EFFECTS OF NON- LINEAR AMPLIFICATION ON N-GMSK AND N-FQPSK SIGNAL STATISTICS

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ABSTRACT

Digital modulation schemes that are power and bandwidth efficient are highly desirable. After non-linear amplification has been done, signal modulation schemes having constant or quasi-constant envelopes are not as susceptible to spectral regrowth as those with non-constant envelopes. Since such distortion generates interference in the adjacent channels, the power operation of the amplifier in non-constant envelope modulations is typically backed off, resulting in systems with reduced power efficiency. On the other hand, constant envelope modulation may have different bandwidth spectra. This paper examines the statistical characteristics of N-GMSK and N-FQPSK [1] signals to assess the bandwidth efficiency in the presence of amplifier nonlinearities.

KEYWORDS

Modulation, bandwidth efficiency, constellation, non-linear amplifier.

INTRODUCTION

In analog radio, interference in adjacent channels is modeled by the third order intermodulation product of discrete tones generated by nonlinearities in the amplifier. The design of RF amplifiers is constrained by maximized output power and restriction of out of band emissions. To prevent emissions, the amplifier is operated in the linear region and the power is backed off, which limits the power conversion efficiency.

On the other hand, in digital radio, characteristics of the amplifiers also play a role in the spectral regrowth of the different modulations. Non-constant envelope modulations experience spectral regrowth, while constant envelope modulations are considered less sensitive. The use of a nonlinear amplifier achieves better power efficiency, which is critical in a power-limited transmitter. To quantify the spectral regrowth due to nonlinear amplification, the previous intermodulation product model is not applicable to the digital modulation case. Digital signals are characterized by their statistical properties.

A qualitative tool for estimating the effects of non-linear amplification over modulation is the Peak-to-average ratio (PAR). The higher the PAR, the more the modulation is likely to suffer spectral regrowth. Based on this criterion, O-QSPK was selected for the IS-94CDMA reverse-link and the IS-95 CDMA forward-link standards, respectively. However, this measurement does not adequately assess the possible spectrum expansion due to the non-linear amplification. In fact, QPSK with higher PAR than O-QSPK experiences less regrowth. The explanation lies in the statistical properties of the signal, which determine the level of distortion caused by the non-linear amplifier [2]. Research has focused on predicting the Adjacent Channel Power Ratio (ACPR), defined as the power in the main channel divided by the power in the adjacent channels, from the input signal statistics [3].

For a single amplitude (N=1), GMSK has a constant envelope, and FQSPK has a quasi-constant envelope. For this reason, they are not very sensitive to the effects of non-linear amplification. Despite the fact that FQPSK is quasi-constant and should experience some level of regrowth, it has better bandwidth efficiency than GMSK [4]. This constant envelope characteristic is lost for an N-amplitude combination signal constructed after modulating an independent data stream with these schemes. Although the new signal increases the data rate per Hz of spectrum, since it has no constant envelope it will experience some regrowth and distortion under non-linear amplification. In this paper we study the constellation, statistical parameters such as mean, standard deviation, skewness, curtosis, power envelope complementary cumulative envelope distribution function (CCDC), and power spectral density of two modulations: N-GMSK [5] and N-FQPSK signals with an N values amplitude combination.

METHODOLOGY

The simulation study follows the schematic of Figure 1 using the Matlab software packet to generate random data, baseband modulated signal, signal output after filtering, and signal output after non-linear amplification. After amplification, the original signal is modified. To quantify this modification, we calculate the following characteristics:

1. Constellation diagram
2. Statistics parameters:

a) Mean Power, $P_{ave} = E\,[P_i]$, E stands for expected value. In practice, it is taken as the average of the sequence; $\sum P_i$ / # of observations

b) Peak-to-Average ratio, $PAR = P_{max} / P_{ave}$

c) Standard Deviation or root-mean-square deviation, $\sigma = \sqrt{Var}$ where Var is the variance σ^2, also known as second moment (μ^2) about the mean E [X] and it is given by $Var = \sigma^2 = E\,[(P_i - P_{ave})^2]$. It is a measure of the dispersion. A large value suggests a large dispersion, while a small value suggests that the individual values cluster together.

d) Skewness: It is defined as the ratio between the third moment about the mean E [X] and the third power of the standard deviation. It measures the symmetry of the distribution. A positive skewness means that the positive tail is larger. A negative skewness means that the negative tail is larger.

$$S = \mu^3/\sigma^3 = \frac{E[(P_i - P_{ave})^3]}{(\sigma^2)^{3/2}}$$

e) Kurtosis: $C = \mu 4/\sigma^4 = \frac{E[(P_i - P_{ave})^4]}{\sigma^4}$. It determines the peakness of the distribution. The normal distribution has c = 3.

f) Complementary Cumulative Distribution Function (CCDF) [5]. This is a statistical tool to assess the probability that a given value of PAR occurs. Crest factor, another parameter used and defined as the peak power versus the root-mean-square value, describes an extreme occurrence but it does not indicate how often this event arises. The shape of the CCDF can quantify the amount of time the signal hits peak values and is likely to be compressed by the non-linear amplification. If there is no high occurrence of peak values, the signal might tolerate some clipping effects without greatly increasing the bit error rate. Another consequence of the compression effect is the creation of harmonic terms in the adjacent frequency channels. The level is measured by the ACPR. The FCC regulates this parameter. The amplification of the signal may be backed off, either to reach a desired bit error rate performance or to not exceed ACPR specification in the area.

3. Power Spectral Density

The simulation generates 25000 random data. Each digital data is modulated according to the proper modulation scheme, either GMSK or FQPSK. Each symbol is sampled 16 times. The total number of points processed is 25000x16. The simulation is carried out in baseband. For the simulation we use an interpolation expression that describes the input-output characteristics of a Class AB type amplifier. Figure 2 shows the gain and phase of the amplifier versus input power. We specify relative values for the N-levels as 2^N and we modify the actual range of input power values obtained to adjust to the range of input power values of the graph of the amplifier used.

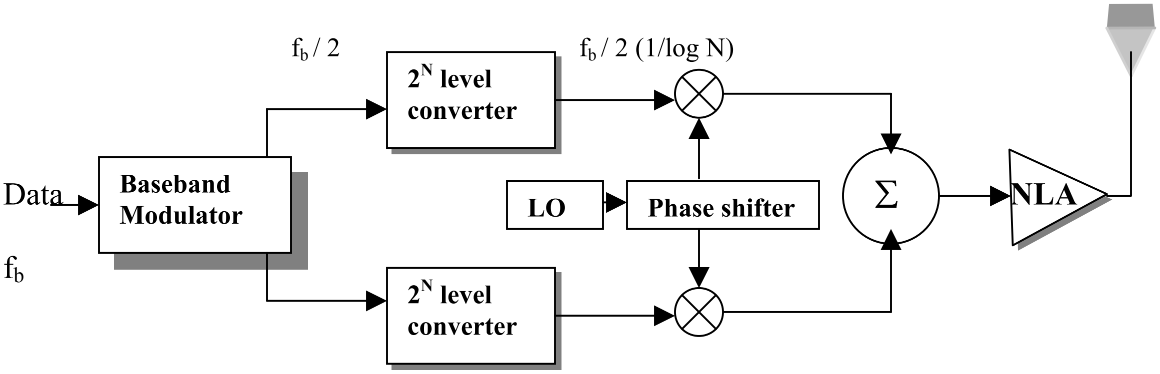


Figure 1 Block diagram of the simulation

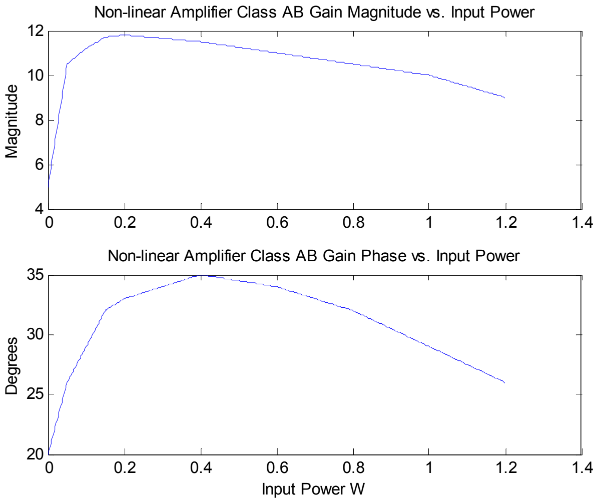


Figure 2 Magnitude and Phase of a Class AB amplifier

SIMULATION RESULTS

The characteristics of the power envelope of a modulation scheme and the trajectory among the different power states generated can be analyzed through the constellation diagram. Figures 3 and 4 shows the constellation for N-GMSK and N-FQPSK signals.
As we increase the number of levels, the number of possible power states increases and the trajectories between states get more diversified. By choosing exponential values of 2, we can get combinations up to 4 signals in which some level of opening is maintained as is also presented on [5]. A combination of values of 2, 4, 6 and 8, for example, will close the opening for a combination of just three levels. The opening for a 4-level combination signal may be enlarged by choosing a proper value for the 4th level, as is shown in Figures 3 and 4. The larger the opening, the smaller is the dynamic range of the amplifier and the less the demand for operating in the linear range of the amplifier. We can observe that the behavior of both modulations is very similar. N-FQPSK constellations tend to be blurrier since the modulation has more envelope variation than

N-GMSK. The constellation after the non-linear amplifier is slightly rotated from the one before amplification. The phase relation between I and Q branches has been modified.

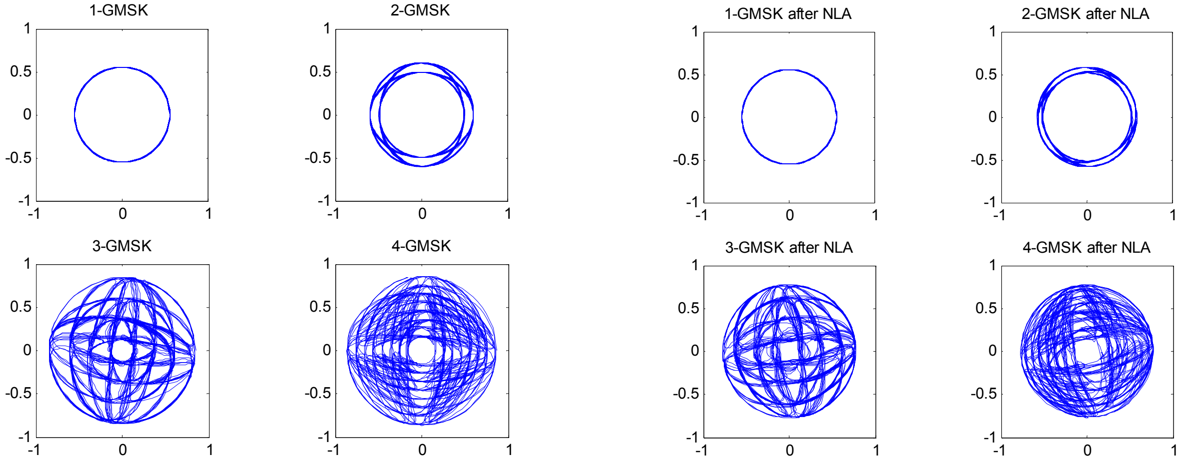


Figure 3. N-GMSK constellation for N= 1, 2, 3, and 4 level combinations with different amplitudes. N=1 uses amplitude 1, N= 2 uses 1 and 8, N=3 uses amplitudes 1, 2, 4, and N= 4 uses amplitudes 1, 2, 4, and 10 mV respectively. By using 10 mV the opening for N = 4 is enlarged from the case of using 8 mV for the last level.

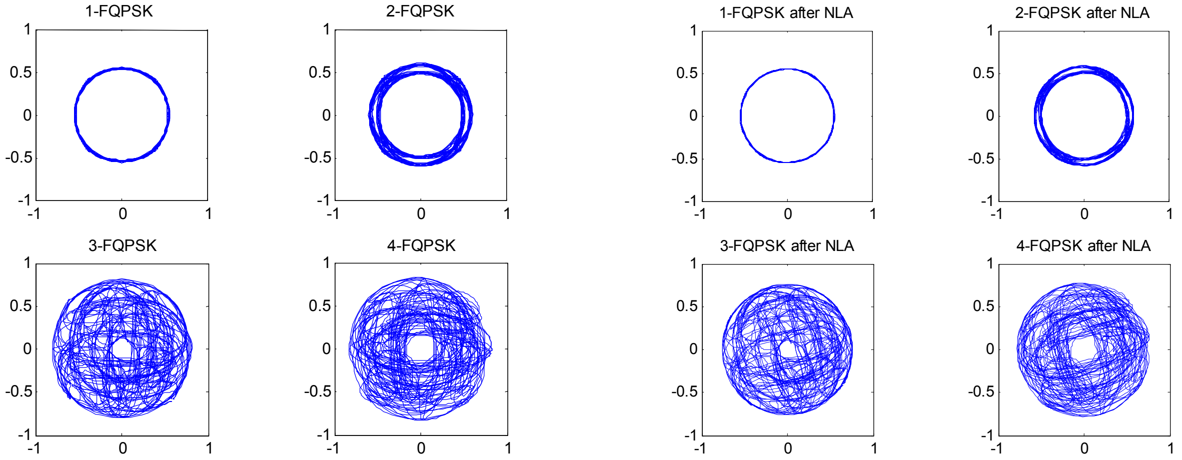


Figure 4. N_FQPSK constellation for N= 1, 2, 3, and 4 level combinations with different amplitude. N=1 uses amplitude 1, N= 2 uses amplitudes 1 and 8, N=3 uses amplitudes 1, 2, 4, N= 4 uses amplitudes 1, 2, 4, and 10 mV respectively. By using 10 mV the opening for N= 4 is enlarged from the case of using 8 mV for the last level.

Tables 1 and 2 shows the statistical parameters calculated for N-GMSK and N-FQPSK before and after the non-linear amplification for this specific simulation study. Since this is a stochastic process, the results will vary, depending on the length of the sequence and run. We can make some observations based on the trend. As the number of levels is increased, the PAR value is increased, indicating a larger dispersion, as is also more explicit in the high values of the standard deviation. After the non-linear amplification, the PAR values are reduced due to the reduction of the range of variation, which is due to the compression effect of the amplifier. The small values in the skewness indicate a high level of symmetry. The curtosis are positive but the tail are less fat that the one of a normal distribution except for the case of N=1

Table 1

N=1 uses amplitude 1, N= 2 uses amplitudes 1 and 2, N=3 uses amplitude 1, 2, 4, and N= 4 uses amplitude 1, 2, 4, and 8 mV respectively.

N-GMSK	**N = 1**		**N = 2**		**N = 3**		**N = 4**	
PARAMETER	Before NLA	After NLA	Before NLA	After NLA	Before NLA	After NLA	Before NLA	After NLA
PAR	1	1	1.7	1.6	2.5	2.1	2.6	2.2
STANDARD DEVIATION	0	0	3.4	29.7	14.5	138	59.1	575.3
SKEWNESS	INF	INF	-0.03	-0.16	0.57	0.27	0.6	0.32
CURTOSIS	INF	INF	1.23	1.24	2.1	1.82	2.3	2.5

Table 2

N-FQPSK	**N = 1**		**N = 2**		**N = 3**		**N = 4**	
PARAMETER	Before NLA	After NLA	Before NLA	After NLA	Before NLA	After NLA	Before NLA	After NLA
PAR	1.16	1.06	2.1	1.79	2.7	2.3	3.0	2.54
STANDARD DEVIATION	0.03	0.23	2.9	28	13.9	139	54	557
SKEWNESS	-3.5	-8.3	0.003	-0.16	0.49	0.26	0.73	0.45
CURTOSIS	44	131	1.52	1.51	2.05	1.8	2.7	2.27

Figure 5 shows the CCDC curves for N-GMSK and N-FQPSK. As N increases, the knee of the curve moves toward higher peak power values for the same probability of occurrence. The fact that the peak value above the mean is less for a given probability also has a favorable performance in terms of ACPR. Comparing the graphs of both modulations, they are very similar. Considering the 0.1 % probability and the 3-level signal, the peak values reach above 4 dB higher than average for the N-GMSK and N-FQPSK. However, the N-FQPSK reaches higher peak than N-GMSK at a much smaller probability value. This suggests that it might need a slightly higher dynamic range in the amplifier. The CCDC curves for the amplified signal shows the effect of the compression by moving the plots toward smaller dB value for a given probability.

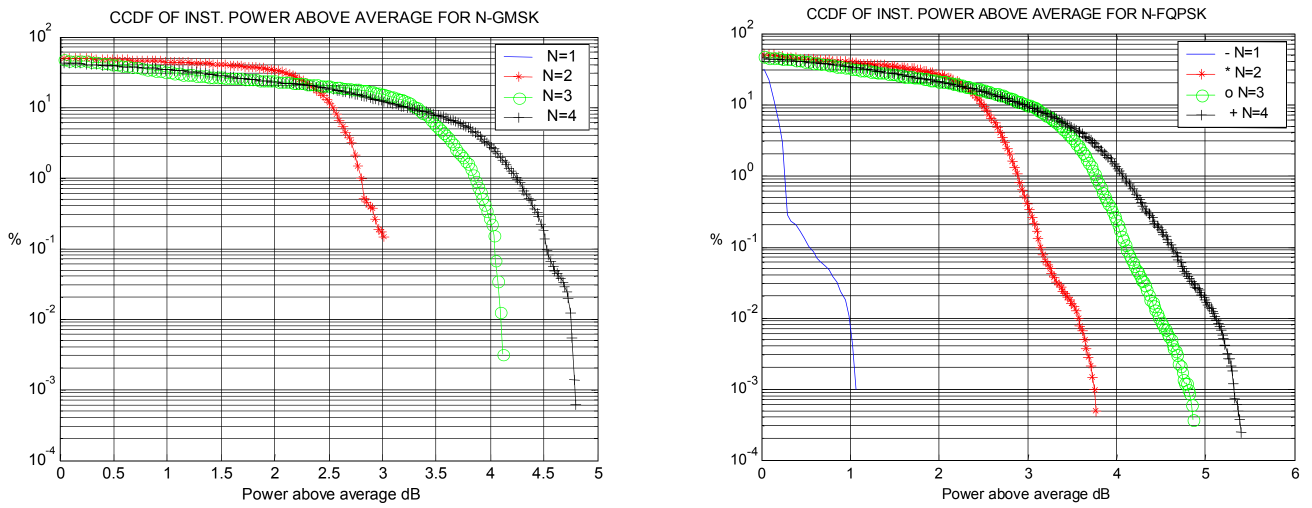
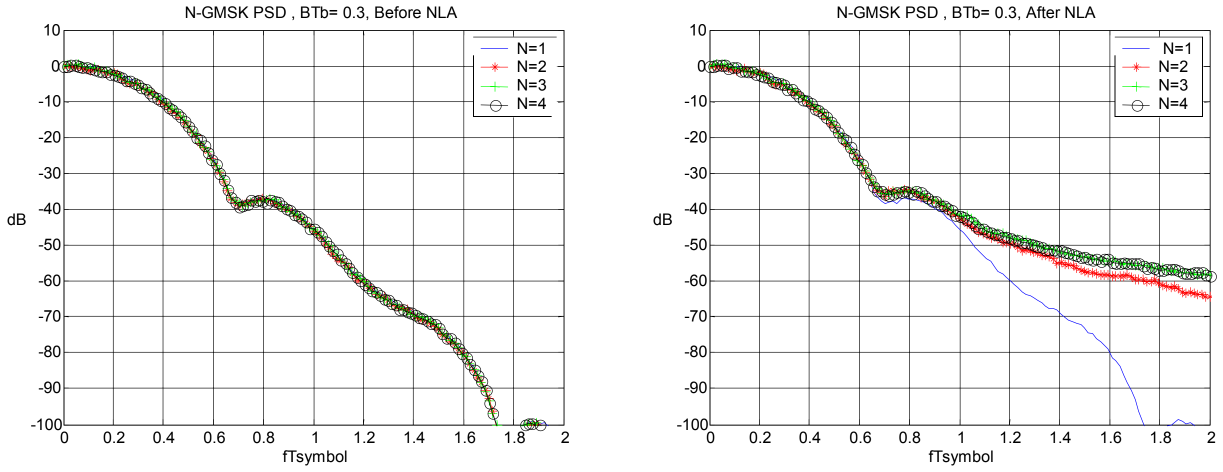


Figure 5. CCDF of instantaneous power above average for N-GMSK and N-FQPSK for N= 1, 2, 3, and 4 signals combination. N=1 uses level l, N= 2 uses level 1 and 2, N=3 uses level 1, 2, 4, N= 4 uses level 1, 2, 4, and 8 mV respectively.

The power spectral density for these two modulations is shown on Figure 6 versus frequency in unit of fTsymbols. As the N increases, the power spectral density is wider due to the regeneration of harmonics created by the nonlinearity of the amplifier. However, since as N increases more bits are transported per Hz, the bandwidth efficiency or bit/Hz is improved. Although for N= 1, the power bandwidth of N-FQPSK is narrower, as the N increases the power spectral density of both modulation are more alike. At fTsymbol = 2, the normalized spectrum is –60 DB for both modulation and N=3 and 4 levels. The N-FQPSK, for N >1, experiences more relative regrowth than the GMSK counterpart, which was not apparent in the CCDC curves for the particular. For example, for fTsymbol=1, and N=2 using amplitude 1 and 2, the power density is between 10 and 20 DB larger than before amplification depending on the BTb of the filter. In 2-GMSK and fTsymbol=1, the power density is comparable to the value before amplification. The value is still above the 2-FQPSK.



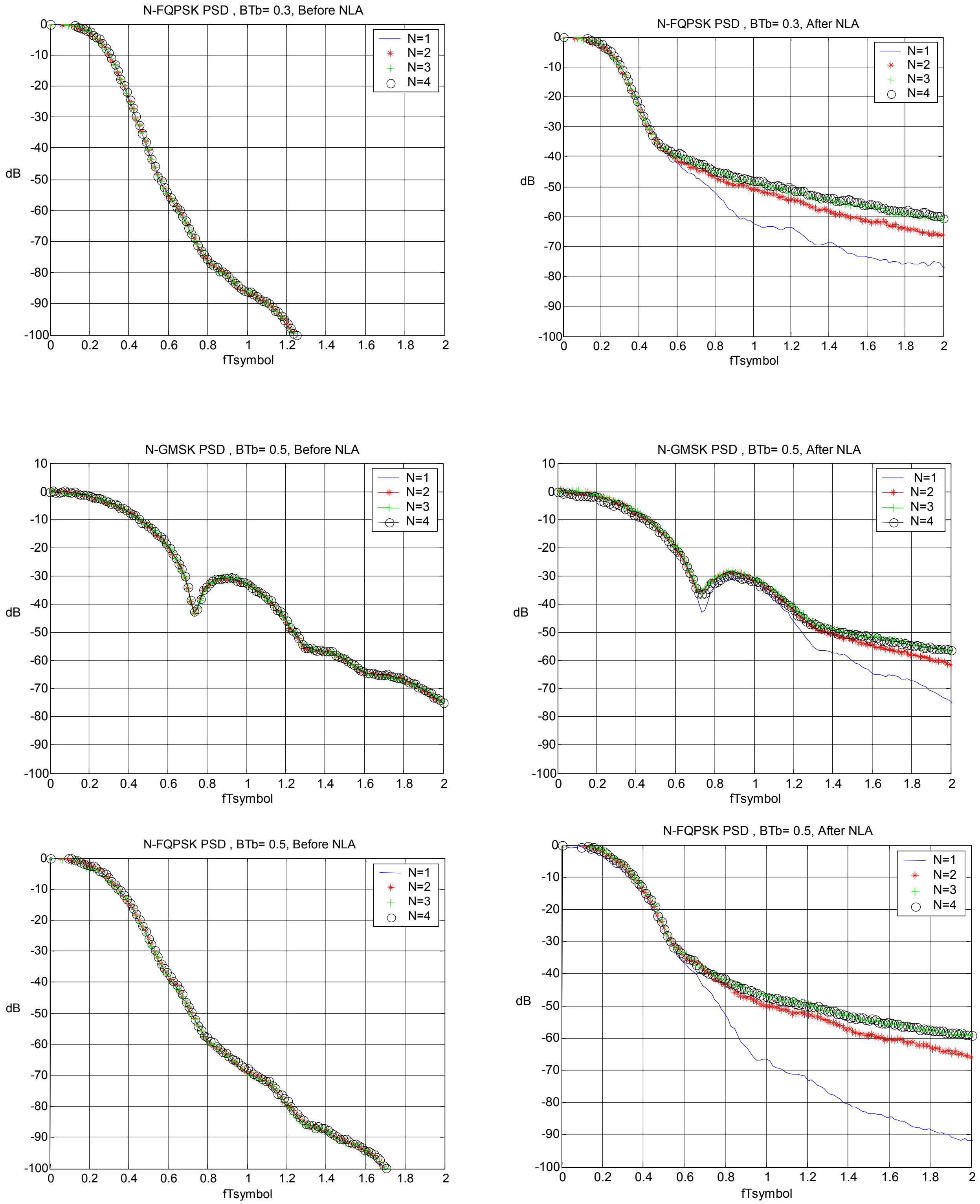


Figure 6. Power spectral density for N-GMSK and N-FQPSK for N=1, 2, 3, and 4 levels combination with amplitude of 1, 2, 4, and m8 V respectively. N=1 uses amplitude l, N= 2 uses 1 and 2, N=3 uses level 1, 2, 4, N= 4 uses level 1, 2, 4, and m8 V respectively.

CONCLUSIONS

N-GMSK and N-FQPSK for N range from 1 to 4 levels, 2^N amplitude range pattern, are generated and the characteristics of the power envelope have been analyzed after non-linear amplification. These signals offer higher spectral efficiency since they increase the bit/Hz ratio, but they undergo some level of spectral regrowth and distortion when non-linear amplified. The constellations for these two modulations (and up to 4 levels) show that the power envelope does not pass through zero, eliminating the need of an extremely high dynamic range in the amplifier. The desired BER performance and/or the required ACPR will determine the required back-off power of the amplifier. CCDF curves shows that the probability of a given peak value above the mean are alike in both modulations. As N increases, the signal from both modulations experiences higher peak values for the same probability of occurrence. These values can be used to assess the degree of tolerated clipping and the operation of the amplifier. The power spectral density for N-GMSK and N-FQPSK for N>1 experiences a level of regrowth. Although the power spectral density for N-FQPSK for N >1 seems to experience more spectral regrowth than the corresponding N-GMSK when compared to the value before non-linear amplification, it still has a narrower bandwidth than GMSK.

REFERENCES

[1] Feher, K. et. al., US Patents: 6,470,055, 4,339,724, 4,339,724; 4,567,602; 4,644,565; 5,491,457; 5,784,402; 6,198,777. For additional information contact Kamilo Feher, DIGCOM Inc., 44685 Country Club Drive, El Macero, CA, 95618, USA, Tel. (530) 753-0738, FAX: (530) 753-1788, e-mail: feherk@yahoo.com

[2] Sevic J. F. and M.B. Steer, "On the Significance of Envelope Peak-to-Average Ratio for Estimating the Spectral Regrowth of and RF/Microwave Power Amplifier", IEEE Transactions on Microwaves Theory and Techniques, Vol. 48, N0. 6, June 2000.

[3] Gard K. G., H.M.Gutierrez, M.B.Steer, "Characterization of Spectral Regrowth in Microwave Amplifiers Based on the Nonlinear Transformation of a Complex Gaussian Process", IEEE Transactions on Microwave Theory and Techniques, Vol 47, N0. 7, July 1999.

[4] Gonzalez, M.C., “The case of mismatched filter in FQPSK-B and GSM”, International Telemetry Conference, Las Vegas, 2003.

[5] Javornik, T., G. Kandus, and A. Burr, “The performance of N-GMSK signals in non-linear channels”, htpp://www.elec.york.ac.uk/comms/papers/burr01_wpmc.pdf

[6] “Characterizing Digitally Modulated Signals with CCDF”, Agilent Technologies Application Note. http://www.agilent.com