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Nonlinearities Influence to RF Satellite Downlink Model with QAM and Raised Square Cosine Filter

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Abstract. Reliability of communications is of vital importance in military applications. Constellations are connecting coded words at different ends of the communication channel that indicate the correctness of the transmitted message. In this paper, we compare the influence of the selected nonlinearity in the transmit amplifier on the constellation diagrams in radio frequency (RF) geostationary satellite downlink and bit-error-rate (BER). Two cases were analyzed: negligible and severe noise in the communication channel. Considering the cubic, hyperbolic tangent, Saleh, Ghorbani, and Raap models, it is shown that the Raap and Saleh models can be used for the lowest BERs when the noise is negligible. In case of severe noise, it is best to use the Raap model from the set of nonlinearities considered. The ANOVA-test showed that there is a dependence between the Raap and Saleh models in the presence of negligible noise, but not in the presence of severe noise.

Keywords: BER; Constellation diagrams; High power amplifier; Satellite downlink model

1. Introduction

The importance of satellite communications for maritime and navy applications is well-known and increasing. If a transmitted message is altered beyond reliable identification, there could be significant consequences for warfare. Hence, communications reliability studies are more important than ever. Although some problems in wireless communications were considered in (Kurniawati *et al.*, 2023; Pamukti, Wijayanto, and Liaw, 2023), and path losses in (Lukman *et al.*, 2022), problems considered in this paper were not investigated in these references. The satellite component plays a fundamental role in Universal Mobile Telecommunication Systems (UMTS) (Janaaththanan, 2008).

High power amplifiers (HPAs), which are highly sensitive to nonlinearities, were the focus of Lakhwal, Pal, and Kumar (2012). Because of these nonlinear responses, signal distortions were also amplified. The paper presents an adaptive method for linearizing the HPA response using a polynomial. There isn't comparative analysis of the nonlinearities' effects studied yet.

A framework for RF systems modeling is described in (Arabi and Ali, 2008). Simulink was used and Quadrature Amplitude Modulation (QAM) was considered. However, only one nonlinearity was considered. On the contrary, the subject of this paper is a comparison of various nonlinearities. Bawa, Pal, and Gupta (2013) concluded that polynomials up to

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the 5th order is useful since higher orders have negligible effects. It can be seen that the most popular nonlinearity is the polynomial. Current trends include multicarrier waveforms and non-symmetrical spectral shaping of subchannels (Jošilo *et al.*, 2014), exploration of RF distortions massive MIMO (Multi-Input, Multi-Output) Systems in millimeter-wave (Khansefid *et al.*, 2016), digital precompensation for multicarrier satellite communications (Kelly *et al.*, 2015), Ku/Ka band satellite services (SES, 2017), and MIMO satellite communications (Ramamurthy, 2018) or novel materials for antenna designs. Wang *et al.*, (2022), (Gupta *et al.*, 2019) focus more on hardware for HPA. Some aspects of nonlinearities in HPAs are also considered in the works of Ssimbwa *et al.* (2022) and Mukherjee, Lajnef, and Krikidis (2020). The importance of this research is emphasized by references on their compensation, e.g. (Maltsev *et al.*, 2022). All of the above topics could be addressed separately.

The contributions of the paper are:

- pointing out an example linking marine electrical engineering education with the practice of readers working in parallel with their studies,
- linking work processes with theory in order to the improve theoretical knowledge of the operator, and help readers to combine study and work,
- simulation in Matlab/Simulink, linked to a problem from practice to complete the education and finish the appropriate level of training,
- comparative analysis of the influence of the different models (cubic, hyperbolic tangent, Saleh, Ghorbani, Raap) on the constellations.

In this paper, QAM is considered for satellite communications. The paper is organized as follows. In section two, the considered model of satellite downlink is presented. In section three, nonlinearities in HPA are defined. The simulation results are presented in the fourth section. The last section contains the conclusions.

2. Considered System and Components

The considered system consists of three parts: the satellite's downlink transmitter, the downlink path (corresponding to the influence of conditions in the transmitting medium, i.e. atmospheric conditions), and the ground station downlink receiver. Ideally, the receiver should read the signal without error. Constellation diagrams show the dispersion of the received signals. The downlink transmitter consists of: QAM modulator, transmit filter (in this case raised cosine transmit filter), HPA, and antenna gain. HPA introduces nonlinearity in real cases. One method to linearize the power amplifier (PA) is to introduce predistortion into the modeling (Raich, 2004). Ideal PA can be with and without memory effects, but wideband signals also tend to introduce memory effects. Memory effects can also be caused by electrical or/and electrothermal sources. Hence, HPAs are modeled with nonlinear functions to compensate for memory effects, and nonlinearity is used instead of memory effects (Šuško, 2013). In memoryless systems, the output is a function of the input at the current time, there are no energy-storing components, and the output is in phase with the input. Input-output (I/O) relationship should be frequency-independent. HPA is also modeled to compensate for system degradation due to amplifier nonlinearities, intermodulation effects, etc. Memoryless models are i.e. polynomial, Saleh, Ghorbani, or Rapp. The transfer function (TF) of the raised cosine filter can be expressed as square cosine. The inputs are the roll-off factor (α) and the cut-off frequency ($1/T_s$), as in equation (1):

$$H(f)=\begin{cases}1, & |f|\le\frac{1-\alpha}{2T_S}\\ \cos^2\left(\frac{\mu T_S}{2\alpha}\cdot\left(|f|-\frac{1-\alpha}{2T_S}\right)\right), & \frac{1-\alpha}{2T_S}\le|f|\le\frac{1+\alpha}{2T_S}\\ 0, & |f|\ge\frac{1+\alpha}{2T_S}\end{cases} \tag{1}$$

Impulse response is given with equation (2):

$$h(t)=\frac{\sin\left(2\pi\frac{t}{T_S}\right)}{2\pi t}\times\frac{\cos\left(2\pi\cdot\frac{t}{T_S}\right)}{1-2\pi\frac{t}{T_S}} \tag{2}$$

The polynomial models used in the Results section are cubic and hyperbolic tangent. In general, a finite order polynomial model fitted to the I/O measurements of an amplifier is defined as follows in equation (3):

$$f(\vec{x})=\sum_{k=0}^{N}\alpha_k\vec{x}^k \tag{3}$$

where $\vec{x}=[x_1\ x_2\ \dots\ x_L]^T$, N is the order of the polynomial and L is the number of measured data. The cubic polynomial has components up to the 3rd order. The hyperbolic tangent has 1st, 3rd, and 5th order variables (Bawa, Pal, and Gupta, 2013). The Saleh model (O'Droma et al., 2009) is considered as a standard. It equation (4) defines the AM/AM and AM/PM TFs as:

$$G(r)=\frac{2r\sqrt{P_{\max}}}{1+r^2},\ \Phi(r)=\frac{2r^2}{1+r^2}\cdot\frac{\pi}{6} \tag{4}$$

where $r(t)$ is the modulated envelope and $P_{\max}$ is the maximum saturation point of the amplifier. In the Ghorbani model (Sajedin and Ghorbani, 2014), the TFs are defined as equation (5):

$$\begin{cases}G(A)=\frac{x_1\cdot A^{x_2}}{1+x_3\cdot A^{x_2}}+x_4\cdot A\\ \Phi(A)=\frac{y_1\cdot A^{y_2}}{1+y_3\cdot A^{y_2}}+y_4\cdot A\end{cases} \tag{5}$$

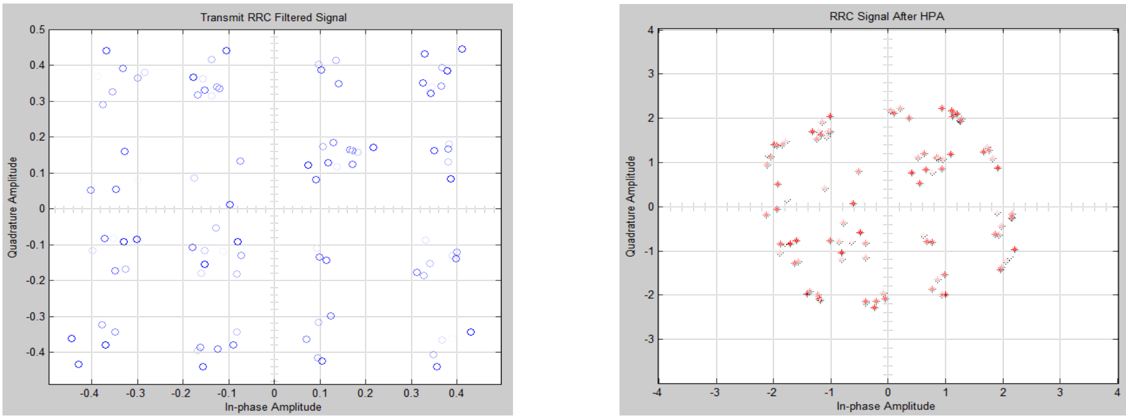
where $[x_1, x_2, x_3, x_4]$ are AM/AM parameters used to calculate amplitude gain for input signal A, and $[y_1, y_2, y_3, y_4]$ AM/PM parameters for phase change computation. In the Raap model (KrishneGowda et al., 2016), the smoothness factor, p, and the output saturation level, A_0, are used to calculate the amplitude gain for the input signal equation (6):

$$G(A)=\frac{A}{\left(1+\left(\frac{A}{A_0}\right)^{2p}\right)^{1/2p}} \tag{6}$$

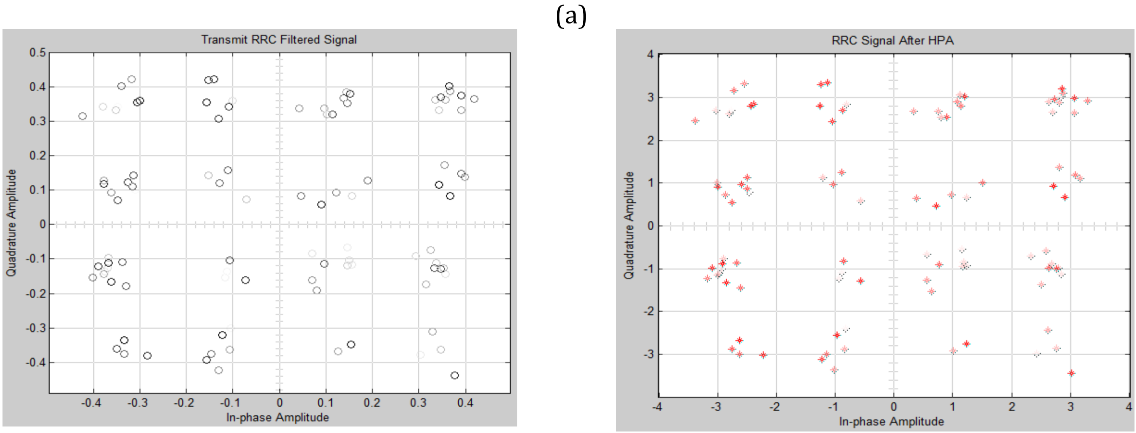
3. Results and Discussion

The simulation is performed for the following parameters: satellite altitude 35600 km, frequency 4 GHz, transmit antenna diameter 0.4 m, receive antenna diameter 0.4 m, phase noise 100 dBc / Hz. HPA nonlinearity is set to values of 30 dB for negligible, and 1 dB for severe. Phase noise is set to negligible (-100 dBc/Hz@100 Hz) and to severe (-48 dBc/Hz@100 Hz). Severe noise is high enough to cause errors even without thermal noise or other RF impairments. Figure 1 shows constellations for various analyzed nonlinearities. As can be seen, the figures on the right side of Figure 1 have higher amplitudes. Figure 1(a) shows 4.4 times magnification. Figure 1(b) shows around 7.7 times magnification. Figure 1(c) shows magnification of around 5, Figure 1(d) 4.8, and Figure 1(e) around 5. The figures on the right side look more clustered, but it could be a visual effect due to magnification. As can be seen in Figure 1, the real constellation looks different from the ideal case, which is expected. However, a different model results in a different deviation from the center of the cluster, i.e. the ideal arrangement of the constellation. The important question to be further explored is how large interference can be that leads to false detection of the transmitted signal.

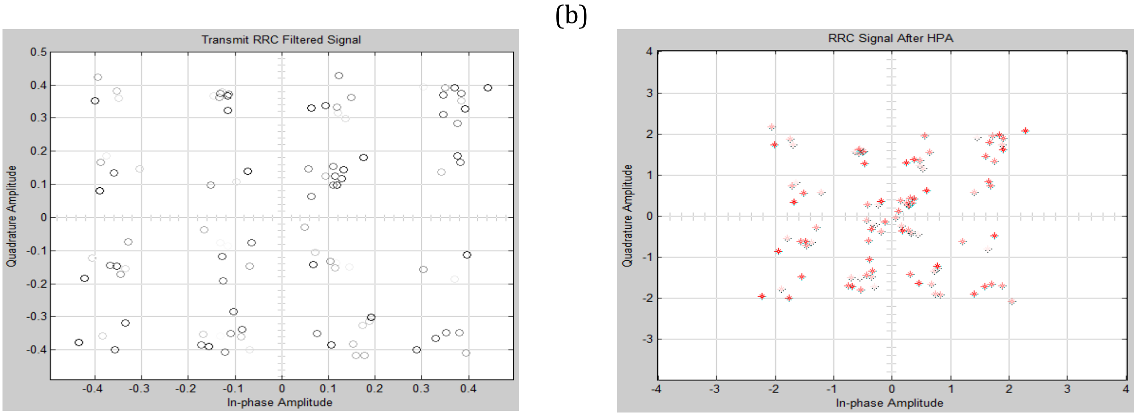
Figure 2(a) shows the input/output characteristics of HPA for various nonlinearities. It can be seen that the HPA characteristic is linear for Saleh, slow exponential growth is exhibited by Gharboani, and other models result in saturation (asymptotic behavior).



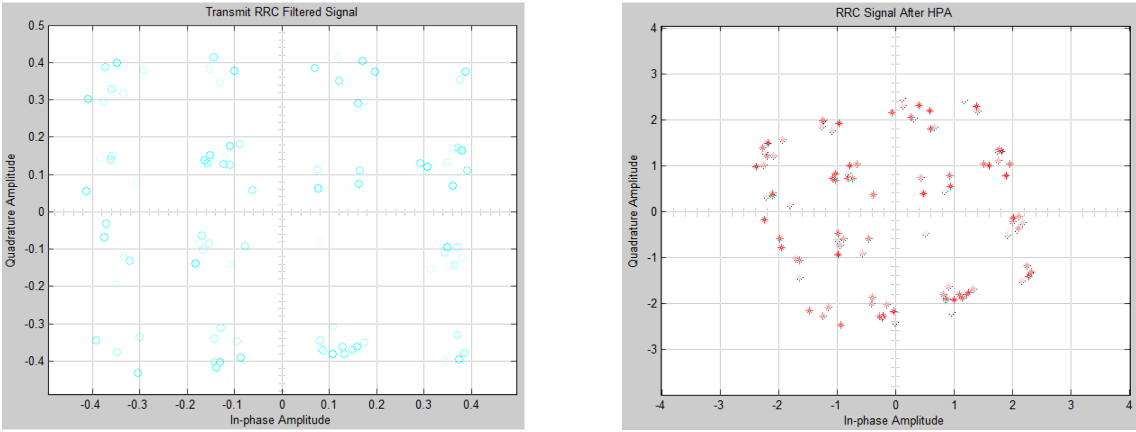
(a)



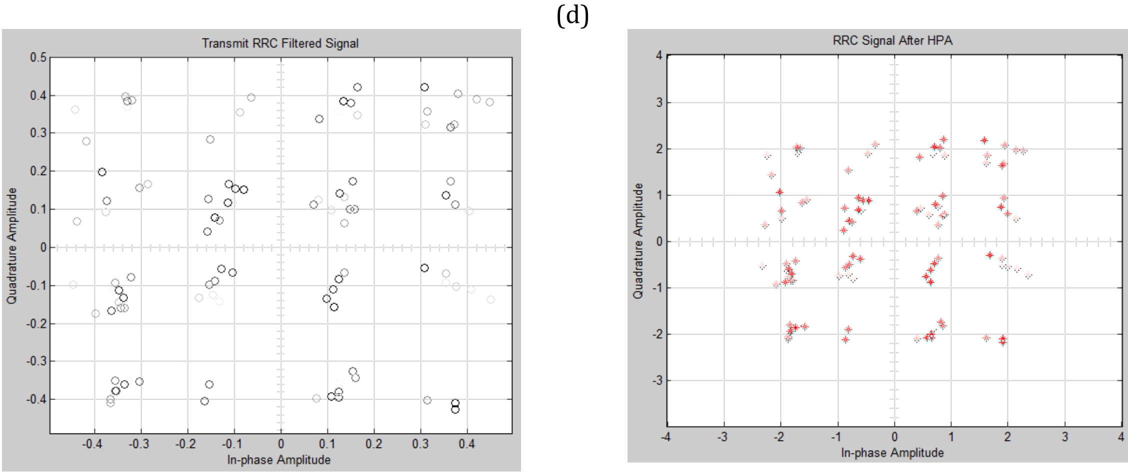
(b)



(c)

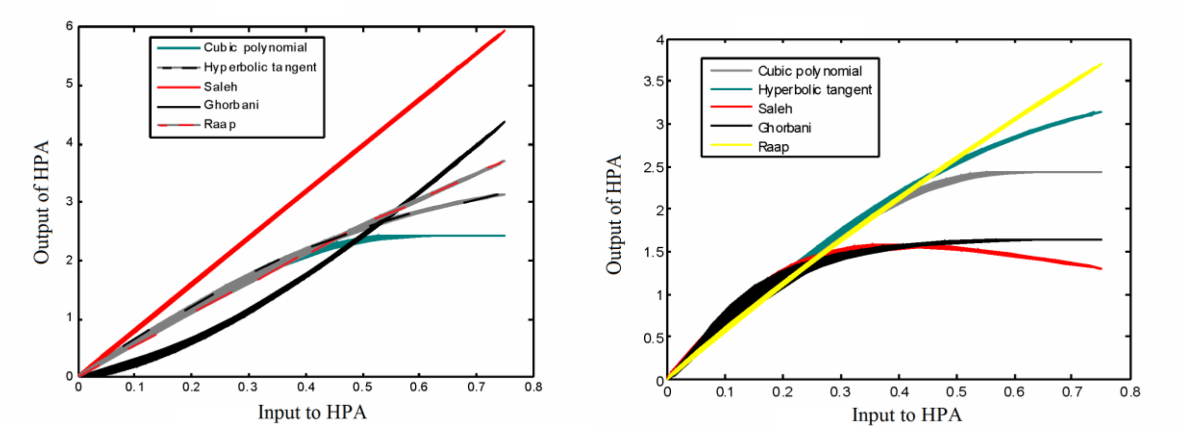


(d)



(e)

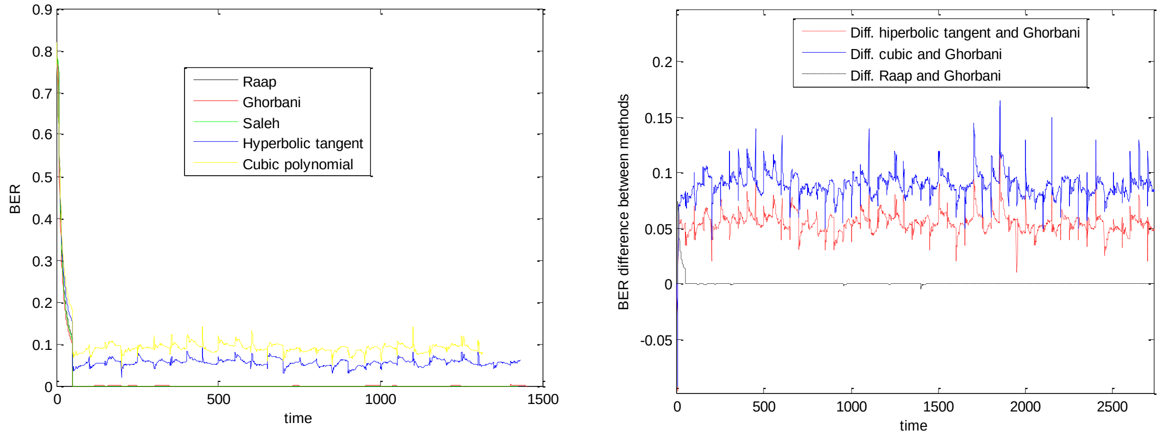
Figure 1 (continued) Nonlinearities in HPA: (d) hyperbolic tangent - constellation before (left) and after (right) HPA; and (e) Raap – constellation before (left) and after (right) HPA



(a) (b)

Figure 2 I/O characteristic of HPA for a) the first scenario, b) the second simulation scenario

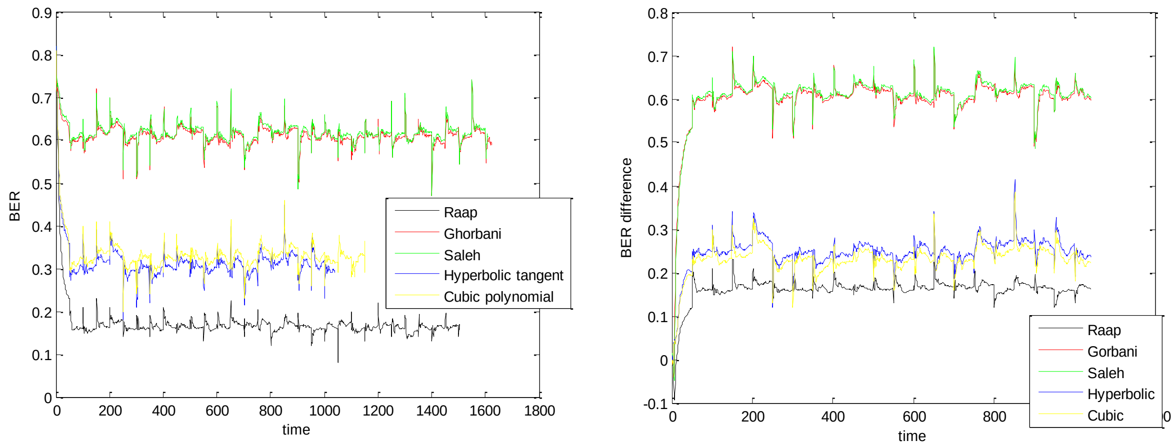
An example of BER for different models is shown in Figure 3 (a). Figure 3 (b) shows the difference between hyperbolic and Ghorbani, cubic and Ghorbani, and Raap and Ghorbani models. Noise is added to the simulation to show the changes in the presence of strong noise in the communication channel. For the following results, the simulation was performed with the following parameters: satellite altitude of 35600 km, frequency of 4 GHz, transmit antenna diameter of 0.4 m, receive antenna diameter of 0.4 m, noise temperature of 290 K, HPA backoff level 1 of dB, and phase noise of - 48 dBc / Hz. While the Saleh model can lead to a linear O/I characteristic, other models are nonlinear. Figure 3(b) indicates that the Raap and Ghorbani models have differences in BER only when they are not in a steady state, e.g. at the beginning in the time domain. Moreover, it can be seen that the calculation of BER leads to high values at the beginning and to non-deterministic values for the rest of the time.



(a) (b)

Figure 3 (a) BER for different models; and (b) difference of BERs for different models

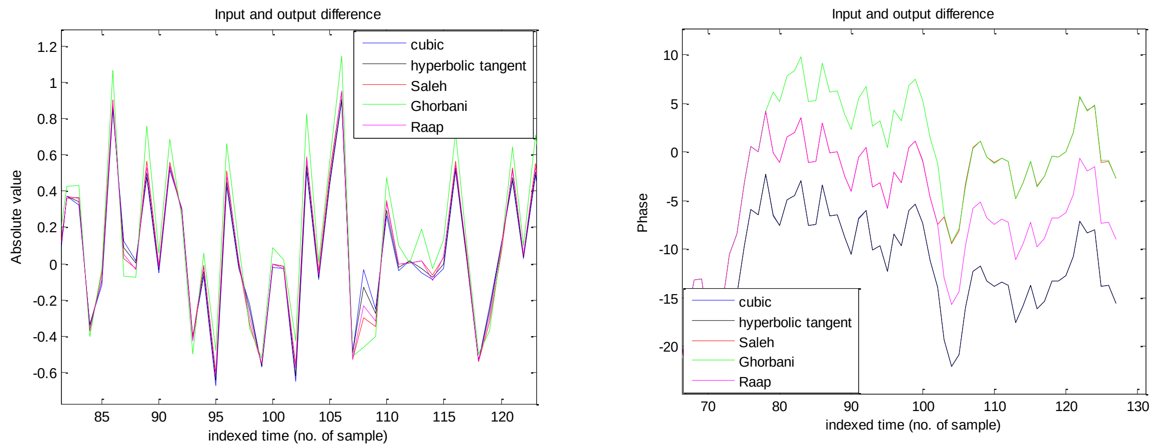
Figure 4(a) shows the BERs in the case of severe noise in the communication channel for all five models considered. It can be seen that the Raap model has the lowest BER, while Saleh and Ghorbani have the highest BERs. Figure 4(b) confirms the conclusions of model quality based on BER and shows BER differences for the low and high noise scenarios in the communication channel.



(a) (b)

Figure 4 (a) BER for the case of severe noise in the communication channel; and (b) BER difference for the same models with negligible and severe noise in the communication channel

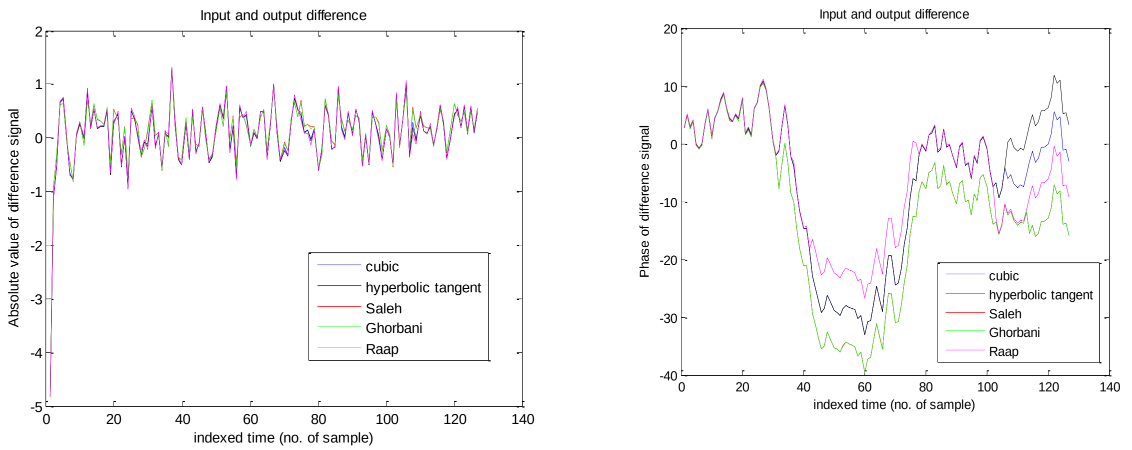
Figure 5 shows the simulation results for the input/output difference for the low noise case. Figure 5(a) shows the absolute value of the difference for all considered nonlinearities in the enlarged part. Figure 5(b) shows the phase diagram of the difference, enlarged part. It can be seen that the Ghorbani and Saleh curves have the same values at the last time point. The Saleh and Raap curves overlapped in earlier time periods. The hyperbolic tangent nonlinearity-produced curve overlaps with the cubic curve. It can be seen that differences are greater in the case of negligible than in the case of severe noise.



(a) (b)

Figure 5 I/O difference for negligible noise (a) absolute value; (b) phase

Figure 6 shows the difference between the input and output signals in the case of severe noise. Figure 6(a) shows the absolute value of the difference signal. Figure 6(b) shows the phase of the difference (I/O) signal for all 10,000 points.

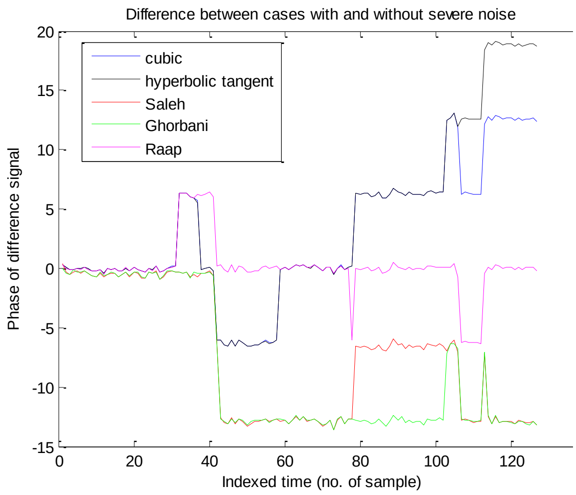


(a) (b)

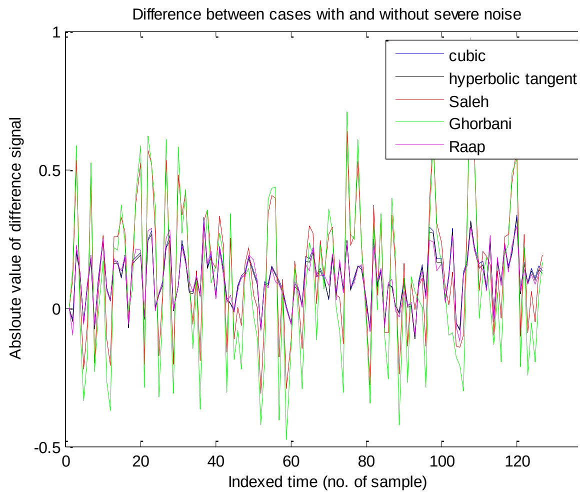
Figure 6 Input/output difference signal for the case of severe noise: a) absolute value, b) phase

Figure 7 shows the difference between cases with negligible noise and those with severe noise for the same type of nonlinearity. For example, the blue line in Figure 7(a) shows the difference between the phases of the considered cases for cubic polynomial nonlinearity. Figure 7(b) shows the absolute value of the difference between cases.

To check for possible dependencies between the results of the models used, we performed an ANOVA analysis. This analysis provides the P-value, the probability that the F-ratio is as large or larger than the observed one. In addition, the mean square (MS), degrees of freedom (df), and sum of squares (SS). The critical value of F (F_{crit}) is the value that represents the boundary between dependence and non-dependence between the data groups. The variation between groups accounts for the overall variation among each group's mean and the overall mean, while the variation within groups encompasses the total variation in individual values within each group and their respective group means.



(a)



(b)

Figure 7 Difference of I/O for two considered cases: (a) phase; (b) absolute value

As shown in Table 1, based on $F>F_{crtit}$, it can be concluded that there are no dependencies between all five models in the presence of negligible noise. In Table 2, it is evident that dependencies exist between the Saleh and Raap models under the condition of negligible noise.

Table 1 Results of ANOVA analysis for negligible noise for all considered models

Source of Variation	SS	Df	MS	F	P-value	F_{crit}
Between Groups	8.526003	4	2.131501	419.6638	0	2.373333
Within Groups	32.20129	6340	0.005079			
Total	40.72729	6344				

Table 2 Results of ANOVA analysis for negligible noise for Saleh and Raap

Source of Variation	SS	df	MS	F	P-value	F_{crit}
Between Groups	3.74E-05	1	3.74E-05	0.006367	0.936406	3.845128
Within Groups	14.90038	2536	0.005876			
Total	14.90042	2537				

Results in Table 3 show that $F>F_{crtit}$. Table 4 leads to the same conclusion that the data sets are not dependent on each other.

Table 3 Results of ANOVA analysis for severe noise for all considered models

Source of Variation	SS	Df	MS	F	P-value	F_{crit}
Between Groups	161,1764	4	40.29409	21130.53	0	2.373641
Within Groups	9.915948	5200	0.001907			
Total	171.0923	5204				

Table 4 Results of ANOVA analysis for severe noise for Saleh and Raap

Source of Variation	SS	Df	MS	F	P-value	F_{crit}
Between Groups	149.5105	1	149.5105	94969.92	0	3.844556
Within Groups	4.729176	3004	0.001574			
Total	154.2397	3005				

Table 5 Results of ANOVA analysis for severe and negligible noise for the Raap model

Source of Variation	SS	df	MS	F	P-value	F_{crit}
Between Groups	16.48115	1	16.48115	3699.667	0	3.845128
Within Groups	11.29729	2536	0.004455			
Total	27.77844	2537				

Since $F>F_{crtit}$, we can conclude that there is no correlation between severe and negligible noise in the case of the Raap model.

As shown in Table 1, based on $F>F_{crtit}$, it can be concluded that there are no dependencies between all five models in the presence of negligible noise. Table 2 shows that there are dependencies between Saleh and Raap when the noise is negligible. Table 3 shows that in the presence of severe noise, there are no dependencies for all models considered. Table 4 shows that there are no dependencies for Saleh and Raap in case of severe noise. Finally, Table 5 shows somewhat surprising results, as one would expect there to be relationships between different noise levels within the same nonlinearity model.

4. Conclusions

Change of a bit due to scattering in the received constellation could change e.g. coordinates of the target, which could be vital information. Figure 1 suggests that encoded words can be significantly altered. Therefore, the transmitted message can be misinterpreted. In our case, the participant (see the 3rd contribution in the Introduction) was employed in the military field. Hence, in his profession, the consequences could lead to influencing decisions in combat and consequently, since it is military communication, cost soldiers their lives. To further explore the issue and examine possible dependencies between the results of the models used, we performed an ANOVA analysis. Implications of existing dependencies could be that researchers will find a relation between them.

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