# ANALYSIS AND DESIGN OF FEEDFORWARD POWER AMPLIFIER

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## Abstract

A linear power amplifier is particularly emphasized on the system using a linear modulation scheme, because intermodulation distortion which causes adjacent channel interference and co-channel interference is mostly generated in a nonlinear power amplifier. In this paper, parameters of a linearization loop, such as an amplitude imbalance, a phase imbalance and a delay mismatch, are fully analyzed to get a specific cancellation performance and linearization bandwidth. Experimental results are presented for Korea PCS frequency band. The center frequency of the feedforward amplifier is 1.855GHz with 30MHz bandwidth. The cancellation performance of the first linearization loop is more than 40dB and the intermodulation cancellation performance of the feedforward amplifier is more than 35dB.

## Introduction

In the past, both theory and practice of mobile communications have emphasized constant envelope modulations, such as FM or GMSK[1]. These techniques allow power amplifiers to be operated in the nonlinear region near saturation, for power efficiency, yet they do not generate intermodulation products which cause adjacent channel interference and co-channel interference. Therefore Class C amplifier can be used to obtain a high power efficiency in constant envelope modulations. However, the limited available spectrum is forcing the development of more spectrally efficient linear modulations, such as 16QAM and QPSK with pulse shaping[1]. Since envelope of linear modulations fluctuates, these methods generate intermodulation products in a nonlinear power amplifier.

When the introduction of a linear modulation scheme to digital mobile communiction systems is considered, it is necessary to achieve power amplification with both high power efficiency and low out-of-band emission of -60dBc. It is possible to achieve out-of band emission of -60dBc using Class A amplifier. However, the backoff requirement to obtain linear operation with Class A amplifier is very large, so the power efficiency is very low. Therefore, a more attractive alternative is the linearization of an existing power amplifier(with high power efficiency) by using external circuitry.

Several linearization approaches have been developed[2,3,4]. Feedforward linearization[5] has advantages in linearization bandwidth and cancellation performance over other linearization methodes. Since the signals are manipulated by inherent wideband analog technology, it can handle multicarrier signals.

In this paper, parameters of a feedforward amplifier are fully analyzed to obtain a specific cancellation performance and linearization bandwidth. Experimental results are presented for Korea PCS frequency band.

## Theory

The block diagram of a feedforward amplifier is shown in Fig. 1. The principle of operation of a feedforward linearizer is well illustrated with two-tone spectrum represented in Fig. 1.

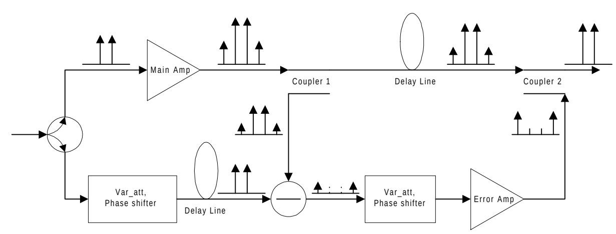


Fig. 1. Feedforward amplifier block diagram

The operation of a feedforward linearizer circuit is based on the substraction of two equal signals and is, therefore, sensitive to amplitude and phase imbalance. The cancellation performance achieved by each independent linearization loop is defined as the power ratio of the suppressed signal over the signal corresponding to the open loop configuration.

Assuming that the signal in each path(upper and lower path) of a linearization loop of a feedforward amplifer is sinusoidal, then signal in each path can be written as

$$V_1 = V_{1m}\cos(\omega_o t + \phi) \quad (1)$$

$$V_2 = V_{2m}\cos(\omega_o t + \theta) \quad (2)$$

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where $\theta = \phi + 180° \pm \phi_{p\_m}$ , $V_{2m} = V_{1m} \pm V_{a\_m}$ . $V_{a\_m}$ and $\phi_{p\_m}$ is an amplitude difference and a phase imbalnce, repectively. A normalized average power at the output port of a linearization loop can be written as

$$P_{(v1+v2),avg} = \{ V_{1m}^2/2 + \left(V_{1m} \pm V_{a\_m}\right)^2/2 + 2V_{1m}\left(V_{1m} \pm V_{a\_m}\right)\cos(\phi_{p\_m}) \} \quad (3)$$

where $P_{(v1+v2),avg}$ (dBm) is a normalized average power. Assuming that a reference signal to be cancelled out is $V_1$ and a normalized power of $V_1$, $P_{v1,avg}$(dBm), is as

$$P_{v1,avg} = V_{1m}^2/2 \quad (4)$$

Using eq. (4) and eq. (3), we can calculate the effects of amplitude and phase imbalance on the cancellation performance of a linearization loop. Cancellation performance is defined as the power ratio of the reference signal to be cancelled out to the output signal of a linearization loop, cancellation performance, CP(dB), including the effects of amplitude and phase imbalance (without delay mismatch) can be written as

$$CP = 10\log(1+\alpha^2 - 2\alpha\cos(\phi_{p\_m})) \quad (5)$$

where α, amplitude imbalance, is $(V_{1m} \pm V_{a\_m})/ V_{1m}$.

Assuming that the signal in each path of a linearization loop is an equal ampliude with anti-phase in order to consider the effects of a delay mismatch on the cancellation performance. Let $V_1 = \cos(\omega_0 t + \theta_1)$, $V_2 = -\cos(\omega_0 t + \theta_2)$, where $V_1$ is the signal in the upper path, and $V_2$ is the signal in lower path. Then $V_{out}$ , output signal of a linearization loop, is $V_1 + V_2$, a normalized average power of $V_{out}$ can be written as

$$P_{vout,avg} = 1 - \cos(\theta_1 - \theta_2) \quad (6)$$

where $P_{vout,avg}$ is a normalized average power of $V_{out}$, and $\theta_1$, $\theta_2$ are an electrical length of each path of a linearization loop. From eq. (6) we can get an infinite cancellation performance if an electrical length of each path is the same. However, in practice, the amounts of time delay of each path are same at a specific frequency which is the center frequency of a linearization loop. Therefore, we can get an required cancellation performance with only certain bandwidth. The cancellation performance of a linearization loop including the effect of a delay mismatch (without amplitude and phase imbalance) can be written as

$$CP = 10\log(1 - \cos(\theta_1 - \theta_2)) + 3 \quad (7)$$

Eq. (7) can be represented by a function of wavelength of the difference in wavelength between two paths to cause an delay mismatch.

$$CP = 10\log(1 - \cos(2\pi(\frac{\lambda_{err}}{\lambda_o})(1 - \frac{f}{f_o})) + 3 \quad (8)$$

where $f_o$ is an center frequency of a linearization loop, $\lambda_o$ is an wavelength at the center frequency, and $\lambda_{err}$ is the difference between two paths at $f_o$. Fig. 2 shows the effects of a delay mismatch on the cancellation performance and linearization bandwidth of a linearization loop.

From Eq. (5) and Eq. (8), an amplitude imbalance, a phase imbalance and a delay mismatch exist in a linearization loop, then the cancellation performance of a linearization loop can be written as

$$CP = 10\log(1+\alpha^2 - 2\alpha\cos(2\pi(\frac{\lambda_{err}}{\lambda_o})(1-\frac{f}{f_o}) \pm \phi_{P\_M})) \quad (9)$$

Fig. 3 shows the effects of an amplitude imbalance, phase imbalance and a delay mismatch on the cancellation performance of a linearization loop.

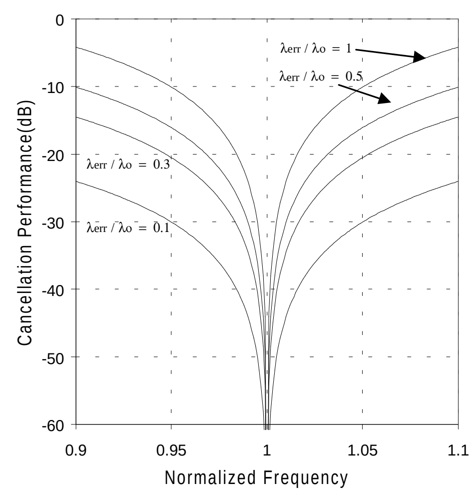
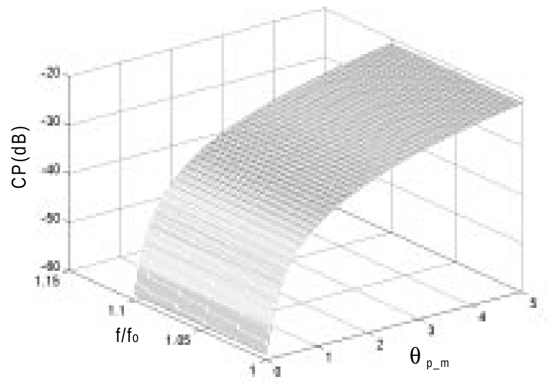
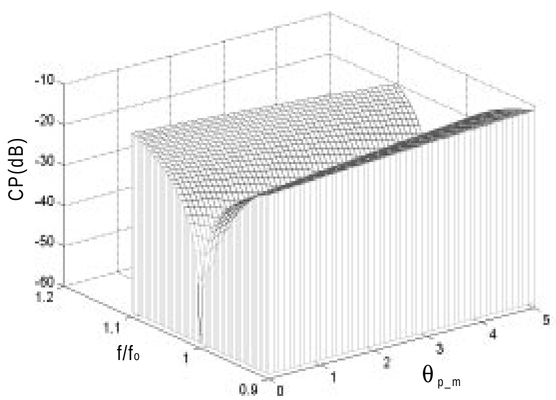



Fig. 2. Effect of a delay mismatch on the cancellation performance of a linearization loop




(a) $\lambda_{err} = 0$




(b) $\lambda_{err} = 0.3\ \lambda_o$

Fig. 3. Cancellation performance of a linearization loop as a function of normalized frequency and phase imbalance($\alpha$ = 0.01dB)

## 3. Experimental results

The main amplifier employed MRF6404 as a final stage amplifier. The center frequency of the main amplifier is 1.855GHz with 30MHz bandwidth. The total power gain of the main amplifier is 37dB with 1dB gain flatness and the phase variation is within 5 degree over the operating bandwidth. The average output power of the main amplifier is 37dBm. The chracteristics of the error amplifier are just like that of the main amplifier.

The 32dB microstrip directional coupler is used for the first linearization loop(coupler 1 shown in Fig. 1) and 11dB directional coupler for the second linearization loop(coupler 2 shown in Fig. 1). The directivity of directional coupler have influences on the amplitude imbalance, therefore additional technique is added to improve it. For substraction circuit, 3dB stripline directional coupler manufactured by ANAREN(4A1305-3) is used.

A reflection type hybrid phase shifter using varactor diode is used. The phase shifter has 200 degrees of the adjustable phase control range by employing two sections of hybrid phase shifter and 360 degrees of the adjustable phase control range by employing three sections of hybrid phase shifter. The variable attenuator is a nonreflective pin diode attenuator and the attenuation range of the variable attenuator is about 10dB.

The 2-tone intermodulation characteristic of main amplifier is shown in Fig. 4. Fig. 4 shows that the intermodulation characteristic of the main amplifier is 24dBc. The sampled output signal of the main amplifier fed to the substracter is shown in Fig. 5. The cancellation performance of the first linearization loop repesented in Fig. 6 is about 45dB. The 2-tone intermodulation characteristic of the implemented feedforward amplifier, as shown in Fig. 7, is about -61dBc and intermodulation cancellation performace is more than 35dB. The multi-tone test result is shown in Fig. 8.

## Conclusions

Parameters, an amplitude imbalance, a phase imbalance and a delay mismatch, of a feedforward amplifier are fully analyzed to get a specific cancellation performance and linearization bandwidth. Simulation results show that the minimization of a delay mismatch has an advantage in order to get a specific cancellation performance and a linearization bandwidth over optimization of other parameters. From the experimental results, the directivity of a directional coupler is an important parameter to influence an amplitude imbalnce. The experimental results on Korea PCS band are presented. The cancellation performance of the first linearization loop is more than 40dB and the intermodulation cancellation performance of the feedforward amplifier is more than 35dB.

## References

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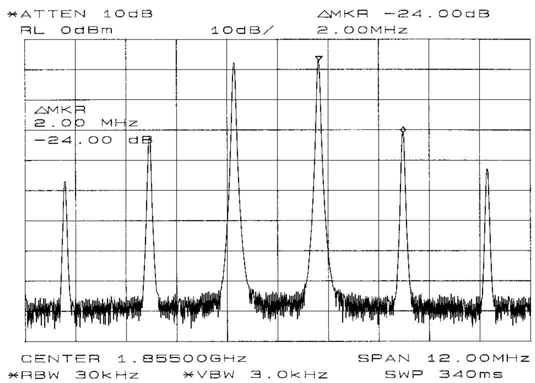


Fig. 4. 2-tone intermodulation characteristic of the main amplifier before linearization.

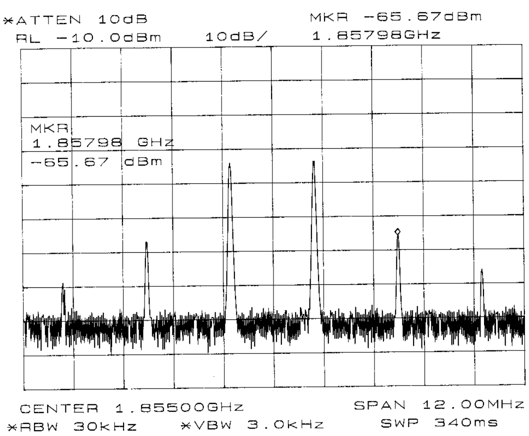


Fig. 5. Sampled signal of the main amplifier output from the coupled port of coupler 1.

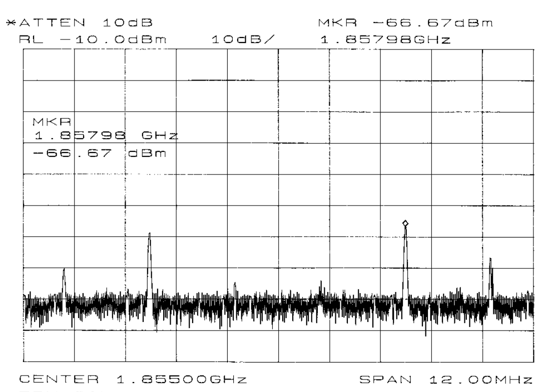


Fig. 6. Substracter output

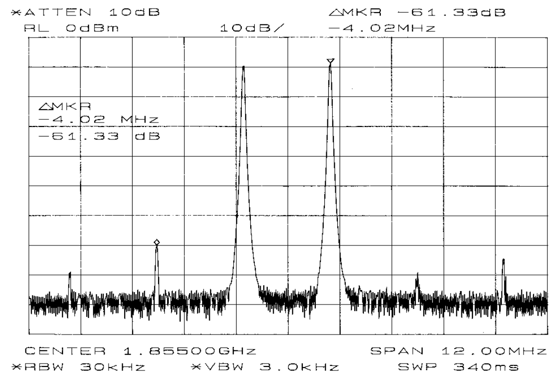


Fig. 7. 2-tone intermodulation characteristic of the feedforward amplifier after linearization.

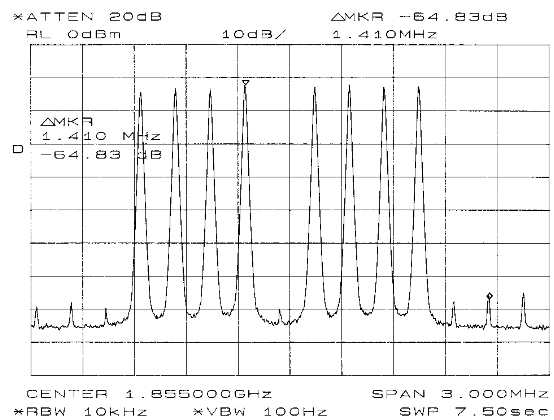


Fig. 8. Multi-tone intermodulation characteristic of the feedforward amplifier after linearization.