Buletin Teknik Elektro dan Informatika
(Bulletin of Electrical Engineering and Informatics)
Vol. 3, No. 3, September 2014, pp. 161~172
ISSN: 2089-3191

Feedback Linearization of RF Power Amplifier for TETRA Standard

Asif Ahmed
American International University Bangladesh
83/B, Road 4, Banani, Dhaka, Bangladesh, Tel: +88028811749 Ext: 278
e-mail: aahmed@aiub.edu

Abstract

In wireless transmission systems, non-ideal response of different functional components along with power amplifier's nonlinearity plays a major role in degrading the transmitter performance. Several parameters defines the performance of a wireless transmitter, such as adjacent channel power ratio (ACPR), error vector magnitude (EVM), spectral mask, etc., and the effect of non-ideal behaviour of the transmitter affects these parameters. For many standards these parameter specifications are defined such that the concern for transmitter linearization is very much relaxed. Standards like Terrestrial Trunked Radio (TETRA) specify strict regulation on these parameters. Therefore, the requirement of linearity is a great challenge for the design of the transmitter. Many linearization schemes is available for linearizing the nonlinear effect of a transmitter, and among those the Cartesian feedback technique is a well known concept for linearization of transmitter operating according to TETRA standard, as well as employing a narrowband operation. In our research, distortion effect of the transmitter has been analysed, and a practical demonstration of the linearization effect over distortion has been implemented using the Cartesian feedback concept.

Keywords*: Linearization, Base station,RF power amplifier, TETRA*

1. Introduction

Radio frequency (RF) communication has surged in the recent years. Research activities in the area of RF communication have become very popular. In response to the demand of efficient, high data rate transmitters, research on commercially applicable transmission system has got massive attention. Given the market demand for a flexible and user-friendly transmitting device, meeting the technical challenges within the radio standard requirements is an important aspect of communication performance. Every communication standard has its own specification of performance metrics and definitions of transmission parameters. Any implementation and organization of transmission system needs to follow the standard specific parameter-definitions. Therefore, in order to construct a transmission concept or implement any transmission system, full standardization of overall transmission system is needed according to the requirement.

Designing a transmission system concept with ideal transmit components involves less concern as to the conformance to the standard. Non-ideal transmit-path components introduce distortions to the ideal transmit signal, and these distortions produce spectral components that are beyond the allocated bandwidth. Any counter measure used for eliminating these non-idealities from the transmit-pathis called linearization.

In a traditional wireless communications chain, radio functions were typically discrete components constructed together to form an overall radio transmitter. Nowadays, the various radio functions are often integrated together to make the signal chain more compact. In recent times, we see transmission system consisting of fully integrated baseband signal processing and RF functional units; as a result we have commercially available discrete building blocks for the overall transmission system. Despite these entire components working together for a reliable transmission of signal, the non-ideal behaviour of different functional units may cause major distortion at the output of the system.

Received April 10, 2013; Revised June 3, 2014; Accepted June 20, 2014

Signal distortion is by definition an unexpected change in the form of a signal which causes degradation of the signal quality during transmission. Distortion can occur at different stages of transmitter, such as in the baseband signal generator, filtering, RF modulator, power amplifier, etc. The major portion of the distortion is caused by the RF power amplifier (PA) which is a final-stage active component of the system. The quality of the signal needs to be as ideal as possible at the output of the PA as it is considered as the final output of the transmitter. In most of the literature about linearization, RF power amplifier has been assumed to be the only nonlinear component of the transmitter. As the power amplifier shows very significant nonlinearity for high power applications, much of the linearization work has been done to eliminate the effect of nonlinearity.

When we do not have any linear relationship between the baseband signal and the envelope of the output signal of the transmitter, then we can consider the system components, in between, as a nonlinear block. The nonlinear block introduces distortion to the expected signal, and produces unwanted frequency components adjacent to the allocated bandwidth. In order to transmit any signal, we need to linearize the nonlinear blocks of the transmitter. All of the block-components do not necessarily contribute to the distortion; rather few inherently nonlinear or marginally linear components are responsible for the overall distortion of the signal. Therefore, any scheme that might be developed for linearization should only consider the effect of the nonlinear components.

We need to linearize all the nonlinear parts of the transmitter in order to obtain perfect signal at the output, and, in doing so, we are linearizing the overall transmitter. Thus, we can consider transmitter linearization as a basic requirement before putting any transmission system in operation.

2. The Proposed Method

The primary objective of this research is to survey several design methods for linearization of power amplifiers and associated transmitter components, describe the effect of nonlinear distortion, and demonstrate the Cartesian Feedback architecture as a very suitable method for TETRA standards.

A major part of this research was involved with the linearization of an RF power amplifier with Cartesian Feedback, as well as calibration of other nonlinear components to obtain an overall linear transmitter. The design of a Cartesian loop involves the design of a complete transmitter; therefore, the design of Cartesian loop and methods like it are referred to as transmitter linearization technique.

The research involves proper diagnosis of discrete transmitter blocks and nonlinearity around it. Analytical description of the nonlinear distortion along with the corrective measures is presented that leads us to conceptual physical layer interpretation. Several modification algorithm and mechanism are shown in order to counter nonlinearity. Furthermore, theoretical and practical implementation criterion and limitations were suggested for proper design of transmitter as well as linearization mechanism around it.

In addition to the theoretical analysis of the nonlinear transmitter along with an analytical solution, an implementation of a linear transmitter with Cartesian feedback loop was presented to experience nonlinear distortion around the transmitter as well as to find a proper solution to be implemented in a real-time development of a transmission system.

3. Research Method

Negative feedback is widely used in circuit design to reduce the effects of distortion in amplifiers as well as sensitivity to process variations, temperature drift, and other parameters that may affect the behaviour of an amplifier.

Figure 1 shows implementation of negative feedback around a nonlinear amplifier. In the forward path we have an amplifier gain block$A$, and the feedback path has attenuation block with gain$\frac{1}{k}$. The subtracter is signal subtracter of unity gain [1]. Due to the negative feedback the error-signal $x_e(t)$ will be generated from the subtracter for an input signal, $x(t)$. After being amplified the output signal is given by $Ax_e(t)$. Reference signal for the subtracter is produced by the feedback path by attenuating the output signal, and given by,

$$y_r(t) = \frac{y(t)}{K}.$$

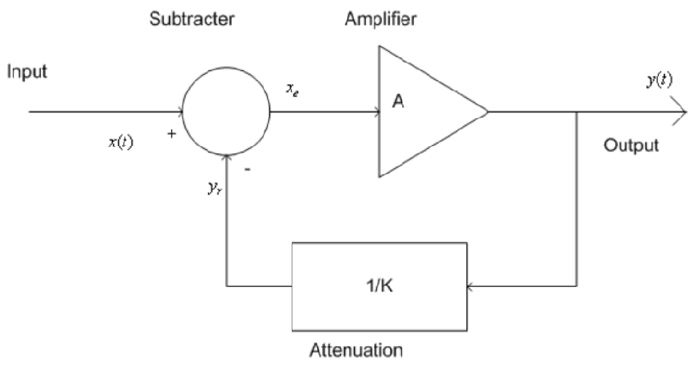


Figure1. Basic Feedback System

The error signal $x_e(t)$, can now be defined as

$$x_e(t) = x(t) - y_r(t).$$

Therefore, we may write, $y(t) = \frac{KA}{K+A}x(t)$.

In order to analyze the effect of nonlinearity and distortion, the distortion component,$d(t)$, can be added in a summing junction in the forward path. Figure 2 shows the addition junction in the forward path.

From the previous analysis of nonlinear distortion, we may define the distortion, $d(t)$, as a function of input of the amplifier,$x_e(t)$:

$$d(t) = f\{x_e(t)\}.$$

Adding this distortion component to the output signal, we obtain:

$$y(t) = Ax_e(t) + f(x_e(t))$$

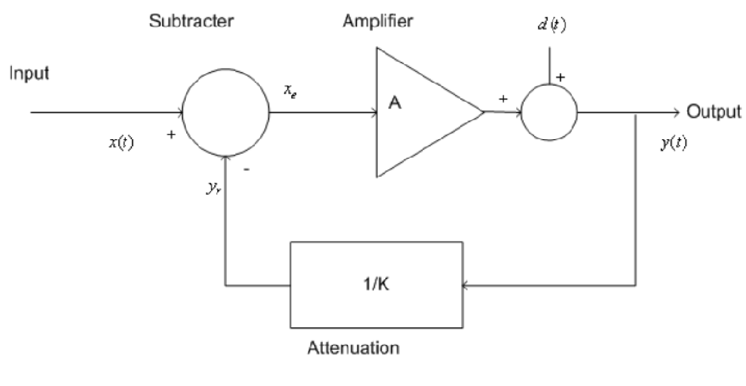


Figure 2. Feedback System with Distortion

Therefore, the output signal can now be represented by,

$$y(t) = \frac{KAx(t)}{K + A} + \frac{Kf\big(x_e(t)\big)}{K + A}.$$

Therefore, from the above equation we can see that the amplifier distortion is reduced by the factor $\frac{x(t)}{x_e(t)}$.

3.1. Cartesian Feedback-Loop Transmitter

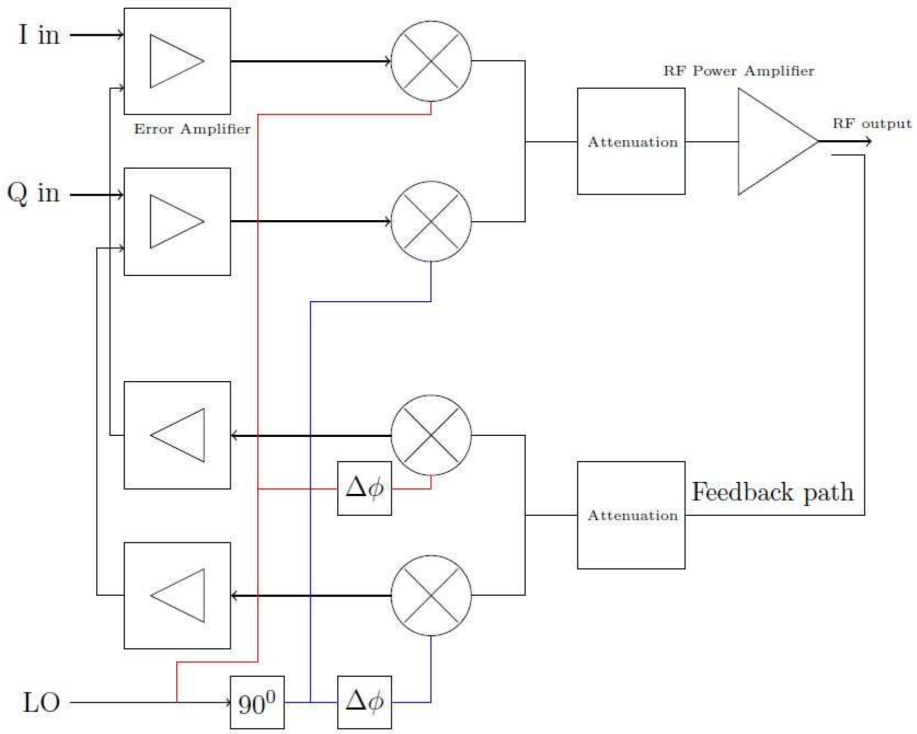


Figure 3. Cartesian loop implementation.

The Cartesian loop technique [1]-[12], first developed and implemented in 1980s, is now treated as a superior form of modulation feedback transmitter. It is called Cartesian feedback because the feedback is based on the Cartesian coordinates of the baseband symbol, I and Q, as opposed to the polar coordinates. This is widely used in highly efficient transmitters to solve the nonlinearity issue. The Cartesian feedback loop can work with different modulation schemes, such asπ/4-DQPSK, QAM, etc. It is widely utilized in transmitters with TETRA standard requirements.

In Figure 3 [12], a block diagram of a Cartesian feedback-loop is shown. We apply two identical feedback processes operating independently onthe I and Q channels. The inputs are applied to the differential input amplifier with the resulting difference (error) signals being modulated onto I and Q sub-carriers, and up-converted to drive the power amplifier. We take a portion of the output of the power amplifier using a directional coupler, decouple the signal, and down-convert it into I and Q signal to independently feed these back to the respective I and Q error amplifiers. A phase shifter in the up-converter local-oscillator path is used to align the phases of the up-and down-conversion processes, thereby ensuring that a negative feedbacksystem is created, and that the phase margin of the system is optimized [13].

3.2. Analysis of Cartesian Feedback-Loop

The Cartesian loop consists of two independent feedback loops. We can analyze the Cartesian loop system with feedback theory. A typical Cartesian loop is shown in Figure 4 with error amplifier, mixer, loop filter and power amplifier in the forward path, and with a feedback attenuator, and down-conversion mixer in the feedback path. The$I$ and$Q$ channel may be analyzed separately [1]. For the I-channel let us consider the input signal to the error amplifier to be$X_I(s)$, and set the$Q$-channel input to be$X_Q(s) = 0$. The open-loop output signal can be written as:

$$S_{out}(s) = X_I(s)F_1(s)M_1(s)A(s) + D(s).$$

where$F_1(s)$ represents the filter gain, $M_1(s)$represents modulation gain, and $A(s)$is the gain of RF power amplifier. The additive term D(s) represents distortion added by the power amplifier.

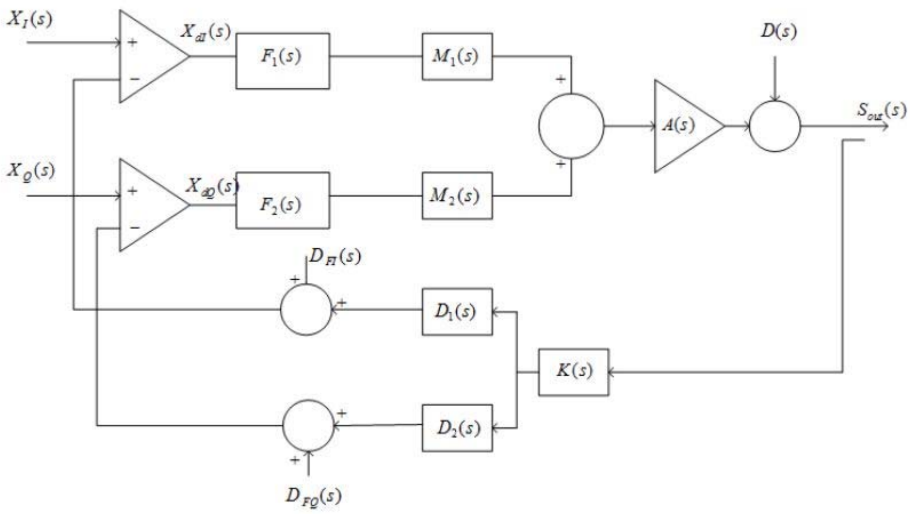


Figure 4. Feedback Analysis of Cartesian Loop

The closed loop expression of the system can be written as

$$S_{out}(s) = X_{dI}(s)F_1(s)M_1(s)A(s) + D(s).$$

where$X_{dI}(s)$ is the I-channel error signal and is given by

$$X_{dI}(s) = X_I(s) - [K(s)D_1(s)S_{out}(s) + D_{FI}(s)].$$

where $D_{FI}(s)$ is the distortion result from the non-deal demodulation. This distortion has significant influence on overall loop stability.

Combining above equation, we get the overall equation for the closed loop system:

$$S_{out}(s) = \frac{A_I X_I(s)}{A_I B_I} + \frac{D(s)}{1 + A_I B_I} + \frac{A_I D_{FI}(s)}{1 + A_I B_I}.$$

where$A_I = F_1(s)M_1(s)A(s)$ and $B_I = K(s)D_1(s)$. From above equation, we can see that two types of distortion may occur within the loop. D(s) will be attenuated by the effect of loop, but we need to eliminate the feedback distortion, $D_{FI}(s)$, for the Cartesian-loop system to provide a benefit. There are many possibilities of error which can contribute towards feedback distortion, among all the most crucial factor is the demodulation phase misalignment.

4. Results and Analysis

In order to demonstrate the effect of the Cartesian loop linearization on the TETRA system transmitter, an experimental set up was implemented. Measurements have been taken to observe the transmitter performance according to the requirements of TETRA standards. A complete transmission unit was deployed for full evaluation of the linearization.

4.1. Description of Transmission Setup

The transmission setup comprises all of the system building blocks that any RF transmitter requires. A commercially available IC was used for implementing Cartesian-loop linearization. The IC was designed and developed by CML Microcircuits which includes built in circuit for implementation of the Cartesian loop. The IC implements the following operations: forward path modulator, error amplifiers forI and Q-baseband signal, a phase shifter for demodulation phase alignment, feedback-path demodulators, an interface for the local oscillator (LO) supply with frequency divider, C-BUS serial interface for controlling registers that are used to define several transmitter options. The IC was used with a custom-made transmitter board comprising the interface for the baseband signal, local oscillator source, feedback signal-path, DC calibration, external amplifier, a serial bus interface for controlling the registers of the IC block, and a low-power RF amplifier for 450 MHz operation. Power amplification is possible both with a low-power PA mounted on the transmitter board, and with an external high-power PA. The different parameters of the IC were controlled from the PC using a custom-made program as a digital interface to the registers of the IC. The transmitter board supply rail was provided with 7.2V DC supply. The IC can support a wide range of modulation formats and standards including TDMA operation. Figure 5 shows the block diagram of the transmitter implemented.

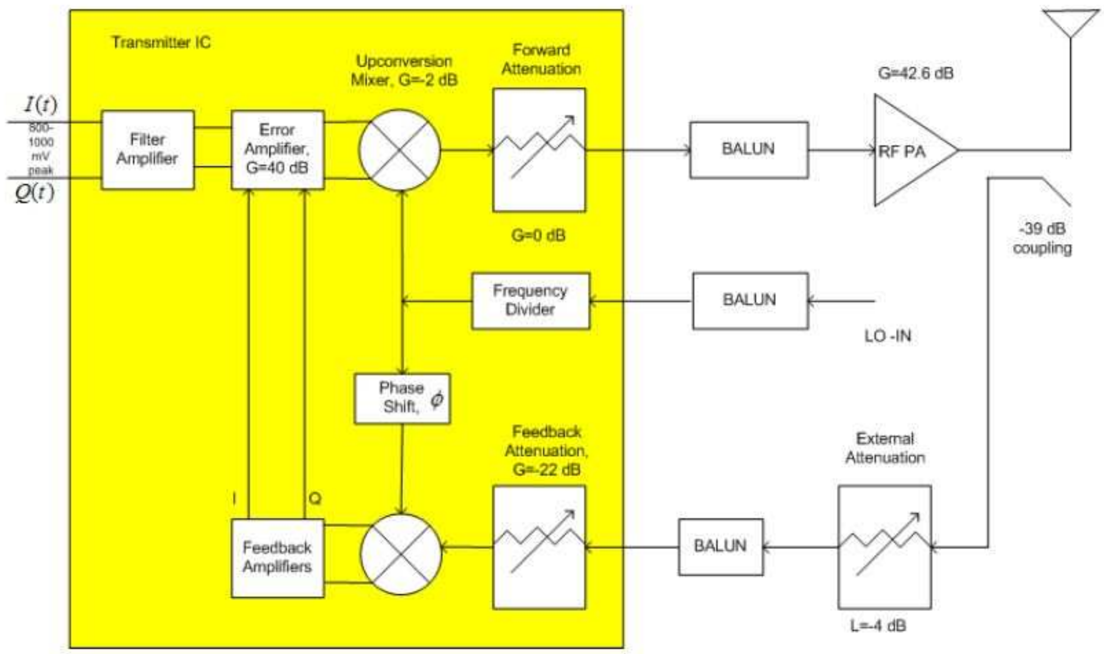


Figure 5. Transmitter Block Diagram with External PA

The following sections describe the different functional blocks of the transmitter IC along with the associated signal-interface board.

4.2. Measurement Setup

For the analysis of the linearization performance of the Cartesian feedback loop, an experimental measurement set-up was constructed.Figure 6 depicts the implementation of the set-up. The following instruments were used for analysis of the transmitter performance:

1. Vector Signal Generator (Baseband): R&S SMU 200A,
2. LO signal Generator: R&S SMA 100A
3. External step attenuator: R&S RSC
4. Signal Analyzer: R&S FSQ.

R&S SMU200A was used for the generation of single-ended digitally modulated baseband I and Q signals. SMU200A is capable of generating different digital modulation schemes in accordance with different system standards. Different choices of symbol rate, and signal levels are selectable manually. The transmitter IC is capable of supporting both differential and single-ended I and Q input signals.

SMA100A generated LO signals for the integrated I/Q modulators and demodulators. This LO signal is processed inside the IC and delivered to the modulator and demodulator in differential form. The signal generator produces an RF signal in single-ended form which is converted to a differential signal using the BALUN transformer. This differential RF signal is applied at the LO input of the transmitter IC. The signal level for the RF signal was set to -10 dBm with two times the carrier frequency which was chosen to be 402 MHz for the external amplifier. The R&S RSC was employed as an external attenuator for the feedback path signal, which was subsequently converted to a differential feedback signal input to the integrated demodulator with the BALUN.

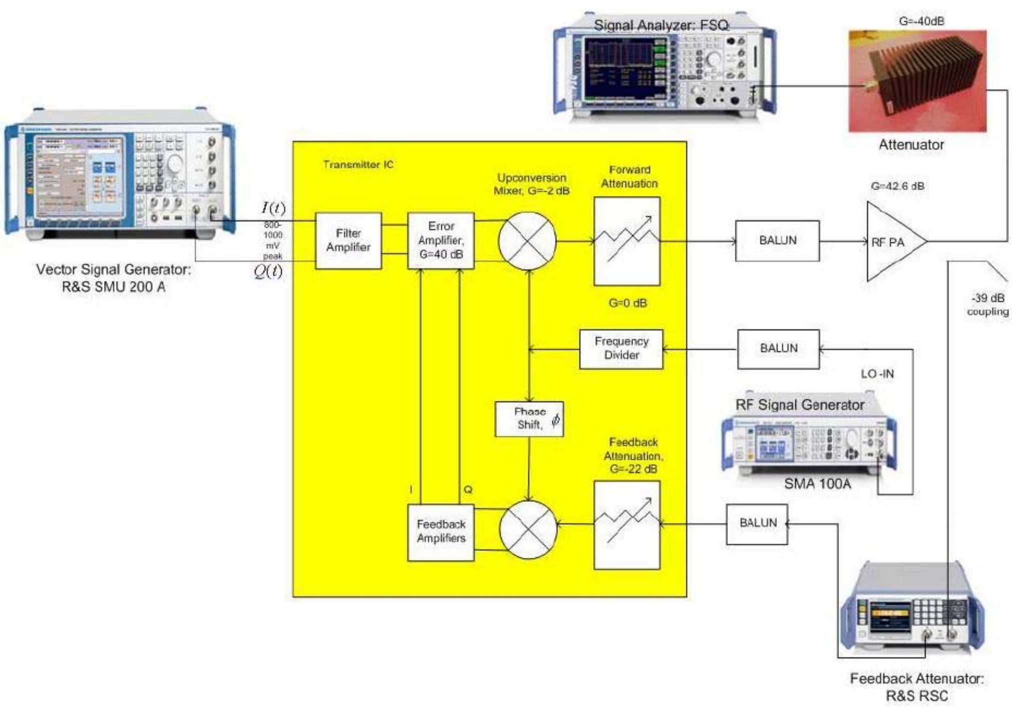
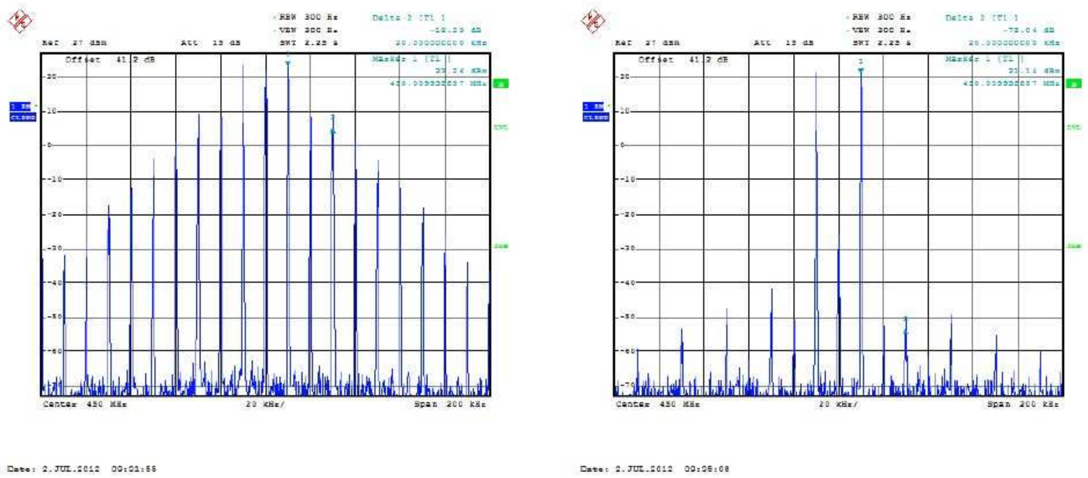


Figure 6. Measurement Set-up for Transmitter Evaluation

For the analysis of the transmit signal at the output of the power amplifier, the output signal was applied to the R&S FSQ signal analyzer after appropriate fixed-attenuation.

4.3. Measurement and Analysis

Measurements were taken for evaluating transmitter performance under the Cartesian loop linearization scheme. The output of the power amplifier was analyzed with the R&S FSQ signal analyzer. Initially, for the analysis of adjacent channel power ratio (ACPR), linearity performance was measured employing a relatively low power RF power amplifier, RF5110g, which could support approximately 33 dBm of PEP. Thereby, the measurement was taken for less than 1 watt of average power. In this case, measurements were taken for ACPR and intermodulation distortion (IMD) performance of the transmitter.



(a) Open loop (b) Closed loop

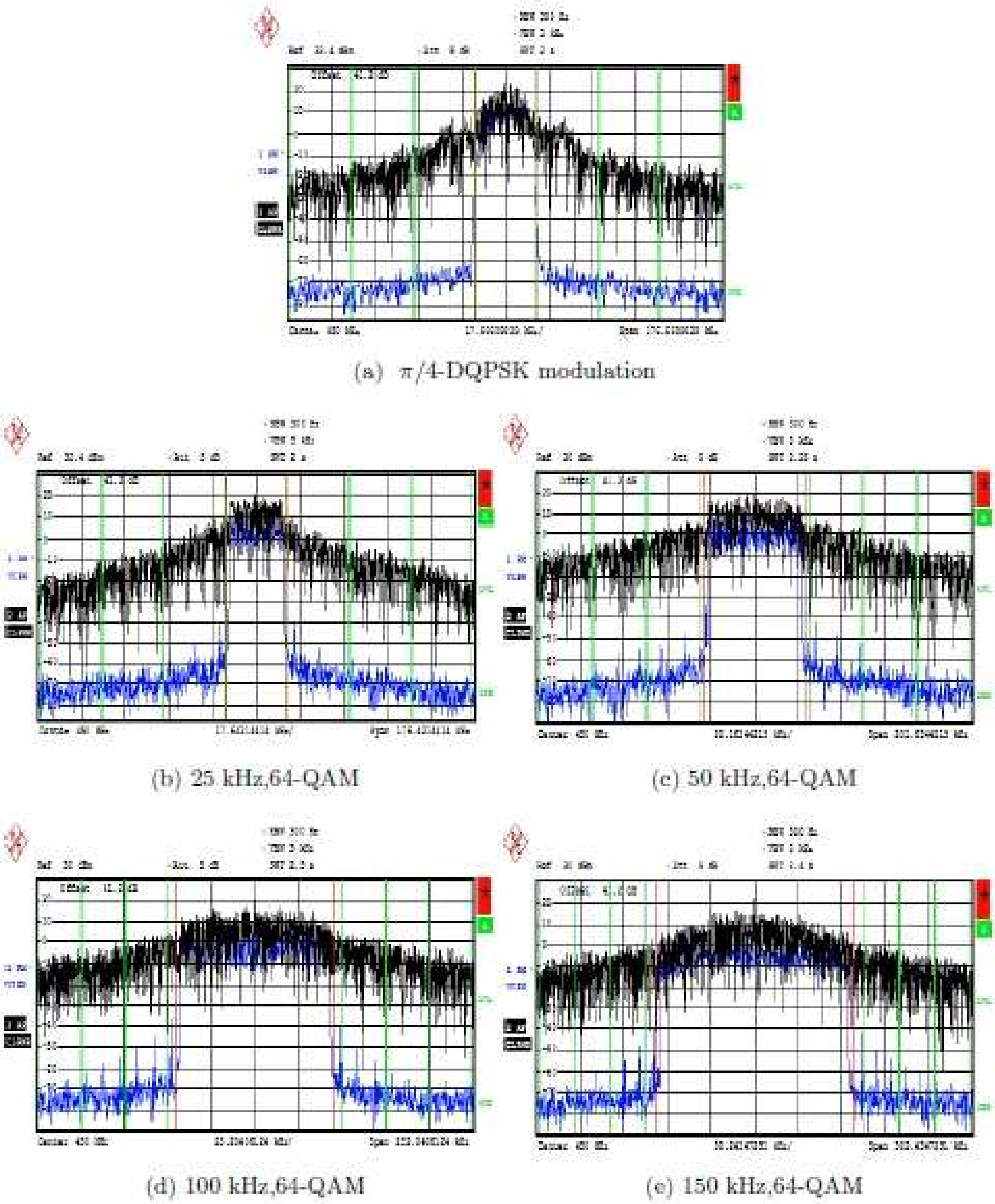
Figure 7. IMD Performance Test of the Transmitter

Figure 7 shows output spectrum for a two tone input where each tone has 10 kHz spacing from the center frequency, i.e., 450 MHz. It can be observed from the spectrum that for open loop operation, IMD performance of the transmitter is poor with very strong intermodulation product of different orders. On the other hand, closed loop operation has very weak odd-order intermodulation product, whereas even-order intermodulation product has almost disappeared.

Figure 8 shows the output spectrum for different modulation scheme with the black traces representing the open-loop performance, and the blue traces represents the linearized spectrum while Cartesian-loop was in operation. In all the cases, the output power of the transmitter was set to 31 dBm of peak envelope power (PEP). To understand the spectrum according to the standard requirement: firstly, the power needs to be observed within the expected band, the width of which is marked with two red-lines in the Figure 8. The bands outside the expected band are divided into several sub-bands which are called adjacent channels. The relative power of the adjacent bands to that of the expected band is the measure of the ACPR.

The spectrum responses in the Figure 8 were taken for modulation schemes: phase modulation and QAM. Spectrum response for phase modulation was measured with pi/4-DQPSK modulation with parameters shown in Table 1. The ACPR were measured to be : -65 dBc, -72 dBc and -76 dBc for the 1st, 2nd and 3rd adjacent channels respectively which are well within the ACPR limit specified in TETRA standard.

The spectrum measurement with 64-QAM modulation was done with 4-different bandwidths: 25 kHz, 50 kHz, 100 kHz and 150 kHz. The baseband modulation was generated according to standard specification described in [14]. For the case of 25 kHz measurement, the ACPR were measured to be -67 dBc, -74 dBc and-77 dBc for the 1st, 2nd and 3rd adjacent channels respectively. The other measurement has the values for the 1st, second and 3rd adjacent channels: -67 dBc, -73 dBc and -78 dBc for 50 kHz, -67 dBc, -74 dBc and -78 dBc for 100 kHz, and -67 dBc, -74 dBc and -77 dBc for 150 kHz bandwidth. These ACPR values meet the standard requirement mentioned in [14].



(a) π/4-DQPSK modulation

(b) 25 kHz,64-QAM

(c) 50 kHz,64-QAM

(d) 100 kHz,64-QAM

(e) 150 kHz,64-QAM

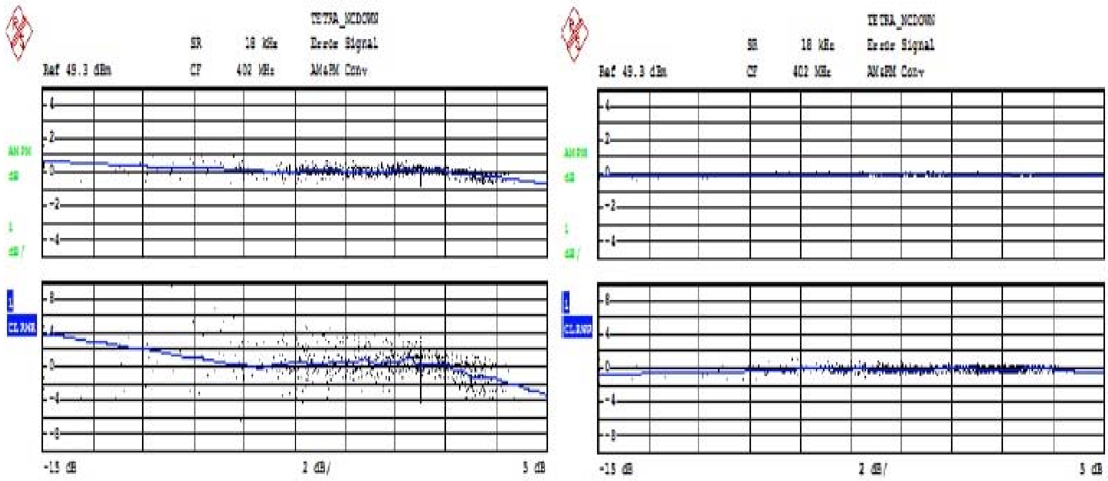
Figure 8. ACPR Performance of the transmitter with RF5110g PA

Table 1. TETRA System Parameter

System Parameter	Values
Madulation Type	Phase Modulation: pi/4-DQPSK
Crest Factor	3.3 dB
Modulation Rate	36 kbit/s
Carrier Separation	25 kHz
Transmit Pulse Shaping Filter	Root Raised Cosine(RRC)
Roll off Factor	$\alpha = 0.35$
Multiple Access	TDMA

The Table 1 shows the parameters of the phase-modulated baseband signal that was used for observing the linearization performance of the transmitter for both on-board and external power amplifier. With the setting of the baseband signal according to the the Table1, the modulator provides average output power of 0 dBm which in turn gives a peak envelope power (PEP) of 3.3 dBm.

Another important characteristic of a transmitter is the AM/AM and AM/PM response of it's power amplifier. Distortion components are generated in the signal spectrum if it has any AM/AM or AM/PM distortion. Therefore, the linearization effect on these characteristics needs to be observed as well. In ideal case, the AM/AM and AM/PM curve should be a straight horizontal line with respect to the amplitude variation, but in practical implementation it is very hard to get ideal response. With the Cartesian-linearization applied in the transmitter, the distortion effects were observed to be reduced in some extent.

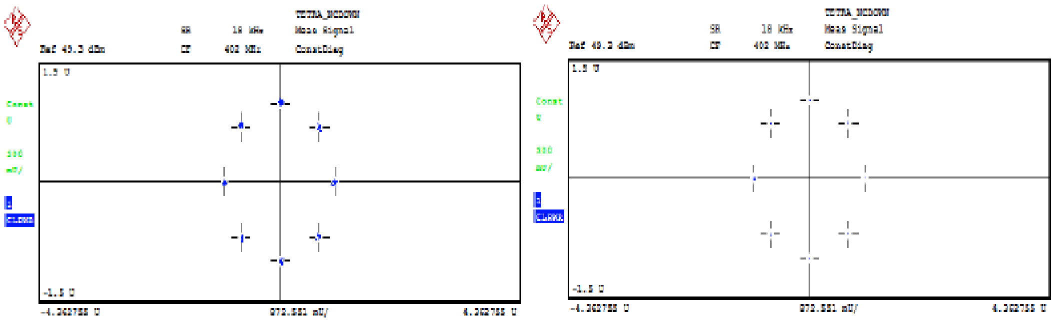


(a) Open-loop (b) Closed-loop

Figure 9. AM-AM (upper curve) and AM-PM (lower curve) response of the transmitter

Figure 9 shows the AM/AM and AM/PM response of the PA before and after the linearization was applied. Without the linearization applied, the responses are non-ideal with non-constant amplitude and phase response. On the contrary, the linearized response shows a flat and constant AM/AM and AM/PM response which shows evidence of linearization. Therefore, with Cartesian-loop linearization in operation, AM and PM distortion can be equalized.

Figure 10 shows the demodulated constellation of the transmitter output. The open-loop constellation is not perfect according to ideal pi/4-DQPSK modulation. So, the open-loop constellation and EVM are non-ideal for any transmitter. With the linearized transmitter output, Figures 10(a) and 10(b) shows the improvement of the constellation. Therefore, it can be said that the linearization effect works on eliminating constellation impairment
effectively.



(a) Open-loop constellation (b) Closed-loop constellation

Figure 10. Contellation of the output Signal

5. Conclusion

The non-ideal response of the transmitter are defined by several parameters, such as phase error, IQ mismatch, carrier leakage, AM/AM and AM/PM distortion from the PA, and gain variance of the power amplifier. The functional modeling of the distortion of the otherwise perfect transmitter components is useful tool to understand the non-ideal response, and achieve appropriate compensation method against distortion. In the theoretical analysis part of transmitter, mathematical descriptions of both ideal and non-ideal components have been analyzed in this thesis. Any linearization scheme that might be deployed should consider the mathematical distortion model of different components of the transmitter. For exploring the linearization effect on the transmitter nonlinearity, the Cartesian feedback loop linearization has been applied.

The Cartesian feedback loop utilizes the distortion effect of nonlinear response of power amplifier on the individual I and Q component of the output envelope. The loop employs a error amplifier which pre-distort the baseband I and Q signal, as such the signal after being travel through all the non-ideal components provides a perfect output signal. In this scheme, the distortion components are pre-subtracted to reduce the distortion on the output. The comparison between linearized and distorted output signal shows us a clear evidence of improvement. Therefore, the application of the Cartesian feedback loop is proved to be a suitable method for linearizing the TETRA system transmitter.

There have been proposed many modification possibilities for the Cartesian feedback system in existing literatures. Most of the literature-works lack the implementation of wide-band Cartesian feedback loop. However, the idea is to implement a digital pre-compensator for countering the nonlinear response. The digital pre-compensator is somewhat different than the digital pre-distortion (DPD) which employs the power amplifier model for constructing a look-up table for linearization, whereas digital pre-compensator act as a digital implementation of the error amplifier. The feedback signal should be converted to digital signal to pre-distort the generation of baseband signal. With this proposed linearization scheme, the hardware implementation of the transmitter would be somewhat relaxed. The ease of hardware implementation would make a tradeoff with the signal processing power of the DSP.

References

[1] PB Kennington. High Linearity RF Amplifier Design. First Edition. London: Artech House. 2000: 136-183.
[2] B Razavi. RF Microelectronics. NJ: Prentice Hall Inc. 1998: 121-130.
[3] M Johansson. Linearization of RF Power Amplifiers Using Cartesian Feedback. Tech. Rep., Lund University. 1991.
[4] M Boolorian, J McGeehan. The frequency-hopped Cartesian Feedback linear Transmitter. *IEEE Trans. On Vehicular Technology*. 1996; 45: 688-706.

[5] A Bateman, RWD Haines. *Linear Transceiver Architechtures*. IEEE Conf. On Vehicular Technology. 1988: 478-484.
[6] M Johansson, L Sundstrom. Linearised High-Efficiency Power Amplifier for PCN. *Electronic Letters*. 1991; 27: 762-764.
[7] M Briffa, M Faulkner. Gain and Phase Margins of Cartesian Feedback RF Amplifier Linearization. *Journal of Electrical and Electronics Engineering*. 1994; 14: 283-289.
[8] M Johansson, L Sundstrom. Linearization of RF Multicarrier Amplifiers using Cartesian Feedback. *Electronic Letters*. 1994; 30: 1110-1111.
[9] M Briffa, M Faulkner. *Dynamically Biased Cartesian Feedback Linearization*. IEEE Vehicular Technology Conference. 1993: 672-675.
[10] Y Ohishi, TM Minowa. *Cartesian Feedback Amplifier with Soft Landing*. IEEE International Symposium on Personal, Indoor and Wireless Communications. 1992: 402-406.
[11] M Faulkner, MBD Contos. *Performance of Automatic Phase Adjustment Using Supply Current Minimization in RF Feedback Linearizer*. IEEE International Symposium on Personal, Indoor and Wireless Communications. 1997: 858-862.
[12] D Cox. Linear Amplification by Sampling Techniques: A new Application for Delta Coders. *IEEE Transactions on Communications*. 1975; COM-23: 793-798.
[13] Frederick H Raab, Peter Asbeck. RF and Microwave Power Amplifier and Transmitter Technologies. Fouth Edition. London: High Frequency Electronics. 2003: 38-49.
[14] ETSI. EN 300 392-2 V3.2.1. European Standard (Telecommunications Series). France. Sophia Antipolis Cedex. 2007-09.paper.