IMPROVED DESIGN TECHNIQUES FOR THE REALIZATION OF LINEAR POWER AMPLIFIERS FOR WIRELESS TRANSMITTERS

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ABSTRACT

Improved power amplifier linearization techniques are required for next-generation wireless communications systems. An improved microwave feedforward amplifier architecture has been developed, and applied to the 5.725 to 5.850 GHz ISM band (ISM-5700). This FFA is composed of a driver amplifier and a main amplifier, and the phase shift and attenuation functions are performed utilizing vector modulators. This FFA offers a 30 dB improvement in the third order carrier-to-intermod (C/I3) ratio performance at the rated output power level of 30 dBm and is the first demonstration of a 5 GHz FFA utilizing vector modulation.

I. INTRODUCTION

The transmission of high-power radio frequency signals through the antenna port of a handset or base station is fundamentally limited by the distortion generated by the power amplifier and by the dc power consumed by that amplifier. In most cases, distortion can be reduced, but only at the expense of increased dc power dissipation. The distortion in the power amplifier results in spectral regrowth of the output signal — an increase of the transmitted bandwidth and a corruption of the desired signal within the original bandwidth. This is illustrated schematically in Figure 1. This spectral regrowth arises from the fact that any nonlinear operation on a waveform containing multiple frequencies creates new frequencies at sums of integral multiples of the original frequencies. Some of these new signals are at frequencies adjacent to the original signal, and can create significant corruption of the desired signals at these intermodulation frequencies.

Although power amplifier distortion creates problems for all communications systems, it is especially detrimental to mobile wireless communications system, where the wide variations in received power together with spectral regrowth can corrupt adjacent channels in a particularly extreme manner. This is due to the fact that received power, either by the base station or the handset, varies dramatically both with time and frequency, due to the presence of multi-path, shadowing, and other time varying effects; received signal levels can vary by over 60 dB in the millisecond time frame. As a result, the spectral regrowth of a large amplitude channel can corrupt the desired signal in a small amplitude adjacent frequency band.

The amount of allowed spectral regrowth varies between wireless communications standards, and is a complex function of channel spacing, modulation format, and fading environment. As an example, the Adjacent Channel Power Rejection (ACPR) requirement — a measure of spectral regrowth — is shown in Figure 2 for several wireless communication standards. For example, the United States domestic analog AMPS standard utilizes a frequency division multiple access scheme, with a unique frequency allocated to each user during active periods. The spacing between the channels is 30 kHz, so the power amplifier must have sufficiently small spectral regrowth that there is insignificant radiated power 30 kHz from the center of the transmitted channel, this with a carrier frequency of approximately 850 MHz. In particular, the AMPS standard specifies that the spectral regrowth will be less than 26 dBc at a frequency only 20 kHz removed from the desired frequency.

At the same time, the IS-95 digital CDMA standard multiplexes many different users into a single 1.25 MHz wide bandwidth signal, but this signal must co-exist with adjacent analog carriers as well as, potentially, other CDMA signals at differing carrier frequencies. In this case, the linearity requirements can be more severe, as shown in Figure 2, because the wider bandwidth of the modulated signal will lead to wider bandwidth distortion products, although the minimum channel spacing remains nearly the same. In this case, the specifications require that the spectral regrowth be less than 42 dB below the carrier at frequencies between 900 kHz and 1.98 MHz away from the carrier, and less than 54 dB below the carrier at frequencies greater than 1.98 MHz from the carrier. In addition, there

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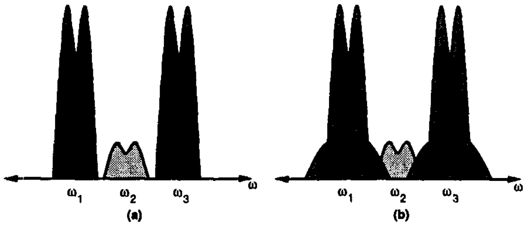

Figure 1: Wireless communications power amplifiers (a) ideal adjacent channel behavior with no spectral regrowth (b)distortion in power amplifier corrupting adjacent received signal.

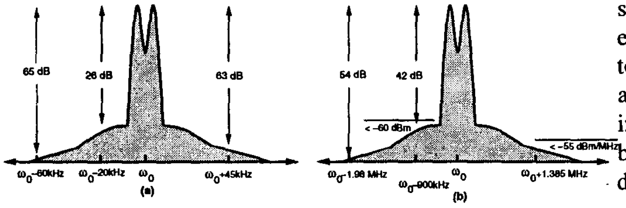

Figure 2: Wireless communications power amplifiers (a) Adjacent channel distortion specifications for analog AMPS system (b)Adjacent channel distortion specifications for IS-95 CDMA system .

is an absolute power specification of less than -60 dBm in a 30 kHz bandwidth greater than 900 kHz from the carrier, or less than -55 dBm in a 1 MHz bandwidth at frequencies greater than 1.385 MHz away from the carrier. All of these specifications require a high degree of linearity in the transmitter power amplifier.

The ISM bands governed by FCC Part 15 specifications have seen dramatic growth in recent years, particularly the 902 to 928 MHz band (ISM-900) and the 2.400 to 2.4835 GHz band (ISM-2400). The ISM-5700 spectrum was allocated in 1996, and since its inception, it is has been experiencing growth similar to the other ISM bands. There is a need for extremely linear RF power amplification in this band because the modulation utilized in many cases will be CDMA. This paper describes an improved feedforward amplifier (FFA) that was designed for highly linear power amplification in the ISM-5700 band with a substantial decrease in the carrier-to-intermod ratio. An FFA topology was chosen for this application, due to the need for high output power and extremely high linearity in a fixed wireless environment. A vector modulation approach yields a high degree of control over intermodulation, and at the same time wideband tuning over the complete ISM band. The FFA topology is also extremely attractive for eventual implementation in completely monolithic form.

II. FEEDFORWARD LINEARIZATION DESIGN USING VECTOR MODULATION

The feedforward linearization method is the most effective technique for the linearization of power amplifiers, where obtaining 40 to 60 dB of (C/I) ratios are necessary[2]. The feedforward scheme utilized in this design is found in Fig. 3 The system contains two cancellation loops; the first loop is called the nulling loop and the first vector modulator provides the proper attenuation and phase shift to ensure out-of-phase cancellation of the main signals. What remains at the output is a sample of the distortion introduced by the main amplifier. This distortion sample is then sent to the second loop, which is called the error loop. The error loop amplifies this replica of the distortion and the second vector modulator adjusts the phase and amplitude of the replica so that it can be injected back into the output coupler. The error loop output is summed back into the main signal path and the main amplifier's distortion products are canceled.

The use of feed-forward techniques has historically been limited by mismatch effects. If there is a relative phase mismatch between the two channels of $\Delta\phi$ and a relative gain error of $\Delta A/A$, then the magnitude of the intermodulation products at the output can be given by.

$$E = \sqrt{1 - 2\left(1 + \frac{\Delta}{A}\right)\cos\Delta\phi + \left(1 + \frac{\Delta}{A}\right)^2} \quad (1)$$

Assuming there is no amplitude error, the phase error required to achieve a 30 dBc cancellation is slightly less than 2 degrees. Assuming negligible phase error, the amplitude error required for 30 dBc cancellation is 0.25 dB. Hence, the phase and amplitude adjusting networks must be very precise, and exhibit a full range of adjustable responses to accommodate the inevitable variations in physical implementation.

The use of vector modulators in FFA designs enables the precise tuning of phase and attenuation required for substantial cancellation. The conventional method of employing the phase shift and attenuation functions was to have a separate phase shift and attenuation circuit. The are several potential problems associated with using this scheme. Variable phase shift networks have a limitation in their phase change ability. They are able to employ the full 360^o of phase shift that may be required but they do not allow random access for specific required values. A full 360^o phase shift is typically required to adjust for the

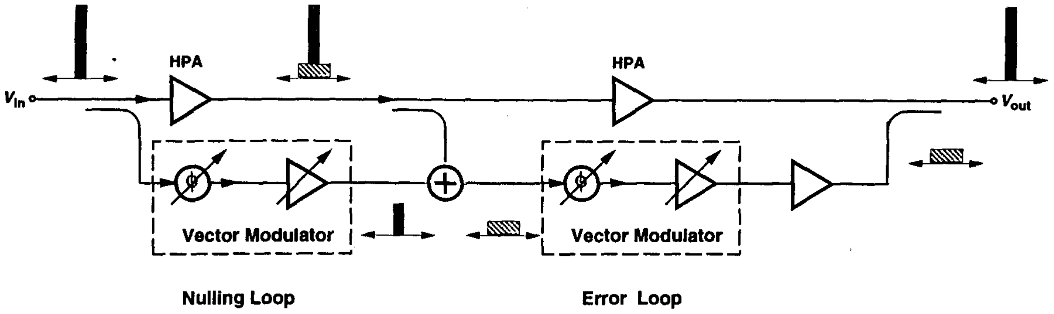

Figure 3: Block diagram of feed-forward amplifier (FFA) used for 5 GHz applications .

inevitable phase variations in the amplifier. Conventional phase shift networks can also suffer from a long transition time. A single reflective phase shifter configured with varactor diodes is limited to 120° of phase shift. Inductance may be added to increase the range but the phase linearity can be reduced over the FFA's operating band. Group delay distortion may also introduced in to the FFA system as the varactors resonate to change their phase. This distortion can degrade the FFA performance. A separate resistive attenuator can also present problems. Attenuators experience group-delay and phase changes as a function of attenuation change. When the variable attenuator changes values, there is also a phase change in this device that must be accounted for with the phase shifter The vector modulator performs the phase and attenuation changes directly without the need for intermediate steps. This ability affords a reduction in the time needed to adjust the loops in the FFA.

The vector modulators used in this FFA provide the attenuation and phase shift functions for both the nulling and error loops. Fig. 4 shows the design utilized in the implementation of the two vector modulators. The input signal is split in-phase via the Wilkinson power divider. The top portion of the split signal is delayed by 90 degrees via a quarter wavelength piece of transmission line. The top signal is now in quadrature with the bottom signal. These two signals are now applied to two Branchline power splitters that have PIN diodes connected to them. The current flow in the PIN diodes controls the impedance presented at each port. These 90-degree hybrids in conjunction with the PIN diodes form a reflective phase shifter and attenuator. The outputs from the phase shifter/attenuator are then combined in-phase by another Wilkinson power combiner.

The vector modulators designed for this FFA provide 360° of phase shift over the entire ISM-5700 band. The maximum attenuation across the band was measured at 14 dB which is more than adequate to ensure maximum cancellation in either the nulling or the error loops.

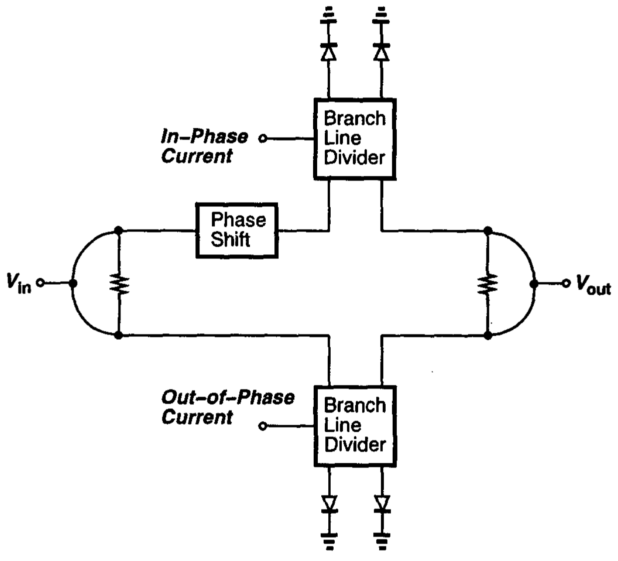

Figure 4: Vector modulator block diagram. .

III. FEEDFORWARD AMPLIFIER PERFORMANCE

Since the object of this design was to transmit 30 dBm of RF power with the best linearity possible, the GaAs MESFET main amplifier was driven with a single tone stimulus at 5.785 GHz (midband of the ISM-5700 frequency range) until the rated output power was obtained. The fundamental tones have been canceled by greater than 50 dB in Fig. 5. Also, Fig. 5 shows that the 3rd order IMD distortion is 7.33 dBc greater than the highest remaining fundamental tone. Once the nulling loop has been optimized for best performance, the error loop is adjusted to inject the amplified distortion products back into the main amplifier. The error loop was connected to the FFA and the second vector modulator was adjusted for

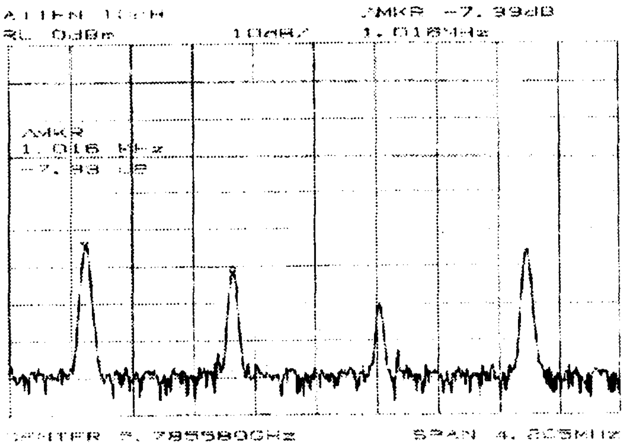

Figure 5: Error-loop fundamental tone nulling.

best (C/I3) ratio at the FFA output. Fig. 6 displays the main amplifier's response to two tones at F1 and F2 with no FFA linearization. The (C/I3) ratio displayed is 11.5 dB. Fig. 7 shows the drastic improvement afforded by the FFA linearization method. The (C/I3) ratio is now 41.5 dB. This is a 30 dB decrease in the (C/I) ratio. Fig. 7 also shows a substantial decrease in the (C/I5), (C/I7) and the (C/I9) ratios. The (C/I5) ratio improvement was 25 dB. The (C/I7) ratio improvement was 15 dB. The (C/I9) ratio improvement was 18 dB. Fig. 8 displays the dramatic improvement afforded by the FFA linearization scheme. This approach can be coupled to an adaptive algorithm to obtain the best adjustment of the two-loops on an on-going basis [7].

IV. CONCLUSION

A low cost FFA architecture has been developed to comply with the FCC part 15 specification in the ISM-5700 band. This FFA offers a 30 dB improvement in the (C/I3) ratio at the rated output power of 30 dBm. It also shows a dramatic decrease in the 5th order, 7th order and 9th order distortion products. The FFA was designed utilizing vector modulators which performed the phase shift and attenuation functions needed in the nulling and error loops. The use of a vector modulator in the error and nulling loops promises a significant improvement in the adaptability and performance of FFA's for microwave applications.

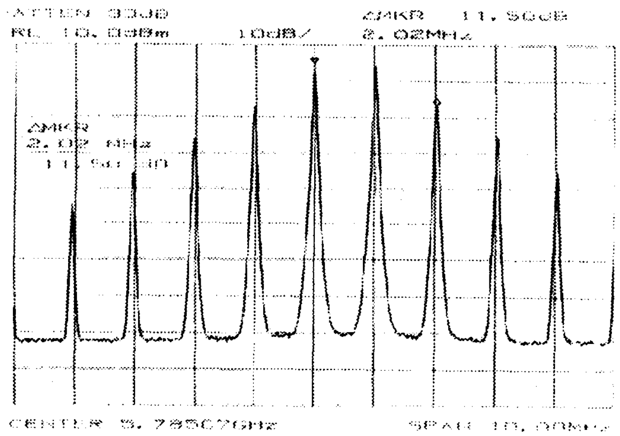

Figure 6: Main amplifier output spectrum with no FFA linearization.

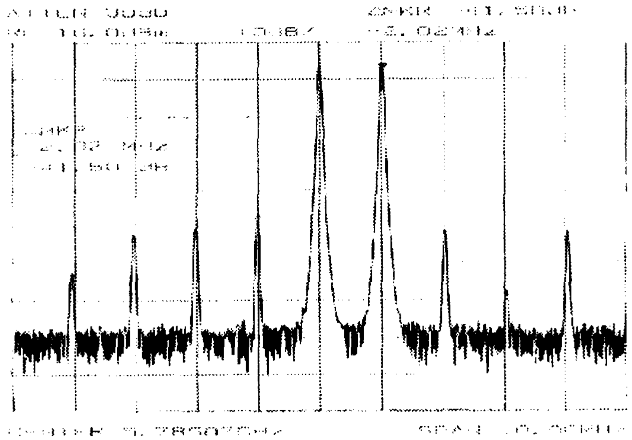

Figure 7: Main amplifier output spectrum after FFA linearization.

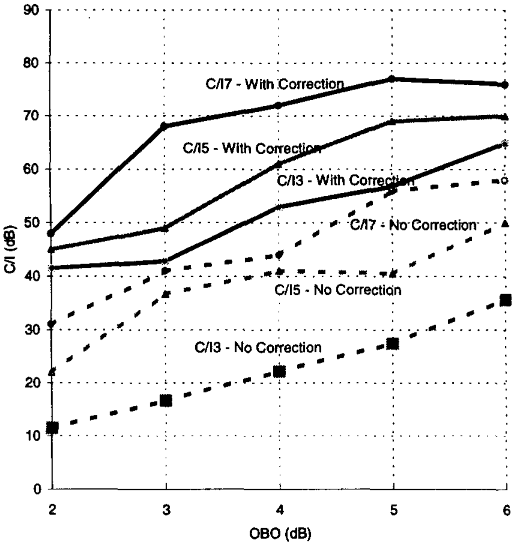

Figure 8: Feed-forward amplifier performance at different levels of output back-off (OBO).

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