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Analysis of the impact of interferers on VCO-based continuous time delta-sigma modulators

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ABSTRACT

Analog to digital converters (ADCs) used in receivers, face desired and undesired signals. Undesired signals are located out-of-band (OOB) of interest and are stronger than the desired signal and degrade the performance of the ADCs. Continuous time (CT) delta-sigma modulators (DSMs) can provide inherent anti-aliasing and hence they relax the requirement of the dynamic range. In this paper the behavior of CT-DSMs, utilizing voltage controlled oscillators (VCOs), for receiver applications are studied. The results indicate that, due to the frequency modulation occurring in the VCOs, when interfering signals are applied at the half of the sampling frequency (f_s), integer multiples of the carrier frequency (f_c) and $f_c/2, f_c/3 \ldots$, modulation tones appear in the bandwidth of the desired channel. This leads to degradation of the signal to noise and distortion ratio (SNDR). An analytical expression for the output signal of the VCO-based integrator in the presence of the interferers has been derived. In addition, behavioral simulations are done for both cascade of integrators in the feedback structure (CIFB) and cascade of integrators in the feedforward structure (CIFF) as well as multi-stage noise shaping (MASH) structures. It will be discussed how the designer should choose the suitable structure.

1. Introduction

Nowadays, there is a growing interest in the wireless communication to reduce the complexity of the analogue part of the radio frequency (RF) receivers. It is not difficult to detect in-band signal (IB), because the required signal to noise ratio (SNR) is not very high. A major problem is to simultaneously manage all the received interfering or blocker signals which are outside the band of interest. These out of band signals are typically stronger than desired signals, and hence, they increase the area and power of the receiver systems.

Fig. 1 shows a simplified receiver architecture. The antenna receives wireless signals. The Low noise amplifier (LNA) amplifies the weak in-band (IB) signal to an adequate level and it is followed by a mixer, which converts the RF-signal to the base-band. Since the IB signals are weaker than the OOB signals, therefore the channel select filter (CSF) is used to attenuate the OOB signals. The CSF has a low pass characteristic and can attenuate the OOB signals. In principle, strong OOB signals cause instability, can saturate the building blocks of the modulator and reduce the A/D conversion accuracy (due to distortion, insufficient ant-aliasing) [1]. The continuous time delta-sigma modulators (CT-DSMs) are a suitable choice for the receiver ADCs [2,3]. This is because anti-aliasing requirements (AAF) are reduced due to the oversampling operation of DSMs. As a result, the CSF can be simplified or even eliminated [4]. Compared to their discrete time counterparts, not only they provide implicit anti-aliasing, but also they can reduce the effect of OOB signals. This is due to their CT signal transfer function (STF). Furthermore, they have more robustness to the circuit non-idealities compared to other ADCs. Hence, due to the mentioned features, CT-DSMs have received increasing attention for broadband wireless communication.

In recent years, several studies and analyses have been conducted on the impact of interferers on the performance of DSMs. The sensitivity analysis should be done when designing a DSM to determine the ADC dynamic range budgeting and requirements of the CSF. As the interferers exceed a certain limit, they cause distortion, spurious tones and an increase noise in the bandwidth. These are some important effects that influence the allowable interferes level: 1-Intermodulation Distortion, 2-Aliasing, 3-Spurious Responses, 4-Stable Input Range. The authors of [5] have explained the impact of these effects on the performance of the DSMs. They came to the conclusion that to have more suppression of alias tones and make the modulator less prone to spurious responses, it is better to use CIFB instead of CIFF

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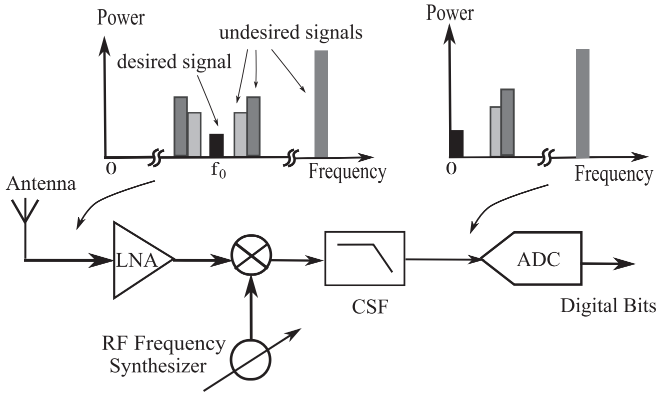

Fig. 1. Simplified block diagram of a receiver.

architecture, because CIFB architecture provides more filtering for interferers.

In Ref. [6] the sensitivity of the CT-DSM to the feedback pulse-width jitter (PWJ) in the presence of OOB signals has been analyzed and discussed. It is shown that, the PWJ induced errors due to OOB signals, dominate the total in-band noise power and can cause a reduction in SNDR by 12 dB. In Ref. [7] the sensitivity of DSMs to the slow rate and the nonlinearity of the integrators in the presence of the interferers have been analyzed. It is shown that if slewing happens at the integrator output, the combined waveform including the desired in-band signal and the OOB signal cause nonlinear settling, which results in distortion and dramatic increase in the noise floor.

In addition to the analysis of the performance of the DSMs in the presence of the interferers which shows the importance of this topic, some attempt have been done in prior works to improve the behavior of the DSMs in the presence of the interferers. As mentioned above, in order to attenuate the OOB signals, a CSF is often placed in front of the ADC, so that the ADC can process the desired signal. However, the order of CSF should be high enough to sufficiently attenuate the OOB signals, which results in design complexity and high power consumption [7].

A filtering ADC is proposed in Ref. [8], where a CSF and a CT-DSM are placed in a same feedback loop. The filtering ADC provides additional noise shaping which can be exploited to save power. In Ref. [9] a passive low pass filter is embedded in a CT-DSM. The delay of the added low pass filter has been compensated without any active elements which, in turn, leads to less power consumption.

Moreover, for modulators which are used in receivers for the next-generation wireless standards, it is necessary to have sufficient dynamic range while increasing the bandwidth [10]. However, as the CMOS IC technology advances, the supply voltage is reduced. As a result, the design of op-amp based circuits becomes more difficult, while, the accuracy of the time-based circuit improves [11,12]. VCO-based ADCs are examples of time-based circuits, therefore, they are a good candidate for modern communication applications. VCO-based ADCs have outstanding features, such as first order noise shaping [13,14]. Moreover, both the time resolution and the speed of these types of converters improve with technology scaling [15]. As a result, they have become more popular among researchers in recent years [16,17].

We have explained briefly prior studies on CT-DSM utilizing op-amp based integrators. The impact of OOB signals on the performance of the DSM utilizing VCOs is not yet studied. Prior works are op-amp based and due to the frequency modulation which happens in the VCO-based modulators, their analysis is different from op-amp based modulators. Assessment of the sensitivities of the DSMs to OOB signals, implemented with VCO-based integrators and quantizers is presented in this paper. The analysis has been done for both CIFF and CIFB architectures, as well as MASH architecture. The rest of the paper is organized as follows. In section 2 we will derive a closed form expression for the output signal of a VCO-based integrator in the presence of both OOB signal and input signal. In section 3 a third-order modulator with a 3-bit quantizer is chosen as a test bed and simulations are performed to evaluate the effect of OOB signals on the performance of the modulator. Behavioral simulations are done for both CIFB structure and CIFF structure. In section 4 and 5 the impact of the OOB signals on the performance of the VCO-based MASH and bandpass DSM will be analyzed, respectively. The comparison of different structures will be done in section 6. Finally, conclusions are drawn in section 7.

2. Analysis of a VCO-based integrator in the presence of OOB signals

In this section, the basic operation of a VCO-based integrator is explained and then, a closed-form expression for the output signal of a VCO-based integrator in the presence of the input signal and OOB signal is derived.

2.1. A VCO as an integrator

As the name implies, a voltage controlled oscillator is an oscillator that its output signal frequency depends on the input signal. Fig. 2 shows a basic architecture of a VCO-based integrator and its equivalent CT model. It consists of a VCO and a phase detector. The relation between the output frequency and the input signal of a VCO can be written as

$$f_{out}(t) = f_c + K_{vco}x_{in} \tag{1}$$

Where f_c and K_{vco} represent the carrier frequency and VCO gain, receptively. Since phase is the integral of the frequency, the oscillator can be considered as an integrator with voltage input and phase output which results in the following transfer function.

$$\frac{\phi_{out}}{x_{in}} = \frac{K_{vco}}{s} \tag{2}$$

The phase of the VCO is captured by comparing its outputs with those of a reference VCO (ϕ_{REF}). The above transfer function reveals that a VCO acts as a true integrator [18].

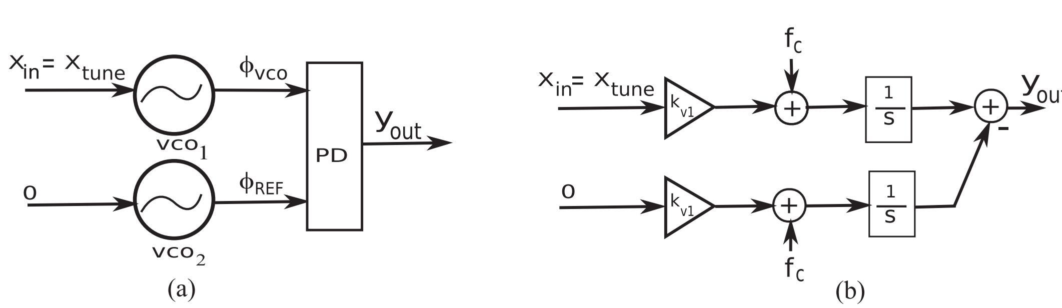

Fig. 2. (a) Basic architecture of a VCO-based integrator [18]. (b) Equivalent system level model.