.00850	16QAM1/2	0.15	BPSK1/2	0.40	BPSK1/2
80216dstbc Rayleigh	0.0	16QAM1/2	0.00210	16QAM1/2	0.10	BPSK1/2	0.34	BPSK1/2
80216dstbc Rician	0.0	16QAM1/2	0.00091	16QAM1/2	0.14	BPSK1/2	0.39	BPSK1/2

Note: SNR_{up} = 20 dB; the case of moderate aircraft transmitter nonlinearity with correctible pre-distortion; in models *80216d Rayleigh* and *80216d Rician* the uplink was taken with frequency-selective fading; in models *80216d Rician* and *80216dstbc Rician* in the down link Doppler shift of line-of-sight component and Doppler shifts of diffusive components were the same.

As follows from Table II, the BER performance of all models is degraded with the increase of the Doppler frequency shift. The modulation order is decreasing at the same time.

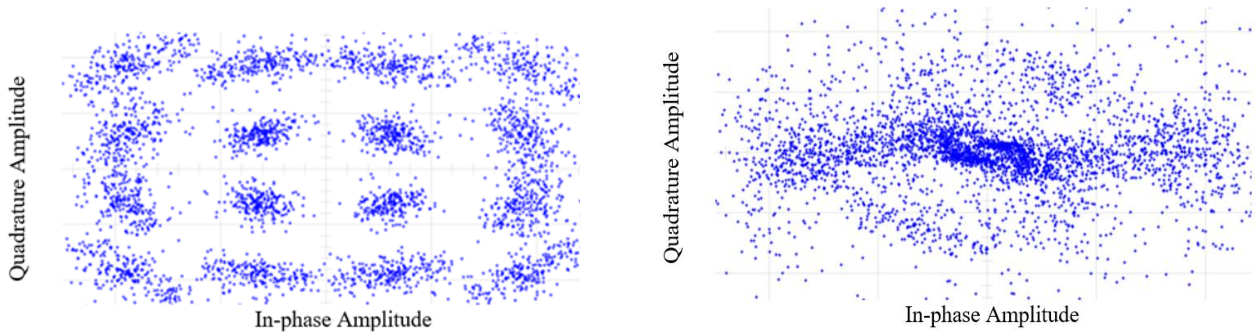
The change in the behavior of multipath components along with Doppler frequency increase is shown in Fig. 9 and is typical for all the models considered.

Fig. 10 depicts the signal constellations changing along with the increase of the Doppler frequency shift, which is similar for all the models under the given conditions.



a) b)

Fig. 9. Typical dependences for all the models of multipath fading components in case of Doppler shift 1 Hz (a) and 500 Hz (b); SNR_{up} = 20 dB; the case of moderate aircraft transmitter nonlinearity with correctible pre-distortion.



a) b)

Fig. 10. Typical received signal constellations for all the models in case of Doppler shift 1 Hz (a) and 500 Hz (b); SNR_{up} = 20 dB; the case of moderate aircraft transmitter nonlinearity with correctible pre-distortion.

VII. Conclusion

This paper deals with the ADS-B satellite channel (Fig. 1) and original models (Table I) of the communication channel "Aircraft-Satellite-Ground Station" link based on IEEE 802.16 standard (Fig. 2–5).

The influence of aircraft transmitter nonlinearity for different types of fading was studied (Fig. 6, Fig. 7) and the possibility of nonlinearity correction using pre-distortion was revealed.

The combination of OFDM with spectral efficient multiple antenna techniques is used to overcome the frequency selective problems [16]. Benefits and shortcomings of various MIMO technologies like spatial multiplexing, space time coding, spatial modulation and transmit antenna selection for performance optimization are considered in [17].

In this paper, the effect of space-time diversity for different types of fading was investigated (Fig. 8) and the graphs were compared.

Joint iterative channel and data estimation in high mobility MIMO-OFDM systems are set forth in the book [18]. Doppler shift (1 Hz, 10 Hz, 100 Hz, 500 Hz) impact on the MIMO OFDM system in vehicular channel condition is analyzed with the change in m value of Nakagami channel and with the variation in the modulation schemes [19]. The effect of Doppler shift on the MIMO-OFDM systems in troposcatter fading channels is that a slight Doppler shift influences the system performance significantly [20]. The effect of Doppler shift on the performance of the 2 × 2 MIMO system [21] has been studied for 4-QAM, 8-QAM, 16-QAM, and 64-QAM modulations and for different values of Doppler shift (5 Hz, 50 Hz, 100 Hz).

The analysis of model performance in mobility condition, i.e. the effect of the Doppler shift on the system (Table II, Fig. 9, Fig. 10) showed that with the increase of Doppler frequency the BER increases and the higher modulation order in the system becomes more sensitive towards Doppler change.

The significance of the obtained results lies in the fact that with the help of calculations and modeling (non-linearity, MISO 2 × 1, Doppler shift) it is possible not only to identify problems at the early stages of designing aeronautical satellite communication channels, but also to minimize design errors, reduce the time and cost of setting up equipment, assembling a laboratory measuring system, and ensure maximum performance and scalability in accordance with future needs. As a result, the data of such calculations quickly turns into the necessary tool of the researcher and developer engaged in the design and integration of MIMO components and systems in the satellite communication network.

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