Simulation of a Multi-Frequency Satellite Communication Channel

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***Abstract*—The growing number of subscribers and the volume of transmitted information requires an increase in the capacity of satellite communication systems. This is possible through the use of high orders of signal constellations, spatial separation of channels, effective noise-resistant codes. In addition, the new standards require the effective use of non-linear power amplifiers that must operate close to saturation. Of interest is the increase in the capacity of satellite communication systems due to the multi-frequency mode in the transponder channel. The article reveals the channel structure, gives a detailed description of the input and output multiplexers, a nonlinear amplifier, a mixer, and a local oscillator. The structure of the computer model of the transponder channel and the multi-frequency signal of the ground station is shown. The simulation results show that the multi-frequency mode introduces additional intermodulation distortion of the carriers of one channel. This requires the development of nonlinear predistortion systems at transmitting ground stations, as well as equalizers at receiving stations.**

Keywords— Satellite communication systems, modeling, broadband signal, multi-frequency mode, multiplexer, non-linear amplifier, intermodulation

I. INTRODUCTION

Currently, the next generation 5G communications standards are being developed even further. This requires a significant improvement in the performance of telecommunication equipment in terms of increasing throughput. This is possible through the use of high orders of signal constellations, spatial separation of channels, effective noise-resistant codes. In addition, the new standards require the effective use of non-linear power amplifiers that must operate close to saturation. This applies not only to terrestrial communications systems, but satellite communications systems. To increase the throughput of a satellite communication channel, it is necessary to use high modulation orders of the DVB-S2, DVB-S2X and DVB-RCS2 standards. To efficiently multiplex a broadband channel and transmit several carriers on the same channel with MF-TDMA and SC-FDMA/SC-OFDM [1] multiplexing, it is necessary to increase the bandwidths of the channel filters.

Typical for transmitting data using satellite transponders use one carrier per channel. This channel consists of an input multiplexer filter (IMUX), a nonlinear amplifier, an output filter, and a multiplexer (OMUX) (Fig. 1).

The structure of such a data transmission channel is well described in [2]. An increase in repeater throughput requires an increase in channels, which leads to an increase in the mass and power consumption of the spacecraft. It is necessary to use a large number of carriers on one broadband channel with one non-linear amplifier to eliminate this drawback.

This allows you to reduce the number of filters and nonlinear elements, but leads to mutual intermodulation distortion of the carriers of one channel after passing through the power amplifier. A possible structure of a multi-frequency satellite channel was described in [3] (Fig. 2).

In this paper, we will simulate a broadband satellite channel in the multi-frequency mode in accordance with Fig. 2.

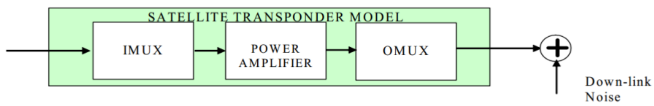

Fig. 1. Single-Carrier satellite transponder channel model

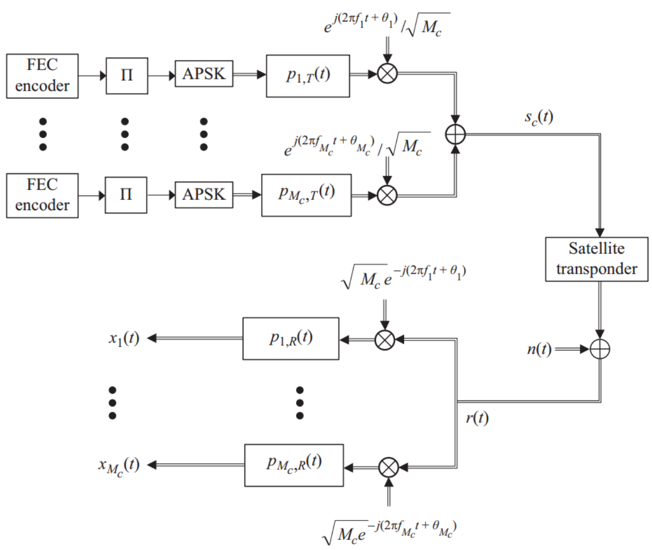

Fig. 2. Block diagram of multicarrier satellite channel

II. COMPONENTS OF A MULTI-FREQUENCY CHANNEL OF A SATELLITE REPEATER

A. *Input multiplexer*

The input multiplexer allocates the bandwidth of a particular channel. The IMUX is a microwave filter. The frequency response and group delay are specified in [4] (Fig. 3).

B. *Non-linear power amplifier*

As a nonlinear amplifier, as part of a satellite repeater, amplifiers based on a traveling wave tube (TWT) are usually selected. Non-linearized TWT can be used to minimize the cost and weight of the amplifier module. The characteristics of the introduced nonlinearity of such lamps are determined by the conversion of amplitude modulation (AM / AM) to amplitude and phase (AM / PM) (Figure 3). These characteristics are given in [4].

The introduction of nonlinearity is determined by the following expression:

$$y(t) = M(x(t)\cdot \exp(j[\Phi(x(t) + \mathrm{angle}(x(t))]), \qquad (1)$$

Where $M(x(t)$ – AM / AM; $\Phi(x(t)$ – AM / PM.

C. *Output multiplexer*

The output multiplexer selects the bandwidth of a particular channel and partially suppresses third-order intermodulation components (I3) that occur when the amplifier operates in a mode close to saturation.

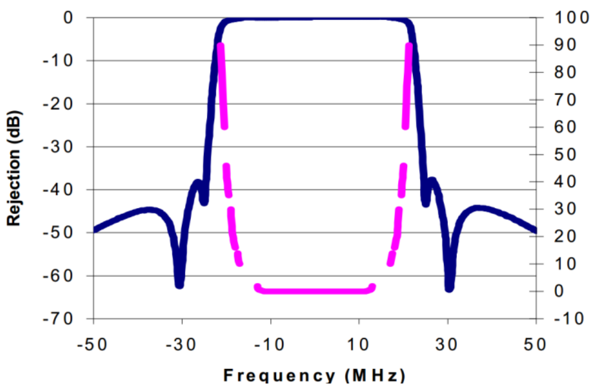

Fig. 3. Frequency response and group delay of IMUX

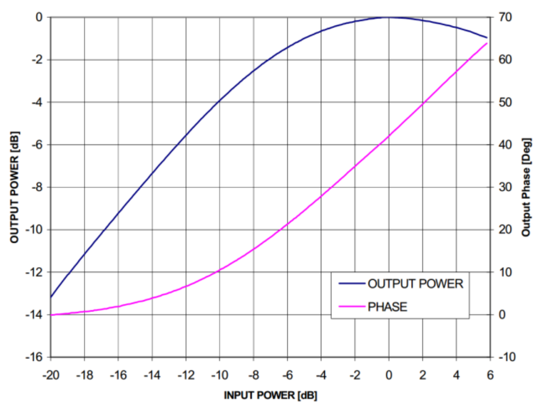

Fig. 4. Characteristics AM / AM and AM / PM of a typical TWTA as part of a repeater

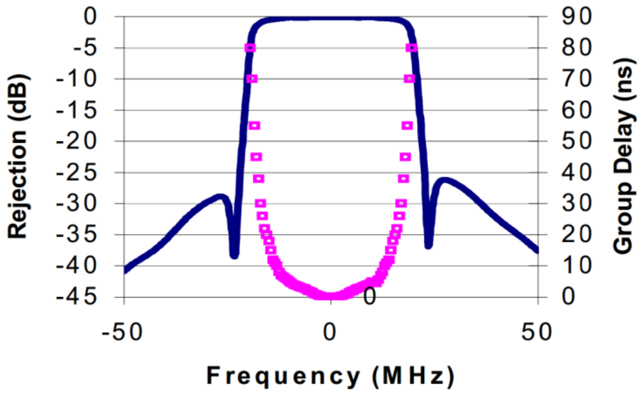

Fig. 5. Frequency response and group delay of OMUX

TABLE I. AGGREGATE PHASE NOISE MASKS FOR SIMULATION (IN DBC/HZ)

Frequency	100 Hz	1 kHz	10 kHz	100 kHz	1 MHz	10 MHz
Aggregate1 (typical)	-25	-50	-73	-93	-103	-114
Aggregate2 (critical)	-25	-50	-73	-58	-103	-114

The IMUX is a microwave filter. The frequency response and group delay are shown in Fig. 5 [4].

D. *Adding to phase noise*

Phase noise is added by a local oscillator, used in conjunction with a mixer to convert the frequency. Frequency noise masking characteristics are given in Table 1.

III. IDENTIFICATION OF THE COMPONENTS OF THE REPEATER

The modeling of a nonlinear channel in the MATLAB package can be carried out using analytical expressions of a digital solver. In addition, the RFBlockset library can be used, which operates with differential equations and well describes the electronic components. In this simulation, the second option was chosen.

A. *IMUX authentication in RFBlockset library*

In the RFBlockset library, you can simulate Butterworth, Chebyshev type I and II bandpass filters, but there is no way to model filters with an arbitrary number of transmission zeros. However, it allows the use of simulated filters with arbitrary S-parameters.

A possible implementation of IMUX is presented in [5]. Having adapted a similar filter of the 11th order for a carrier of 10992.5 MHz and a bandwidth of 123 MHz, the coupling matrix was calculated (Table 2).

Based on the coupling matrix, S-parameters are calculated, which are stored in the touchstone file (s2p) of the RFBlockset library, where fitting a rational function to the specified data is performed (Fig. 6).

B. *Configure the non-linear amplifier traveling wave tube*

The RFBlockset library can model nonlinear amplifiers based on semiconductor elements, but it does not have TWTA models. You can simulate arbitrary amplifiers in the library using the Power Amplifier RFBlokset, based on the the function Memory-Polynomial Identification [6].

TABLE II. COUPLING MATRIX OF IMUX CHANNEL FILER

	1	2	3	4	5	6	7	8	9	10	11
1	0	1,289	0	0	0	0	0	0	0	0	0
2	1,289	0	1,129	0	0	0	0	0	0	0	0
3	0	1,129	0	0,684	0	0	0	0	0	0	0
4	0	0	0,684	0	-0,593	0	0	0	-0,052	0	0
5	0	0	0	-0,593	0	0,477	0	-0,349	0	0	0
6	0	0	0	0	0,477	0	0,839	0	0	0	0
7	0	0	0	0	0	0,839	0	0,477	0	0	0
8	0	0	0	0	-0,349	0	0,477	0	0,593	0	0
9	0	0	0	-0,052	0	0	0	0,593	0	-0,684	0
10	0	0	0	0	0	0	0	0	-0,684	0	-1,129
11	0	0	0	0	0	0	0	0	0	-1,129	0

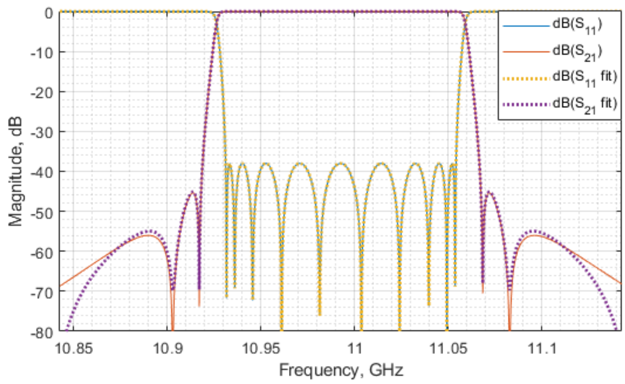

Fig. 6. Calculated S-parameters and fitting by a rational function for IMUX

Non-linearity of TWTA can be described using the function Generalized Memory Polynomial:

$$y_{MP}(n)=\sum_{k=0}^{K-1}\sum_{m=0}^{M-1}C_{k,m}x(n-m)\left|x(n-m)\right|^{k} \qquad (2)$$

where $C_{k,m}$ are the coefficients of the function Generalized Memory Polynomial; k is the current degree; K is the maximum degree of a polynomial for modeling; m is the current memory depth; M is the maximum depth of memory for modeling.

The coefficients $C_{k,m}$ are calculated using the following equation (3).

To identify the coefficients, it is necessary to have reference recorded samples of the input x and output y signals of a real nonlinear device. If such a device is not available, you can use the characteristics shown in Fig. 4. To do this, it is necessary to restore dependencies and identify function (1).

TWTAs are usually described using the Saleh model [7]:

$$\begin{cases} M(x)=\dfrac{\alpha_1 x}{1+\beta_1 x^2}; \\ \Phi(x)=\dfrac{\alpha_2 x^2}{1+\beta_2 x^2}. \end{cases} \qquad (4)$$

In this case, the Saleh model does not describe the given curves accurately, therefore, the characteristics of the approximating functions were obtained as follows:

$$\begin{cases} M(x)=\dfrac{3.468x^2+2.084x}{0.6445x^3+3.146\,x^2+0.7555x+1}; \\ \Phi(x)=\dfrac{13.68x^3-0.07774x}{6.127x^3+11.68x^2-0.2627x+0.9085}. \end{cases} \qquad (5)$$

The captured points interpolated by the spline interpolation function and polynomial relation (5) are shown in Fig. 7.

$$\begin{bmatrix} x_M & \cdots & x_1 & x_M\left|x_M\right| & \cdots & x_1\left|x_1\right| & \cdots & x_M\left|x_M\right|^{K-1} & \cdots & x_1\left|x_1\right|^{K-1} \\ x_{M+1} & \cdots & x_2 & x_{M+1}\left|x_{M+1}\right| & \cdots & x_2\left|x_2\right| & \cdots & x_{M+1}\left|x_{M+1}\right|^{K-1} & \cdots & x_2\left|x_2\right|^{K-1} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \ddots & \vdots & \ddots & \vdots \\ x_N & \cdots & x_{N-M} & x_N\left|x_N\right| & \cdots & x_{N-M}\left|x_{N-M}\right| & \cdots & x_N\left|x_N\right|^{K-1} & \cdots & x_{N-M}\left|x_{N-M}\right|^{K-1} \end{bmatrix} \cdot \begin{bmatrix} C_{1,1} \\ \vdots \\ C_{M,1} \\ C_{1,2} \\ \vdots \\ C_{M,2} \\ \vdots \\ C_{1,K} \\ \vdots \\ C_{M,K} \end{bmatrix} = \begin{bmatrix} y_M \\ y_{M+1} \\ \vdots \\ y_N \end{bmatrix}. \qquad (3)$$

TABLE III. THE COEFFICIENTS $C_{K,M}$ CALCULATED USING THE GENERALIZED MEMORY POLYNOMIAL FUNCTION

Real component $C_{k,m}$								
m\k	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***
1	2.1E+00	3.9E-01	-3.0E-01	6.2E-02	-6.5E-03	3.9E-04	-1.2E-05	1.6E-07
2	1.3E-02	-7.7E-03	-4.1E-03	2.4E-03	-4.5E-04	4.1E-05	-1.8E-06	3.3E-08
3	6.2E-03	-1.1E-02	8.7E-03	-2.7E-03	4.3E-04	-3.5E-05	1.5E-06	-2.5E-08
Imaginary component $C_{k,m}$								
m\k	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***
1	-3.3E-01	3.6E-01	9.3E-03	-1.9E-02	3.2E-03	-2.4E-04	8.9E-06	-1.3E-07
2	-6.4E-02	1.0E-01	-3.6E-02	5.8E-03	-4.7E-04	1.6E-05	-1.9E-08	-8.4E-09
3	4.5E-02	-5.9E-02	1.8E-02	-2.5E-03	1.4E-04	1.0E-06	-4.1E-07	1.2E-08

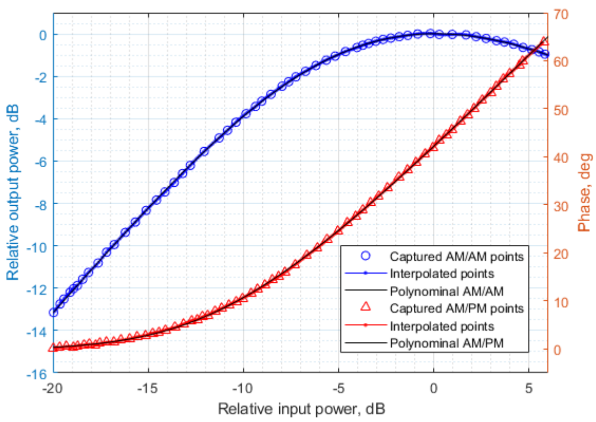

Fig. 7. Captured points, Spline interpolation and polynomial ratio identification of AM/AM and AM/PM

The model for recording the characteristics of *x* and *y* signals for 32APSK modulation is shown in Fig. 8. Based on the recorded characteristics, the coefficients $C_{k,m}$ with $K = 8$ and $M = 3$ were calculated (Table 3).

A comparison of the characteristics of the Power Gain Transfer Function model and polynomial is shown in Fig. 9.

C. OMUX Authentication in the RF Blockset Library

A possible implementation of OMUX is presented in [8]. Adapting a similar filter of the 8th order for a given carrier 13500 MHz and a bandwidth of 114 MHz, a coupling matrix was obtained (Table 4).

Based on the coupling matrix, S-parameters are calculated, which are stored in the touchstone file (s2p) of the RFBlockset library, where fitting a rational function to the specified data is performed (Fig. 10).

IV. SIMULATION RESULTS MULTI-FREQUENCY SIGNAL TRANSMISSION THROUGH THE SATELLITE TRANSPONDER CHANNEL

Previously, a repeater model was built using clustering of standard blocks of the RFBlockset library with loading s-parameters of IMUX and OMUX, loading Generalized Memory Polynomial coefficients for the power amplifier and setting the phase noise mask for the local oscillator (LO) (Fig. 11).

The transmission spectrum of three carriers at the input and output of the repeater is shown in Fig. 12

As can be seen from Fig. 12, the TWTA normalized amplifier introduces non-linear distortion of the intermodulation components that are attenuated by OMUX.

The distortion of the signal constellation of the central carrier at the output of the repeater under the influence of intermodulation components in comparison with the reference location of the constellation points is shown in Fig. 13.

TABLE IV. COUPLING MATRIX OF IMUX CHANNEL FILER

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
1	0	0,9912	0	0	0	0	0	0
2	0,991	0	0,8232	0	0	0	0	0
3	0	0,8232	0	0,5378	0	-0,251	0	0
4	0	0	0,5378	0	0,7765	0	0	0
5	0	0	0	0,7765	0	0,5378	0	0
6	0	0	-0,2514	0	0,5378	0	0,8232	0
7	0	0	0	0	0	0,8232	0	0,9912
8	0	0	0	0	0	0	0,9912	0

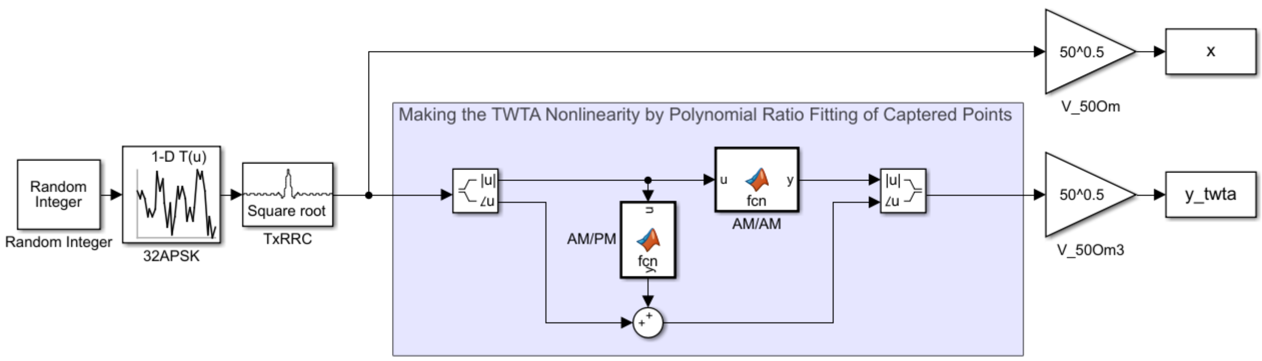

Fig. 8. A model for recording input and output signals through a non-linear amplifier model

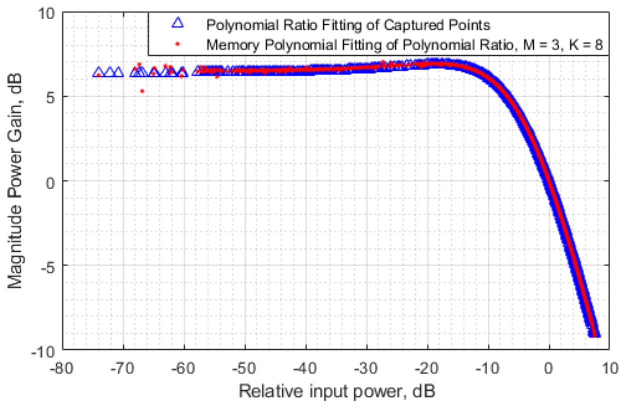

Fig. 9. Comparison of the characteristics of the Power Gain Transfer Function model and polynomial

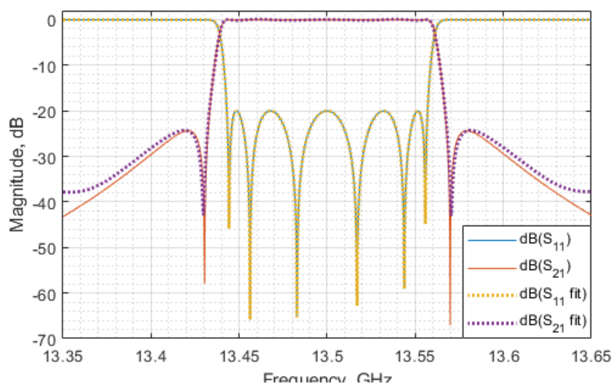

Fig. 10. Calculated S-parameters and fitting by a rational function for OMUX

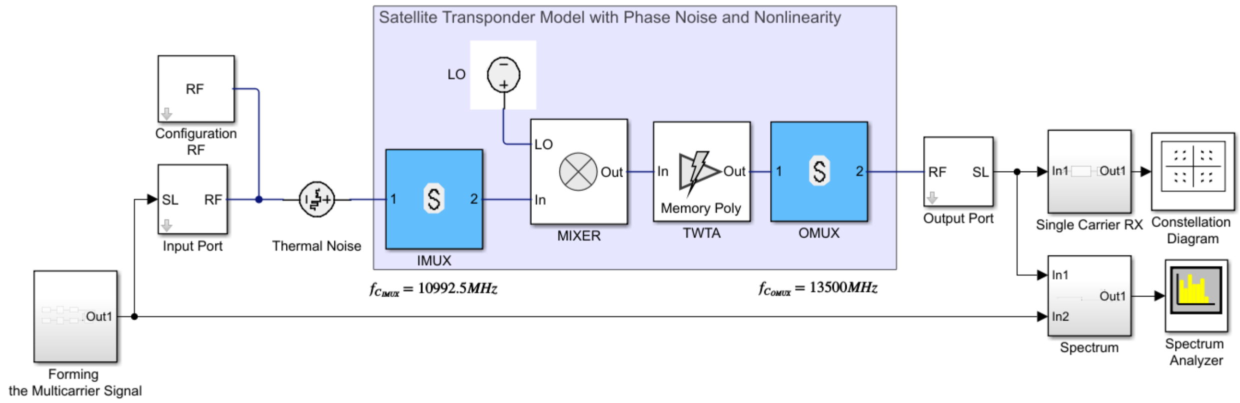

Fig. 11. Block diagram of a broadband satellite channel for three carriers

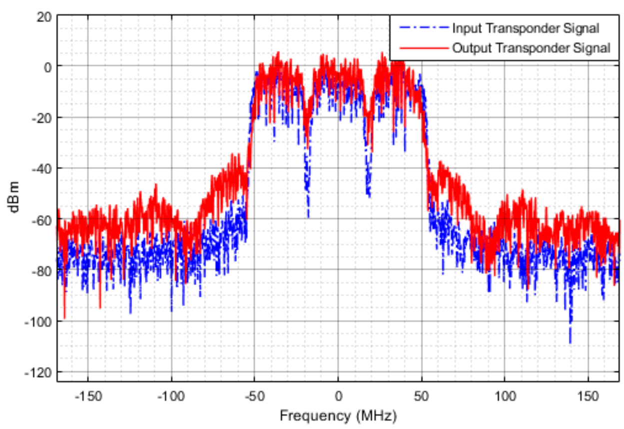

Fig. 12. Transmission spectrum of three carriers at the input and output of the repeater

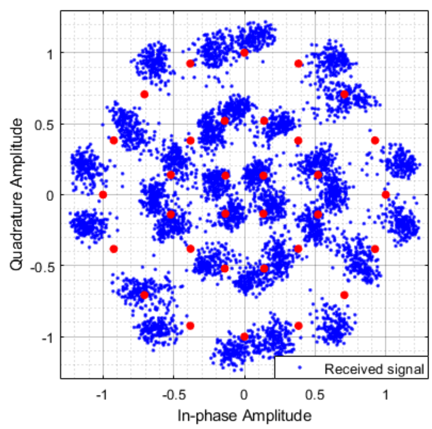

Fig. 13. Distorted and reference constellations 32APSK one of the carriers

From Fig. 13 it is seen that the signal constellations are strongly distorted under the influence of the nonlinear TWTA, as well as as a result of operation in the multi-frequency mode (mutual intermodulation components in the band of the broadband channel).

V. Conclusion

In the work, a simulation of a broadband satellite communication channel in multi-frequency mode was carried out.

The characteristics of the coupling matrix for IMUX (Table 1), OMUX (Table 3), as well as the coefficients of the Generalized Memory Polynomial function for the normalized TWTA were identified. Using broadband IMUX, OMUX in multi-frequency mode allows using one TWTA for several carriers, thereby proportionally reducing the number of filters and non-linear amplifiers onboard the spacecraft. However, this mode introduces additional intermodulation distortion of the carriers of one channel, which requires the development of nonlinear predistortion systems at transmitting ground stations, as well as equalizers at receiving stations. This will be considered in the following papers.

ACKNOWLEDGMENT

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