Generation of RF Pulsewidth Modulated Microwave Signals Using Delta-Sigma Modulation

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ABSTRACT- **With RF pulsewidth modulation, microwave signals are encoded in a binary signal having one pulse per period of the microwave signal, in which the pulse timing varies with the phase of the RF signal, and the pulse width varies in accordance with the signal amplitude. RF pulsewidth modulated signals are advantageous for use with high efficiency amplifiers (Class D switching mode amplifiers or Class C amplifiers) for the quasi-linear amplification of signals with time-varying envelope. This paper demonstrates a digital technique to generate RF pulse modulated signals for narrowband microwave signals such as those used in wireless communications. The technique makes use of delta-sigma modulation of the phase and amplitude of the signal. The generation of OQPSK signals is shown as an example. The approach is a candidate for the design of single-chip, DSP-based transmitters.**

I. INTRODUCTION

Microwave signals associated with spectrally-efficient modulation formats used in wireless communications have time-varying envelope, and as a result power amplifiers in the transmitters must have adequate linearity. One of the most significant challenges for power amplifier architecture development is to provide the required linearity without sacrificing efficiency. To this end, one promising approach is to use high efficiency amplifier configurations together with appropriate modulation formats that can provide envelope variation. As shown by Raab [1], the RF pulsewidth modulation technique is useful to provide both efficiency and linearity in amplifiers. One of the challenges for the implementation of this technique, however, is the generation of the requisite signals. This paper demonstrates a new technique in which RF pulse modulated signals at microwave frequencies can be simply generated with digital signal processing (DSP).

The use of CMOS-based DSP to implement RF functions is increasingly effective as DSP performance increases and its cost in terms of power dissipation and circuit area drops. According to the ITRS Roadmap, the clock rate of high performance chips will reach 3.5 GHz in 2005. This suggests that CMOS will have a significant role in microwave functions, not just as analog-based "RF CMOS", but in the form of digital circuits. DSP based systems potentially can provide many benefits for an RF transmitter: no tuning requirements, no temperature drift or aging problems, higher integration and smaller size, ability to time-delay, error-correct and control nonlinearity, easier circuit test, and, potentially, much greater flexibility and programmability.

In this work we demonstrate a technique to generate RF pulse modulated signals based on input signals prescribing desired phase vs. time and envelope vs. time. These inputs are fed into corresponding delta-sigma modulators [2], whose outputs are used with a digital pulse delay modulator and pulsewidth modulator. Using OQPSK signals (similar to those used for IS-95 CDMA) as an example, it is shown that the resultant output spectrum has the requisite linearity to meet the communication system specifications on adjacent channel noise generation. Experimental signals generated with high speed digital circuits are shown (up to a carrier frequency of 400MHz only, limited by the experimental apparatus).

II. SIGNAL GENERATION APPROACH

Figure 1a illustrates a representative microwave signal to be encoded, with narrowband phase and amplitude modulation. Fig. 1b depicts a corresponding RF pulsewidth modulated signal, composed of a binary level signal with pulse period corresponding to that of the microwave signal, and pulsewidth varied in accordance

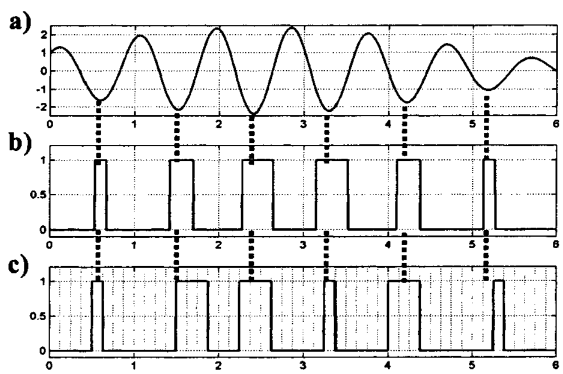

Fig. 1: Representative RF pulse modulated waveforms: (a) Desired microwave signal; (b) RF pulse modulated waveform; (c) Δ−Σ RF pulse modulated output.

with its amplitude. For linearly amplified pulses, the width of each pulse should be varied in proportion to the inverse sine of the microwave amplitude [1]. The pulse spacing and pulse width are continuous variables. The generation of accurate pulse waveforms using analog electronics is a challenging task. In this work, an alternative modulation scheme is proposed, which approximates the RF pulsewidth modulated signal, and can be easily generated using digital techniques. The proposed RF pulse signals are clocked binary level waveforms, so that pulses are produced only at integer multiples of the (unmodulated) system clock period, and have widths that are also multiples of that period. Fig. 1c illustrates a specific example, where the high-speed digital clock frequency is at approximately 8x the center frequency of the microwave signal. The output pulses are centered on any one of 8 possible positions in the RF cycle. If the desired phase to be encoded has a value intermediate between the allowed phase choices, then the output alternates between allowed values on either side of the desired phase, providing an average phase with the proper value. The alternation between signals of incorrect phase produces phase noise. If the alternating sequence of phases is produced using delta-sigma techniques, however, the noise thus introduced becomes largely shaped out of the frequency band of interest. The noise can be substantially removed from the output using moderate Q filtering at the output of a power amplifier. Similarly, in order to encode the amplitude, the pulse width can be selected to be one of a discrete set of values; in this example, it is chosen to be three clock periods wide, one clock period wide or zero periods wide. To encode any intermediate value, an alternation of allowed values is used, given the proper average on the time-scale of the modulation.

The output signals can be encoded using the system shown in fig. 2. The inputs are the desired phase and amplitude modulation signals, typically available within a DSP unit. These signals are fed to digitally driven delta-sigma modulators (also known as requantization filters), operated with a clock frequency f_c chosen to be near the desired microwave output frequency. The phase delta-sigma modulator provides a digital output word corresponding to the allowable choices of pulse position (in the example, one of 8 possible values together with possibly a phase overflow and/or underflow bit). The delta-sigma modulator output controls a digital pulse delay modulator, which acts on an input periodic pulse train with period f_c, and pulse width $1/8f_c$, as shown in fig. 2, to produce an output pulse train. This, in turn, is fed to a pulse width modulator, which selects a pulsewidth of $1/8f_c$, $3/8f_c$ or zero, in accordance with the amplitude delta-sigma modulator output.

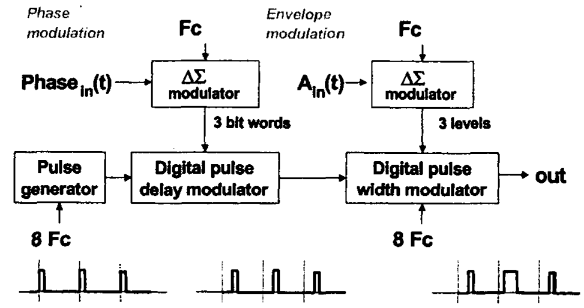

Fig. 2: Block diagram of delta-sigma RF pulsewidth modulation system. Representative output signals are shown.

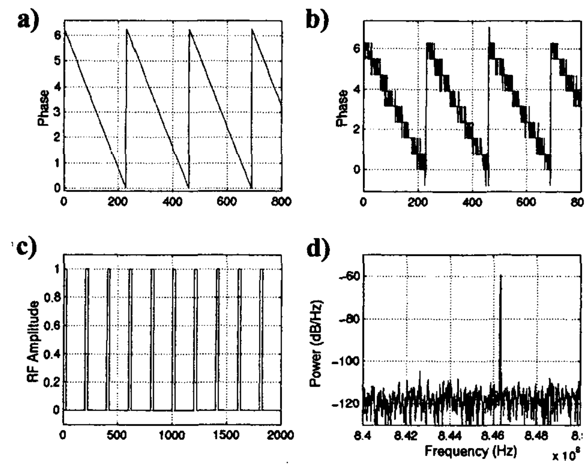

Fig. 3: Simulated waveforms for phase modulator: (a) Input phase vs. time; (b) Δ–Σ modulator output vs. time; (c) RF pulse position modulated output vs. time; (d) Computed output power spectrum of RF pulse.

The pulse modulators require the use of digital clocks at $8f_c$ (approximately 7GHz for cellular band communications), but the remaining digital circuits have clocks at f_c. Since the signals to be encoded have small fractional bandwidths, a high effective oversampling ratio can be obtained in the delta-sigma modulators (of order 16-30).

Operation of the modulation technique has been studied using Matlab simulations. In fig. 3 are shown the waveforms corresponding to the phase modulator portion of the system. The input phase modulation vs. time (fig. 3a) is a linear ramp (expressed modulo 2π), corresponding to a sinewave of fixed amplitude and frequency shifted

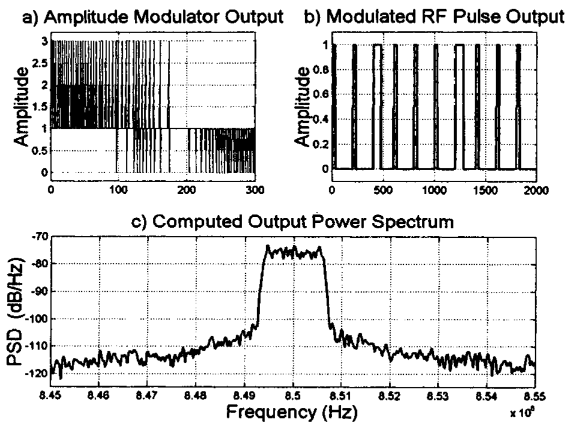

Fig. 4: Simulated waveforms for full CDMA modulation.

from the clock frequency f_c. A first order delta-sigma modulator is used, with 3 output bits plus an overflow bit and an underflow bit, corresponding to 8 possible output pulse positions; the output is shown in fig. 3b. The encoded digital output pulse train is shown schematically in fig. 3c, and its power spectrum (obtained by FFT) is shown in fig. 3d, over a narrow frequency range around the clock frequency f_c. The output spectrum shows the desired output frequency, together with broadband noise at a level of -60 dBc/Hz and several spurious tones, the largest of which is at a level of -45dBc. These nonideal output components result because the modulation approach (which separates the phase from amplitude modulation) is not strictly linear. Some of the quantization noise is folded back into the frequency band of interest by the residual nonlinearity. An alternative technique has also been devised which has improved linearity, at the cost of increased computational complexity. Nonetheless, with the present approach, the levels of noise reduction and spurious frequency suppression can be adequate for a wide range of applications. With a two-tone input signal, the levels of 3rd order intermodulation tones are below -45dBc, for input signals that are up to 10 dB below the maximum input signal. Figure 4 shows corresponding waveforms for a CDMA input signal. The output of the envelope delta-sigma modulator is shown in fig. 4a, while the output waveform for the full pulse modulated signal is shown in fig. 4b, and the associated power spectrum in fig. 4c. The noise generated in adjacent channels is below the level specified for the IS-95 format.

III. EXPERIMENTAL TECHNIQUE AND RESULTS

To experimentally demonstrate the proposed modulation technique applied to wireless communications signals, a bit stream was computed (using MATLAB) and stored in a

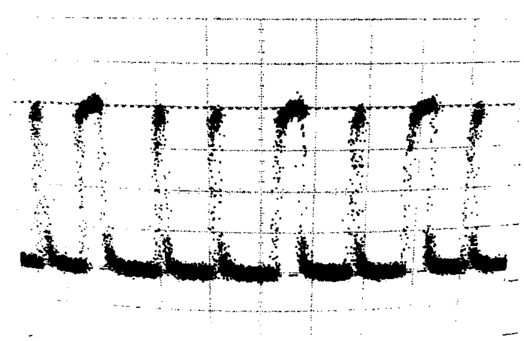

Fig. 5: Measured digital output data stream (scale: 2nS per division, 200 mV per division).

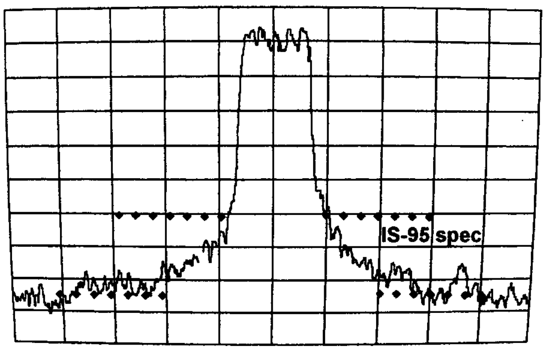

Fig. 6: Measured output spectrum for OQPSK signal (span 5 MHz, center frequency 400MHz, 5 dB/div vertical scale). Limits for adjacent and alternate channel power for IS-95 signals are shown.

pattern generator [3]. The digital signals could be read out (in a repetitive fashion) at a rate of up to 200Mb/S per channel. In order to demonstrate signals at higher frequencies, a digital 16:1 serializer (Conexant CX60061 chip implemented in GaAs HBT technology) was used to combine the data of 16 separate channels, providing an output at 3.2Gb/S [3]. A representative output pulse stream is shown in fig. 5.

After programming the logic analyzer with an OQPSK signal (such as used in CDMA IS-95), the output data stream was measured with a spectrum analyzer. The maximum achievable clock frequency for our system was 3.2GHz (limited by the logic analyzer); correspondingly, the output frequency was chosen to be 400MHz (rather than 850MHz as needed for IS-95 CDMA). Fig. 6 shows representative results, on a fine-grained frequency resolution. The OQPSK characteristic output signal is visible, and the background noise in the neighboring frequency band is low. The figure shows schematically the limits on spurious power for the transmitter in the

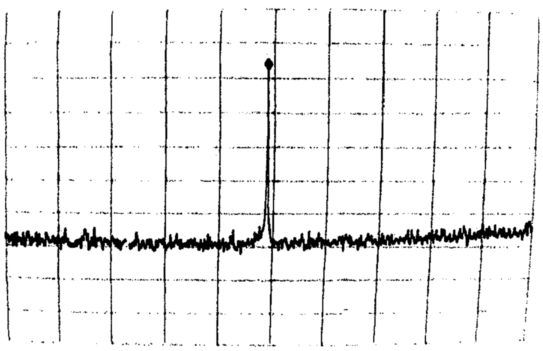

Fig 7: Measured output spectrum for single frequency output (span 140 MHz, center frequency 400 MHz, 10 dB/div vertical scale).

adjacent and alternate channels imposed by IS-95 specifications. The digital signal is within the bounds of the adjacent channel power specification. The broadband noise background extends to the receive band of the CDMA system, however, and special filtering is required to eliminate it from the output [3].

Fig. 7 shows a corresponding output spectrum for single frequency generation. The clock frequency corresponds again to 400MHz (limited by the experimental system), and a frequency shift of 1.8MHz is encoded. The output spectrum shows the desired frequency, with broadband noise also present, at the level of -90 dBc/Hz. The lineshape of the signal is limited by the windowing of the signal record.

IV. APPLICATION TO CLASS C AMPLIFIERS

RF pulsewidth modulated signals are advantageous for use with Class D switching-mode amplifiers [1], and can lead to efficiency greater than what can be obtained with other more general forms of modulation, such as delta-sigma modulation [3]. Such amplifiers are not in common use at present, stemming partly from the difficulty of implementing these amplifiers with n-channel (or npn) transistors only. Here we show that the RF pulsewidth modulated signals are also useful for operation with Class C amplifiers, which are easier to implement with a single output transistor. Fig. 8 shows waveforms simulated for a Class C amplifier, driven by the RF pulsewidth modulated signals. The transistor output voltage waveform reaches a minimum during the period when the transistor output current is flowing, maximizing efficiency. For signals requiring backoff for full output power, the amplifier efficiency is reduced, however, in a manner similar to Class AB amplifiers. Class C operation typically is highly nonlinear, inadequate for representative communication

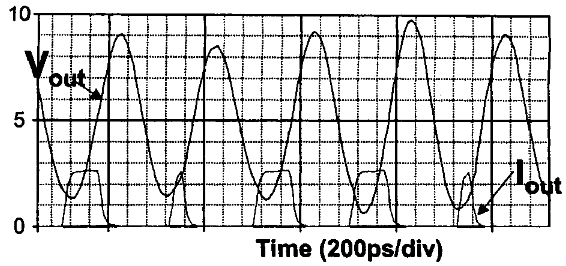

Fig 8: Simulated waveforms for Class C amplifier, driven by RF pulsewidth modulated signals.

signals. The present technique provides the opportunity for obtaining quasi-linear outputs. In conventional Class C amplifiers, finite risetime can significantly degrade linearity. In the present situation, the finite risetime of the current output can be compensated by changing the relative weighting function associated with the different output pulse widths, in the amplitude delta-sigma modulator.

V. CONCLUSION

A simple DSP-based architecture for generation of RF pulsewidth modulated signals has been demonstrated. The use of these signals eliminates the need for a high resolution DAC, and enables the use of Class C or Class D amplifiers, which have the potential of higher efficiency. The architecture offers a variety of potential advantages, including easy integration into a single chip IC, absence of tuning problems, and programmability of the transmitter functions.

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