QUADRATURE INTEGRAL NOISE SHAPING FOR GENERATION OF MODULATED RF SIGNALS

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ABSTRACT

This paper introduces a method to produce a modulated RF signal using a digital pulse signal switching at the carrier frequency. The entire modulation and amplification lineup is implemented in the digital domain. Integral Noise Shaping (INS) is used to create the baseband signals (I,Q) as digital PWM signals which are then mixed with a pair of digital carrier signals. All the edges of the digital pulse modulated signal line up with an edge of a fixed frequency clock signal at twice the carrier frequency. The resulting digital signal has high linearity and low quantization noise. All switching spurs and the quantization noise can be cleaned up with a bandpass filter with reasonable Q factor. Simulation results are presented for an offset tone test signal.

1. INTRODUCTION

Generation and amplification of amplitude and phase modulated RF signals in the digital domain is desirable from stand point of cost, efficiency of the output stage and overall reduction of power drain. There have been numerous attempts to produce a modulated RF signal using a pulse signal but they often need to switch the pulse waveform at rates significantly higher than the carrier frequency [1]. This reduces efficiency and is not feasible at higher carrier frequencies. Analog PWM has also been used to produce a modulated RF signal by switching at the carrier frequency [2], [3]. While it produce a very efficient final stage it does not eliminate the sensitive analog circuits in the transmitter lineup. It in fact needs additional sensitive high speed analog circuits.

The goal of this method (Quadrature INS) is to switch at the carrier frequency using a fixed frequency clock and use a nominally 50% duty ratio. While these goals make the signal processing harder the RF power stage has the most desirable pulse waveform to produce and amplify. The overall goal is to make a more digital and flexible RF transmitter lineup with higher power conversion efficiency and reduced current drain.

2. THEORY

2.1 Integral Noise Shaping (INS)

INS is a technique for noise shaping the quantization noise of PWM which has performance similar to that of quantized PCM[4]. The INS algorithm takes the difference between the input unquantized PWM and the output quantized PWM. This difference signal is analytically integrated multiple times at twice the rate of the switching frequency. The input duty ratio is modified by the weighted sum of the integrals. This compensates for the previous quantization errors. The modified duty ratio is then quantized to produce the output duty ratio. The INS algorithms is thus used to produce a PWM signals (IPWM and QPWM) corresponding to each of the based signals (I and Q). The details of the algorithm are provided in reference [4], [7].

2.2 Natural Sampling

Natural sampling is a necessary step for linearization of digital PWM. In absence of this step the PWM output has harmonics of the input baseband signal. Natural sampling for digital PWM produces a PWM duty ratio that is identical to the comparison of a continuous analog signal with a linear ramp. Detailed description of this techniques has been provided in the literature including references [5], [6].

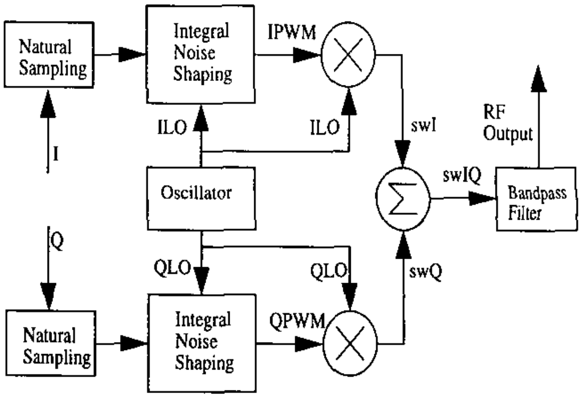

Figure 1. Quadrature INS Schematic

2.3 Quadrature INS

Quadrature INS works by taking the individual baseband signals (I,Q) in digital domain and creating a PWM signal corresponding to each (IPWM, QPWM). The switching frequency of the PWM is limited only by signal processing constraints and is chosen to be a subharmonic of the carrier frequency. A pair of clock signals (ILO, QLO) corresponding to the carrier for the in phase and quadrature paths is generated from the local oscillator. The PWM signals are also quantized such that the PWM edges for the in phase PWM IPWM is synchronized to the respective clock signal ILO and QPWM is synchronized to QLO. The digital PWM signals are mixed with the digital local oscillator signals. The mixing is simply a digital logic operation. The output of the mixers generates the two switching signals swI and swQ. These are sent to the power stage and combined.

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Figure 1 shows a block diagram of the Quadrature INS system. Figure 2 shows the corresponding digital signals in time domain. Note that the final pulse signals are switching at the carrier frequency rate. The duty ratio for most cycles is exactly 50%. When the PWM signals (PWMI or PWMQ) has a transition the corresponding switching signal (swI or swQ) skips a pulse transition.

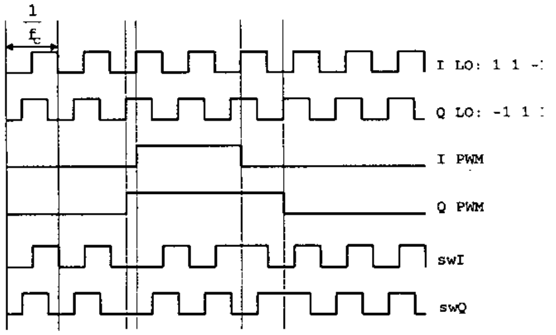

Figure 2. Signals of Quadrature INS

2.4 Interleaved Quadrature INS

By allowing the in-phase and quadrature clocks (ILO and QLO) to be ternary rather than binary the combined quadrature modulated signal can be made binary. This would allow the signal to be produced by a half bridge and reduce matching requirements for a full bridge application. The only additional constraint is that in cycles when the PWM has a transition the power stage has to produce a 25% duty ratio signal. The signals are shown in time domain in figure 3 below.

Note that in figure 3 the switching drive signal is binary. In an implementation the ternary signals for ILO and QLO don't actually need to be produced. The oscillator in this case needs to produce a clock at 4 times the carrier frequency or a 50% duty ratio clock at twice the carrier frequency.

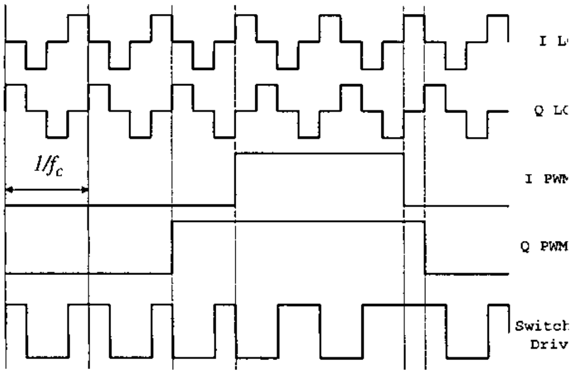

Figure 3. Interleaved Quadrature INS Signals

3. SPECTRAL MAPPING OF QUADRATURE INS

The mapping of a complex baseband signal from dc to the carrier frequency using pulse square wave carrier signals is not trivial. Figure 4 and Figure 5 show the incorrect and correct way of doing this transposition. The original baseband signal is sampled and held and then multiplied by the respective carrier signals. The quarter cycle delay between the two pulse carrier signals (ILO and QLO) is critical to correct mapping of the complex baseband signal to the carrier frequency.

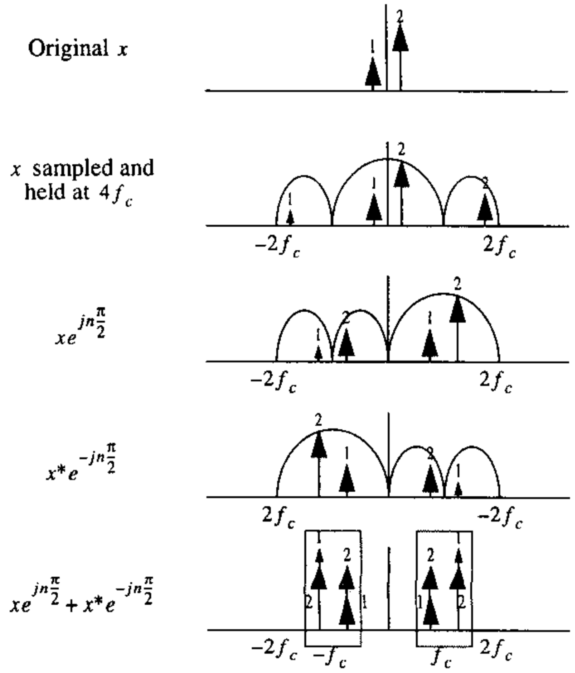

Figure 4. Incorrect Spectral Mapping

Since the fundamental sample rate of the system is $4f_c$, it suffices to consider the spectrum within the band $[-2f_c, 2f_c]$. The I- and Q-LO's are sampled versions of the signal $\cos(2pf_ct)$. One may consider the combined I- and Q-modulation to be the complex modulation of the signal $x = pwm_I + jpwm_Q$. Since x is produced at a lower rate than $2f_c$, it exhibits repeated spectra at most every $2f_c$. Consequently, the complex modulation translates x up in frequency and x^* (x conjugate) down in frequency. This conjugate image overlaps the desired modulation, as shown in Figure 4.

On the other hand, if the imaginary portion of x (i.e. pwmQ) is delayed by a quarter period of the carrier, we effectively produce a phase shift of π near 2fc, leaving pwmQ virtually unchanged near dc. This phase shift is only applied to pwmQ. Consequently, the imaginary part of x is inverted near $2f_c$, while the real part is changed. We have in effect produce the conjugate of x at frequencies near 2fc. Consequently, upon down-conversion, we obtain a replica of x which overlaps our desired modulation. As a result, we do not see the conjugate image problem, as shown in Figure 5.

In this paper we use PWM to convert the baseband signals (I,Q) into pulse signals before being translated to the carrier frequency. However, the spectral mapping analysis above shows that other pulse modulation schemes like pulse density modulation (PDM) would also produce the correct modulation.

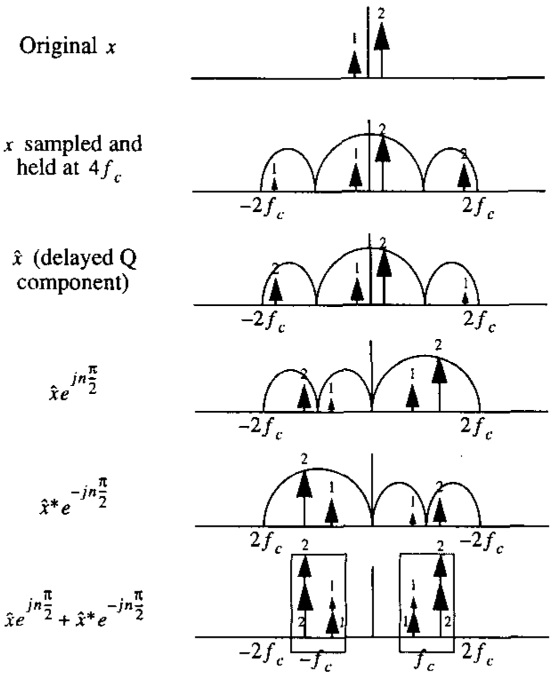

Figure 5. Spectral Mapping for Quadrature INS

4. SIMULATION RESULTS

4.1 Simulation conditions

The carrier frequency is chosen to 2GHz. The PWM frequency is chosen here to be 50MHz. The passband is 20MHz. For the purpose of the simulation the modulation is chosen to produce a single tone offset from the carrier center frequency by -8MHz. Figures 6 and 7 show spectrum and near spectrum for this case. Note that we get spurs at the carrier frequency plus and minus the PWM switching frequency. There is also intermodulation of these frequencies with the modulation frequency

The noise shaping is chosen to be fourth order which results in a pair for nulls in the baseband signal. After translation to the carrier frequency we see 4 nulls in the passband.

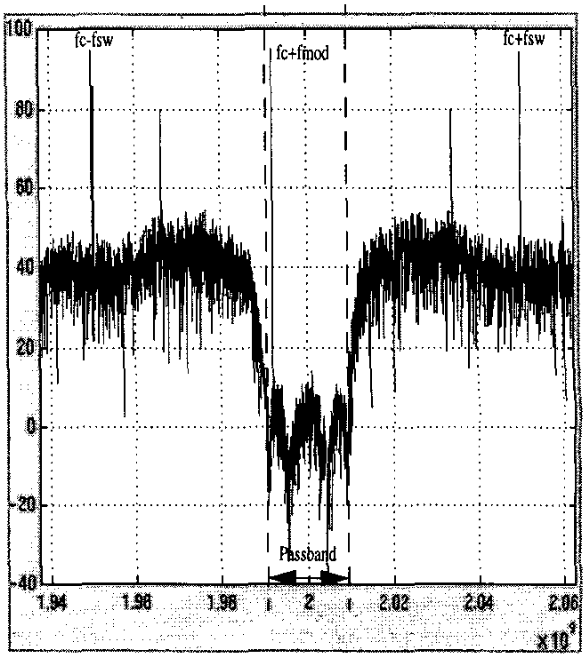

Figure 6. Simulated Spectrum of Quadrature INS

The loop coefficients in the noise shaping INS loop are optimized to provide a very flat low noise in the passband. The total SNR over the entire passband is found to be about 60dB. The ACP over a smaller channel is much higher. In the example chosen a single tone is created offset from the carrier. Any arbitrary complex modulation could have been created using the same step. The input baseband signals I and Q would have to be chosen accordingly.

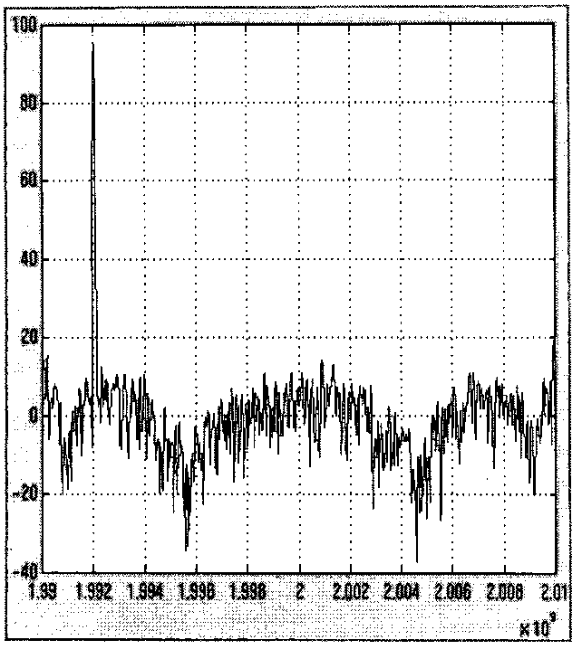

Figure 7. Near Spectrum of Quadrature INS

Table 1 below shows the total SNR plus distortion number for three different examples with the same carrier frequency but different switching frequencies and passbands. The wider passbands make the bandpass filter after the power stage easier to realize.

Table 1: Ratio of Signal to total Noise plus Distortion in the Passband

Carrier Frequency	PWM Frequency	Passband	SNR over the entire passband	Order of Noise Shaping
2.0GHz	200MHz	20MHz	97dB	4
2.0GHz	200MHz	80MHz	51dB	4
2.0GHz	50MHz	20MHz	60dB	4

5. OUTPUT STAGE CONSIDERATIONS

The output stage of the amplifier sees a switching signal at the carrier frequency with a nominal 50% duty ratio. The output stage is a class D switching stage as opposed to a tuned class C, E or F stage. In the non interleaved version a fullbridge power stage is required. This is not a big limitation since a push-pull fullbridge stage produces more power with better linearity. Mismatch between the two sides of the power stage results in unequal gain between the I and the Q signals. When the digital PWM signal has a transition a pulse edge is skipped.

In the interleaved version the transitions are marked by a 25% duty ratio cycle. In this case the complex baseband signal can be mapped entirely to a single pulse signal and can be generated by a half bridge. Most applications would use a full bridge to get higher power and better linearity. The nature of the switching signals with nominal 50% duty ratio and minimum off and on times make it suitable for use at high frequency RF bands.

The power stage is not resonant and the same stage can handle different carrier frequencies. The switching spurs and the quantization noise that has been shaped outside the passband are filtered by a bandpass filter. Depending on the linearity and SNR requirements the PWM frequency is chosen. The higher the PWM frequency the wider the bandwidth of the passband filter. The order of noise shaping in the INS noise shaping is another design variable that can be used to optimize the design given bandpass filter constraints and computational constraints.

6. CONCLUSION

A method to produce amplitude and phase modulated RF signals using digital PWM signal has been described and simulated. Using a fixed quantization clock frequency no higher than twice or four times the carrier frequency a complex baseband signal can be modulated to the carrier. The digital pulse signals switch at the carrier frequency with a nominal 50% duty ratio. This method has potential to be the preferred way to generate modulate and amplify linear RF signals.

7. DISCLAIMER

The technologies described in this paper are covered under US Patent No. 6,414,613, and other pending Motorola Inc. patents.

8. REFERENCES

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[7] US Patent No. 6,414,613, July 2, 2002, "Apparatus for noise shaping a pulse width modulation (PWM) signal and method therefor", by Pallab Midya and Matt Miller.