A SIGMA-DELTA BASED OPEN-LOOP FREQUENCY MODULATOR

Denis Daly and Anthony Chan Carusone

University of Toronto
Dept. of Electrical and Computer Engineering
10 King's College Rd., Toronto, CANADA, M4S 3G4

ABSTRACT

A constant-envelope, continuous phase modulation architecture is presented in which a sigma-delta modulator is combined with an open-loop modulator. Compared to existing architectures, Σ-Δ based open-loop modulation can be implemented with minimal analog circuitry. The architecture is demonstrated with a discrete implementation performing frequency modulation at a carrier frequency of 120 MHz. By increasing the Σ–Δ modulation frequency, the quantization noise is filtered out by the VCO and disappears beneath the measurement noise floor.

1. INTRODUCTION

Sigma-delta modulators have been applied to a variety of electronic circuits because they can often be used in place of complicated analog circuits like DACs. In phase-locked loops, Σ–Δ modulation has been applied to fractional-N frequency synthesis, whereby a Σ-Δ modulated signal controls the instantaneous frequency division modulus [1].

This paper will present a constant envelope modulation architecture in which a Σ–Δ modulator is combined with an open-loop modulator. In this approach, the sigma-delta modulator switches the frequency of the voltage controlled oscillator (VCO). When the Σ–Δ modulator is properly matched with the VCO, the Σ–Δ quantization noise can be filtered out directly by the VCO.

In Section 2 of the paper, the proposed Σ–Δ open-loop modulation architecture will be presented and compared with existing modulation architectures. Section 3 will outline how the Σ–Δ modulator and voltage controlled oscillator were implemented, and Section 4 will present the experimental results.

2. ARCHITECTURE OVERVIEW

2.1 Existing Architectures

There are three popular methods to perform phase/frequency modulation of a digital signal: quadrature modulation, open-loop modulation, and modulated synthesis. Fig. 1 shows block diagrams for each of these methods.

Quadrature Modulation

Of these three methods, quadrature modulation is the most commonly used approach for digital phase/frequency modulation.

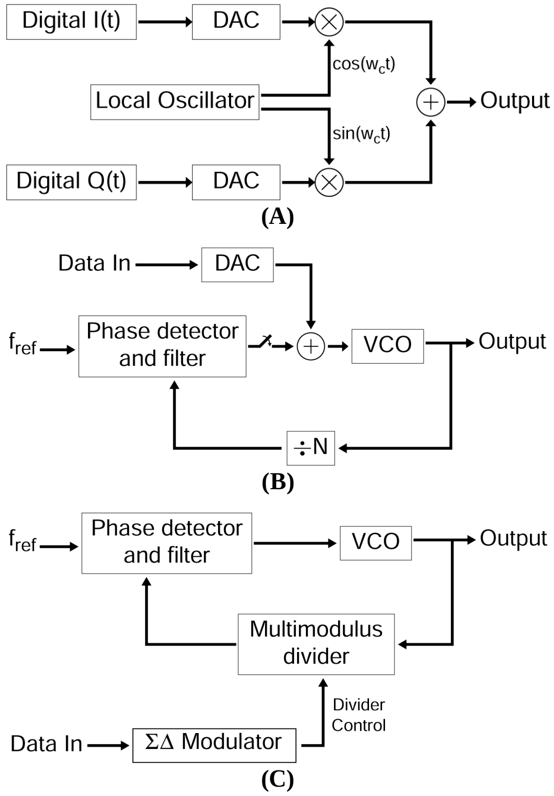


Figure 1. Three popular methods to modulate a signal
A) Quadrature modulation
B) Open-loop modulation
C) Modulated synthesis

This method allows for a high-quality signal to be generated because the oscillator is disassociated from the baseband signals [2]. The architecture is also very flexible. However, these advantages come at the cost of increased circuit complexity. There is the need for two DACs and two analog multipliers to accommodate the in phase and quadrature signals.

Open-loop Modulation

An architecture that eliminates the need for quadrature baseband DACs and a separate local oscillator is the open-loop modulator. Although the open-loop modulator still requires a single DAC, the architecture is simple to implement and is an attractive option for a low-cost, low-power modulator. Unfortunately, there are several problems inherent in the open-loop modulator architecture. While transmitting data, the open-loop modulator must periodically halt transmission to stabilize the center frequency of the VCO. In addition, the VCO must have a linear tuning curve to ensure that the output is not distorted. Even if the VCO has a linear tuning curve, the slope of the curve determines the bandwidth of the output signal and thus must be calibrated to control the output bandwidth.

Modulated Synthesis

Like the open-loop modulator, the modulated synthesizer does not require as much analog circuitry as the quadrature modulator. As well, the modulator synthesizer does not suffer from the open-loop modulator’s requirements of a linear VCO tuning curve and periodic frequency stabilization [3]. However, the modulated synthesizer requires a multimodulus divider and precompensation or two-point-modulation of the input signal to compensate for bandpass filtering caused by the PLL [4].

2.2 Proposed Architecture

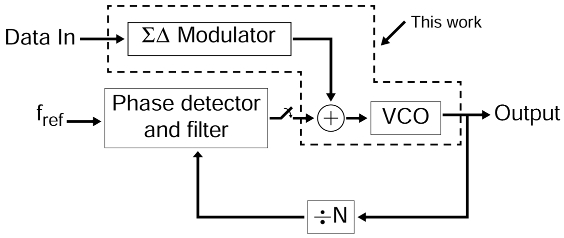


Figure 2. A sigma-delta based open-loop modulator

The proposed architecture, seen in Fig. 2, is a sigma-delta based open-loop modulator. Like the modulated synthesizer, this approach uses a Σ–Δ modulator to avoid using a DAC and thus decreases the analog circuit requirements. In a Σ–Δ based open-loop modulator, the output frequency switches between a discrete set of frequencies as the output of the Σ–Δ modulator switches between discrete levels. As with the traditional open-loop modulator, the loop must periodically close to stabilize the center frequency.

When a one-bit Σ–Δ modulator is used, the VCO only switches between two frequencies and the tuning curve of the VCO is assured to be linear, regardless of the linearity of the tuning device. In traditional open-loop modulators, high quality varactors are needed to achieve a linear tuning curve. Even though a one-bit Σ–Δ modulator can ensure a linear VCO tuning curve, it is still necessary to control the slope of the tuning curve, which defines the output bandwidth. An additional benefit when using a one-bit Σ–Δ modulator is that the adder is trivial to implement.

A drawback with using a Σ–Δ modulator is that its quantization noise must be filtered out before transmitting the output signal. Modulated synthesizers filter out the quantization noise by using the bandpass filtering built into the PLL. However the PLL bandwidth cannot be easily controlled as it is primarily determined by other system requirements such as frequency tracking and jitter specifications.

Similar quantization noise issues arise with the Σ–Δ based open-loop modulator, except that the VCO bandwidth needs to be considered instead of the PLL bandwidth. The VCO bandwidth represents the extent to which the signals outside the frequency bandwidth of interest are attenuated. This attenuation is primarily determined by how quickly the VCO can switch between frequencies. At low Σ–Δ frequencies, the VCO frequency switching can be considered to be instantaneous, and thus all of the quantization noise is passed to the output of the PLL. However, when the Σ–Δ modulator frequency becomes sufficiently high, the VCO frequency switching time becomes significant and the VCO can ideally act as a bandpass filter, filtering out the quantization noise.

3. IMPLEMENTATION

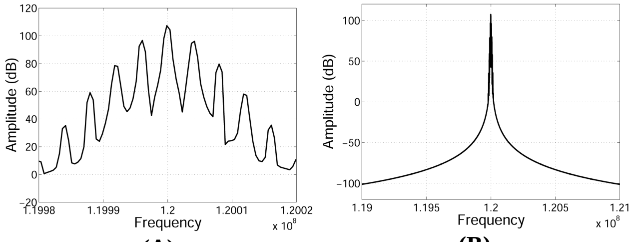
3.1 S-D Modulator

The Σ–Δ based open-loop modulator was tested by implementing frequency modulation (FM). Implementing a more complicated, constant envelope modulation scheme would require additional signal processing before the Σ–Δ modulator. To generate an FM signal, the output frequency is varied with continuous phase around a carrier frequency in direct proportion to the signal being modulated.

$$f_{out}(t) = f_{carrier} + k \cdot v_{in}(t) \qquad (1)$$

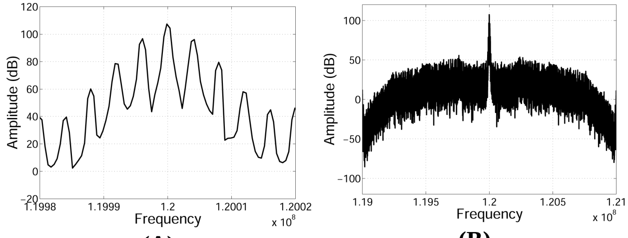
A one-bit Σ–Δ modulator was used to guarantee a linear tuning curve. When a one-bit Σ–Δ modulated signal is passed through a voltage controlled oscillator, the oscillator switches between two discrete frequencies. Near the carrier frequency, the quantization noise is not significant and the output frequency spectrum looks identical to that of a normal FM signal. Figures 3 and 4 show the narrow band and wide band frequency spectrums of a FM signal and a FM, Σ–Δ modulated signal. In Fig 4B), one can see the quantization noise that is not present in Fig. 3B).

By increasing the oversampling ratio of the Σ–Δ modulator, the noise is pushed farther away from the carrier frequency and a higher SNR can be achieved in the bandwidth of interest.



(A) **(B)**

Figure 3. (A) Narrow band and (B) wide band frequency spectrum of a FM sine wave



(A) **(B)**

Figure 4. (A) Narrow band and (B) wide band frequency spectrum of a FM, S-D modulated sine wave

3.2 Voltage Controlled Oscillator (VCO)

The voltage controlled oscillator can be implemented in a variety of ways, most commonly in the form of a LC oscillator or a ring oscillator. An LC oscillator was chosen because it is more stable over temperature variations than a ring oscillator. A single ended Colpitts oscillator was implemented instead of a differential oscillator because it can be easily constructed using discrete components. Fig. 5 shows the circuit topology of a Colpitts oscillator.

The output frequency of the Colpitts oscillator can be tuned in two separate ways:

1. Biasing a varactor in parallel with C1 and C2 to adjust the LC tank
2. Adjusting the bias current I1

Tuning was accomplished by adjusting the bias current I1, because the slope of the tuning curve could be easily controlled by adjusting a resistor.

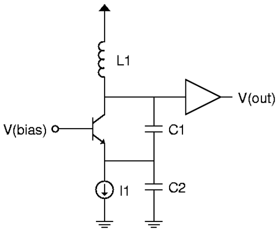


Figure 5. A Colpitts Oscillator

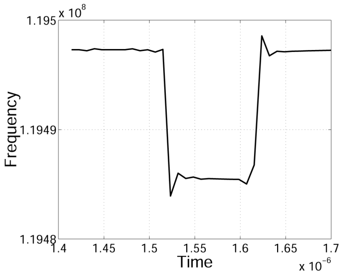


Figure 6. Instantaneous output frequency of oscillator when switching the bias current I1

Frequency Switching Considerations

As discussed in Section 2.2, the VCO bandwidth must be sufficiently large to ensure that it does not cause attenuation in the bandwidth of interest. Ideally, the delta-sigma modulator should be operated at a frequency such that the VCO filters out the quantization noise but not any components of the actual signal. The bandwidth of the VCO is significantly affected by the time it takes to switch between the two frequencies. The VCO should switch smoothly (but not instantaneously) between frequencies with no overshoot [5].

Fig. 6 shows the instantaneous output frequency of the Colpitts oscillator when switching the bias current I1. The time-domain representation of the VCO output is:

$$v_{out}(t) = A\cos\left(2pf_c t + q_0 + k\int_{-\infty}^{t} f(t)\,dt\right) \quad (2)$$

In (2), ϕ is a time-dependent function representing the output of the Σ–Δ modulator. For a one-bit Σ–Δ modulator, ϕ switches between 1 and -1. Because the phase of the output signal is continuous, this architecture is well suited to implement continuous-phase modulated (CPM) signals like CPFSK and MSK [6].

4. EXPERIMENTAL RESULTS

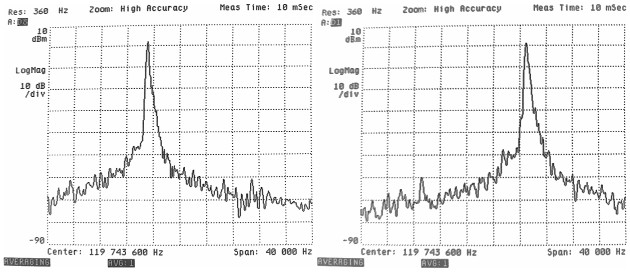
A 4 kHz sinusoid was passed through a second-order, one-bit Σ–Δ modulator at various oversampling ratios. The output of the Σ–Δ modulator switched the bias current through the oscillator, thereby switching the oscillation frequency between the two frequencies shown in Fig. 7.

When the Σ–Δ modulator was clocked at 1 MHz, the narrow band and wide band output frequency spectrums, shown in Fig. 9, closely match the simulated spectrums in Fig. 4. As expected, the Σ–Δ quantization noise is at a minimum at the carrier frequency and at 1 MHz away from the carrier frequency.

To reduce the quantization noise in the output, the Σ–Δ frequency was increased. Fig. 10 shows the narrow band and wide band frequency spectrums when the Σ–Δ modulator was clocked to 10 MHz. A 10 MHz Σ–Δ modulator still generates quantization noise, but at a frequency sufficiently far away from the carrier frequency such that the noise is filtered out by the VCO. No quantization noise is observable above the spectrum's noise floor.

The generated FM signal is narrow band, meaning that its bandwidth is not significantly larger than the 4 kHz signal being transmitted. The carrier frequency of the FM signal is 120 MHz.

Fig. 8 shows the printed circuit board of the VCO.



(A) **(B)**

Figure 7. (A) Lower frequency and (B) upper frequency that the oscillator switched between

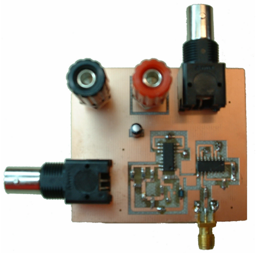


Figure 8. Printed Circuit Board

5. SUMMARY

In this paper we outlined Σ–Δ based open-loop frequency modulation, a modulation architecture that requires minimal analog circuitry to generate a constant envelope signal. Σ–Δ based open-loop modulation is superior to traditional open-loop modulation of a digital signal in that a DAC is not necessary.

To demonstrate the architecture, a one-bit, second-order Σ–Δ modulator was operated at 10 MHz with its output controlling a VCO. The VCO was implemented with discrete components, and the Σ–Δ modulator quantization noise disappeared beneath the measurement noise floor when implementing frequency modulation of a digital signal. Areas for continued research include designing an integrated PLL and fully-differential VCO on-chip, building a Σ–Δ modulator and DSP capable of generating GMSK modulated signals, and investigating multi-bit or bandpass Σ–Δ modulators in this architecture.

6. REFERENCES

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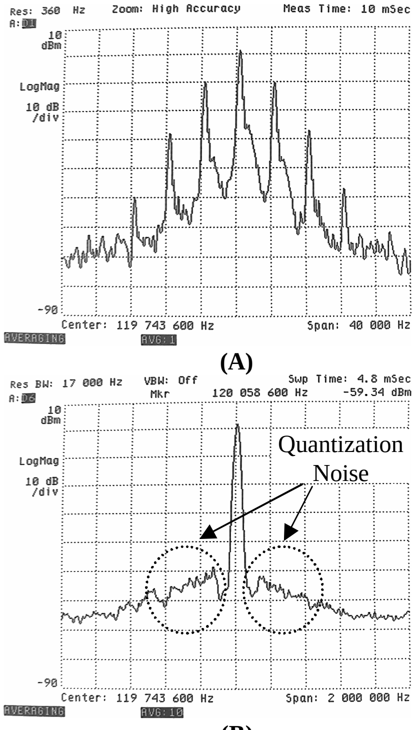
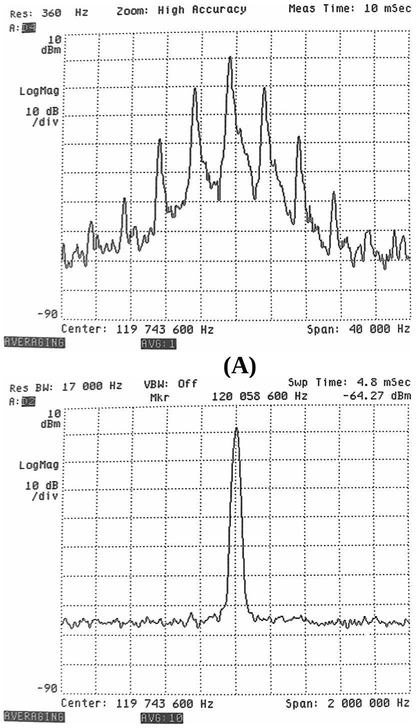


(A)

(B)

Figure 9. (A) Narrow band and (B) wide band frequency spectrum of a FM sine wave (S-D modulator clocked at 1 MHz)



(A)

(B)

Figure 10. (A) Narrow band and (B) wide band frequency spectrum of a FM sine wave (S-D modulator clocked at 10 MHz)