DIGITAL CONTROL OF POWER AMPLIFIERS FOR WIRELESS COMMUNICATIONS

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ABSTRACT

The advance of CMOS-based digital circuits enables new strategies for optimisation of wireless transmitters. Co-design of DSP algorithms and power amplifier characteristics can lead to improved efficiency and linearity through a variety of strategies, including: a) DSP control over bias conditions, particularly the power supply voltage; b) predistortion, in simple amplifiers, and in compound architectures such as LINC and Doherty amplifiers; and c) DSP generation of digital input signals for switching amplifiers. We envision for the future a generation of "smart power amplifiers" in which DSP optimization of amplifier parameters is carried out for changing environments.

INTRODUCTION

Digital signal processing (DSP) using Si CMOS integrated circuits is rapidly advancing towards higher throughput and lower power, driven by scaling transistor dimensions. Fig. 1 illustrates the trend in the power dissipation required to achieve specific processing throughput rates with general-purpose DSP chips [1]. Attainable clock rates will reach 5GHz by 2006. It is likely that an increasing number of the microwave system functions implemented at present in a purely analog fashion may be realized in the future using digital processing. Such a transition can provide significant benefits, among which are the following:

1) Functions which are linear or nonlinear can be realized, and the degree of nonlinearity can be tightly controlled and reproduced.
2) The precision attainable with digital techniques is an easily controlled design variable. By changing the word length one can tailor the dynamic range of the system.
3) The digital circuits are not subject to aging and temperature drift, and there is no need for tuning of the digital circuits to accommodate manufacturing tolerances.
4) Testing of circuits can be managed more easily.
5) Digital techniques lead to easier implementation of numerous functions, such as signal storage (or delay).
6) Digital processors can in principle be reconfigured to address changing system requirements, leading to systems that are flexible and general purpose. A programmable (software-based) microwave system can in principle be implemented.
7) Integrated systems-on-a-chip can be implemented combining microwave and digital functions with the same technology.

This paper illustrates some approaches to harness DSP in order to improve microwave power amplifiers for wireless communications.

Current development efforts in power amplifiers for mobile communication systems are largely driven by the need to maximise power efficiency (particularly within the handset since the power amplifier is a main determinant of battery talk-time). At the same time, with spectrally-efficient modulation formats such as QPSK, the amplifier linearity must be sufficiently high that adjacent channel power generation is kept within strict bounds. Compounding these problems is the fact that the output power of a handset typically varies over many orders of magnitude as a result of changing multipath and shadow fading. There are a number of strategies for the application of DSP to power amplifiers in communications, some of which have already become widespread. Most strategies fall into the following categories:

1) DSP can be used to predistort the RF signals fed into the power amplifiers to improve the overall system linearity. This can in turn allow amplifiers to be used closer to compression, where they are more efficient, or it can allow more efficient amplifier architectures to be employed.
2) DSP can be used to control various aspects of the power amplifier operation (such as bias point), in order to improve its characteristics.
3) DSP can be used to generate signals in new formats that are better suited to efficient amplifiers.

Approach (1), the use of DSP for signal predistortion, is a very significant technique whose usefulness has been amply demonstrated. For base station power amplifiers, the application of DSP is presently the rule rather than the exception. This technique has been reported extensively in the literature [2,3]. Approaches (2) and (3) are less well established, and are highlighted in this paper. Examples are provided of specific amplifier architectures which implement one or more of the approaches. The Bias-Controlled amplifier, the Doherty amplifier, the LINC amplifier and the Class S amplifier are discussed in the following sections.

BIAS CONTROLLED AMPLIFIER

In Class A power amplifiers, dc bias conditions are kept constant as the signal input power changes. Since the biases must be set to accommodate the maximum output signal, efficiency suffers at low output power. In most wireless handset designs, the output bias current is varied according to signal level over a wide range. This is typically implemented by an analog bias subcircuit, or by exploiting the intrinsic characteristics of Class AB amplifiers. Voltage bias variation is an additional dimension. We have explored architectures in which bias voltage is varied with a fast response dc-dc converter that transforms battery voltage to a value optimised for the instantaneous output power. The use of DSP to control the output voltage, as shown in fig.2, provides considerably flexibility, since the relationship between desired power supply voltage and output power can be optimised. At the same time, the dynamic response characteristics of the dc-dc converter can be taken into account (accommodating the finite response time of the converter). The DSP computes the envelope of the signal, followed by the appropriate control voltage, and computes a suitable delay and pre-emphasis. We also implemented DSP-based predistortion in the amplifier, since the varying power supply voltage induced changes in gain, which constitutes a source of AM-AM conversion [5]. The DSP used a fixed, rather than adaptive, algorithm in this instance for simplicity, since the AM-AM conversion to be compensated has time-invariant, and relatively device invariant, characteristics. The ACPR was improved by 6 dB in our system with the use of predistortion. The efficiency improvement was significant. Despite the limited efficiency of the converter (80%), the overall system efficiency increased by factor of x1.4, since the efficiency for relatively low output powers was improved.

DOHERTY AMPLIFIER

An alternative architecture that maintains high efficiency over a wide range of output powers is the Doherty Amplifier. The main amplifier operates with a high load impedance, and resulting high efficiency, at low power levels. At higher power, the auxiliary amplifier turns on, and in doing so changes the load impedance experienced by the main amplifier to avoid hard saturation. We have designed Doherty amplifiers in which high efficiency can be maintained over a power backoff range of 10 dB, as shown by the experimental results in fig. 3 [6]. To maintain linearity over the entire power range, it is critical to maintain proper bias conditions for the two amplifiers, as well as to provide an appropriate phase and amplitude relationship between the two input signals. We are exploring a DSP-controlled Doherty architecture, in which input signals and bias voltages are established by the DSP, as shown in fig. 4.

LINC AMPLIFIER

DSP can be used to generate fundamentally new signals to drive amplifiers, in order to obtain higher efficiency. If the output transistor is used in switching-mode, for example, the efficiency can be very high, since the transistor dissipates little power in its "OFF" state or in its "ON" state. Switching amplifiers, including Class E and Class D amplifiers have been operated with efficiency of 75% or more, even in the microwave regime. Such amplifiers, however, are not capable of reproducing signals with time-varying envelope; the output power level is controlled by the power supply voltage. The switching-mode amplifiers can be used, however, in more complex architectures such as the LInear amplification with Nonlinear Components, or LINC amplifier, illustrated in fig. 5. In modern implementations, DSP is used to form the Signal Component Separator (SCS), which derives from the input signal two separate signals that have constant envelope (but time varying phase) such that when the signals are summed, the appropriate output waveform (with time-varying envelope) is recovered, as a result of constructive or destructive interference. For the practical implementation, the two amplifiers in the two channels must be very accurately matched (typically 0.5 dB amplitude matching and 0.3 degree phase matching). These specifications are extremely difficult to meet in open loop fashion. We have developed a DSP-based approach to calibrate the system, and derive appropriate signal distortions to be introduced into the two channel inputs to maintain high accuracy in the overall output. Simple calibration signals are inserted into the amplifier. A receiver is used to sample the output and derive correction factors for the signals in the two paths. A sequence of calibration steps converges rapidly to the desired result. Fig. 6 illustrates representative output spectra for CDMA signals before and after the calibration cycle.

BANDPASS DELTA-SIGMA TRANSMITTER

An additional approach to employ switching-mode amplifiers for signals with time-varying envelope is the Class S amplifier, widely used for audio power amplification. To generate suitable waveforms, pulse-width modulation can be used. This requires a pulse repetition rate substantially (>10x) higher than the desired output center frequency. The amplifier output is passed through a series filter that removes the excess quantization noise generated during the modulation process. The power associated with the undesired out-of-band spectral components must be reflected, rather than absorbed in the filter, to preserve high efficiency. This approach is difficult to use directly at microwave freque4ncies, because of the need for very high pulse repetition rates and very tightly controlled pulse widths. We have investigated amplifiers using the band-pass delta-sigma algorithm to generate digital signals that encode the analog signals of interest. The modulated output consists of a single bit digital data stream. The clock rate can be chosen to not very much higher than the center frequency of interest (typically 4x). The bandwidth of interest, however, must be a relatively small fraction of the center frequency and clock rate, such that a high effective "oversampling ratio" is maintained Here the oversampling ratio is the ratio of the clock rate to the signal bandwidth. The unavoidable extraneous signal power present in the digital waveform ("quantization noise") is spectrally shaped to lie out of the signal band of interest, and can be separated with a bandpass filter. Band-pass delta-sigma modulators can be implemented with analog or digital inputs. A representative output spectrum is shown in fig. 7 (corresponding in this case to an IS-95 CDMA signal). The spectral shaping of the quantization noise is evident in the figure. In principle, the BPDS signals can be used to drive a switching-mode amplifier with high efficiency [9].

SUMMARY AND OUTLOOK

DSP provides flexibility in the design of amplifier input waveforms (by predistortion, or by generation of new signal formats such as used in the LINC amplifier). DSP can also be used to control amplifier bias points, to optimise performance. In future "smart" power amplifiers, it is likely that numerous amplifier internal variables will be monitored by the DSP, and the information will be used to reshape the signals and biases. Smart power amplifiers may, for example, sense the chip temperature, or the status of the output load impedance. DSP can also be used to generate digital waveforms to control switching mode amplifiers. At present, the output of the DSP is at baseband (or IF); conventional mixer techniques are used to upconvert the signals to RF. As the speed of DSP advances, signals at RF can be generated (particularly for switching amplifiers, for which the inputs are inherently digital signals). An entirely digital implementation of the entire transmitter chain is shown in fig. 8. Upconversion to RF and band-pass delta-sigma modulation is accomplished digitally. With a one-bit digital output, the inaccuracies of high resolution digital-to-analog converters at high frequency can be circumvented. In the scenario shown, the clock frequency of the DSP is 4x higher than the center frequency of the RF signal. The digital transmitter potentially offers many benefits, including programmability and reconfigurability, absence of tuning or aging problems, as well as easy integrability and testing. It can be an important element in a "software defined radio".

ACKNOWLEDGMENTS

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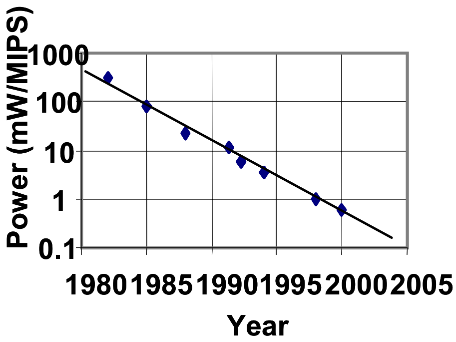

Fig.1: Trends in power dissipation of general purpose DSP chips for a given throughput

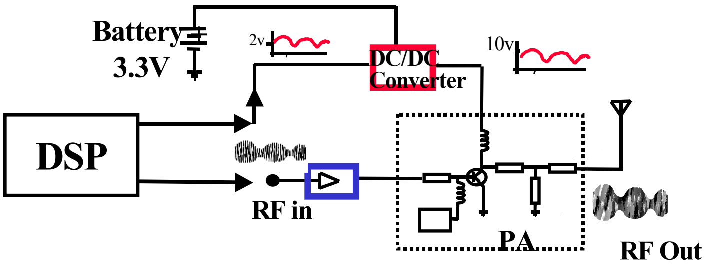

Fig 2: DSP controlled Dynamic Supply Voltage Amplifier

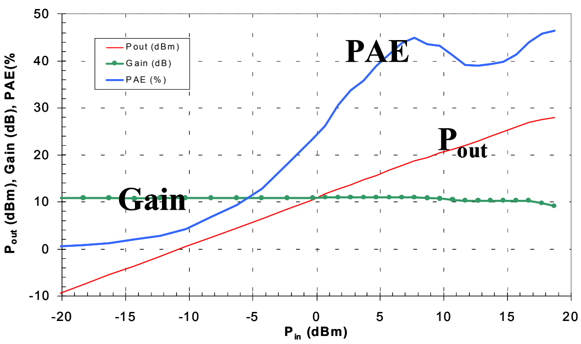

Fig.3: Experimental results for Extended Doherty Amplifier with GaAs HBTs at 900MHz

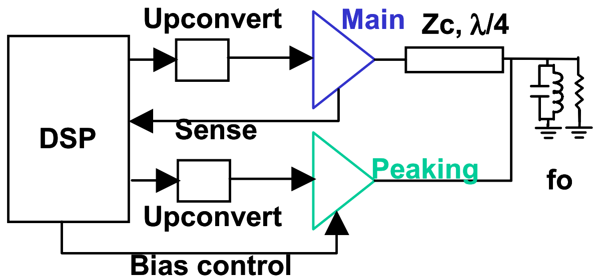

Fig 4: Schematic structure of DSP controlled Doherty Amplifier

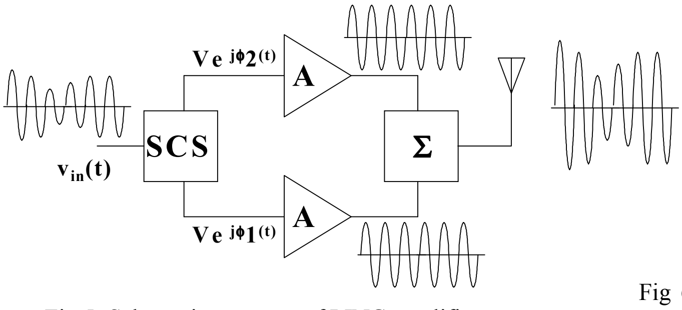

Fig 5: Schematic structure of LINC amplifier

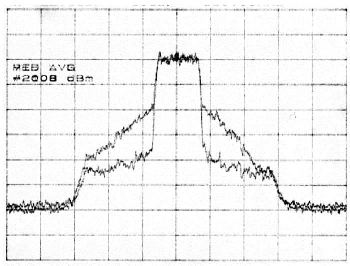
Fig 6: Experimental spectra of LINC amplifier with and without DSP calibration (background technique). Vertical: 10 dB/div. Horizontal: 1 MHz/div. Center frequency: 850 MHz.

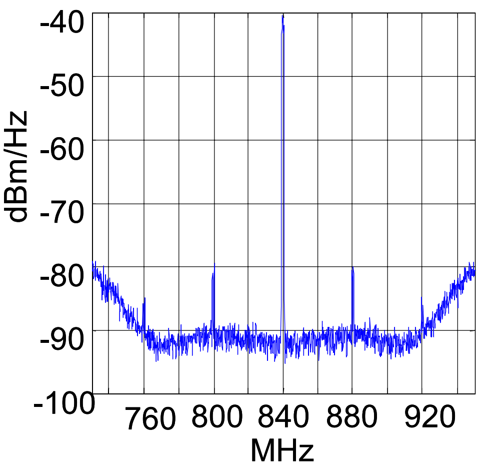

Fig 7: Computed output spectrum of bandpass delta-sigma modulator with CDMA signal (IS-95).

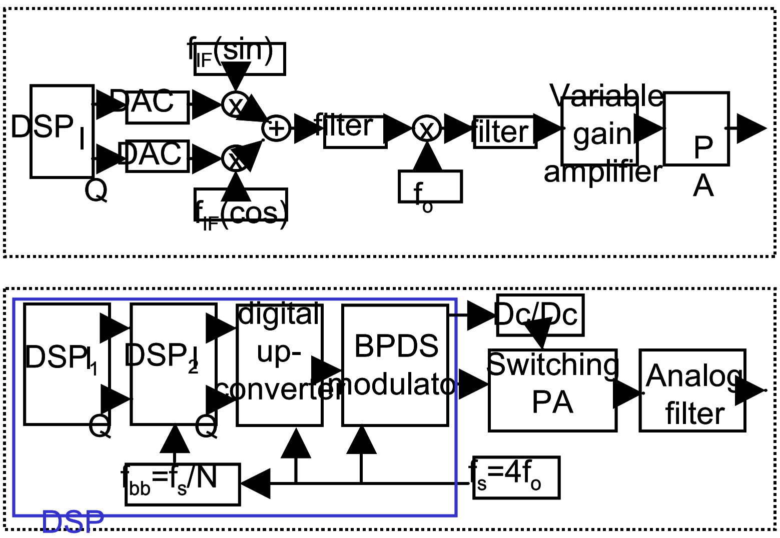

Fig 8: Structure of conventional RF transmitter, and of transmitter based on DSP using BPDS modulation and Class S amplifier