

# BEHAVIORAL MODELING AND SIMULATION OF DATA CONVERTERS

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## Abstract

*This paper presents a behavioral representation for the class of Nyquist rate A/D converters that captures the nominal behavior, as well as all the statistical variations. To describe noise effects we use a joint probability density function. To describe behavioral effects due to process variations we use a covariance matrix,  $\Sigma_v$ . Applications of the model include identification of important A/D error sources, efficient computation of the distributions of integral nonlinearity (INL) and differential nonlinearity (DNL), signal-to-noise plus distortion ratio (TSNR), and efficient worst case and Monte Carlo system simulations. Finally, parameter extraction results are presented that agree well with actual measurements.*

## 1 Introduction

The verification of data converters poses a significant challenge to the design community, partly due to the need for higher yield at high resolutions, and partly due to the emphasis on predicting converter performance when used in a system since more converters will be integrated with entire systems. For example, to verify adequate yield of a high resolution converter, it is not enough to find a deterministic circuit response from a deterministic input. The entire transfer curve, as well as its variations due to process variations, has to be estimated. To compute circuit yield, the distributions of integral nonlinearity (INL) and differential nonlinearity (DNL) are needed. Furthermore, for systems containing these converters, system designers need to estimate system performance degradation, such as signal-to-noise and distortion ratio (TSNR), due to converter non-idealities.

The traditional SPICE simulation is clearly not viable because (a) the simulation speed is too slow for worst case or Monte Carlo simulations for yield predictions (b) SPICE cannot calculate noise effects of sampled data circuits, so TSNR cannot be calculated for architectures with such circuits. Recent approaches[1] model components of A/D converters with behavioral models and are capable of finding the transfer function in a more timely fashion. This type of modeling can be expressed mathematically as

$$\text{code} = A(V_{in}, \theta), \theta = \text{realization}(v) \quad (1)$$

where  $V_{in}$  is the input, and  $\theta$  is a set of parameters describing process variations. Since the sources of non-idealities in analog circuits are statistical,  $\theta$  is a realization of a multivariate distribution  $v$ . There are two problems with this behavioral modeling approach. (a) Suppose  $v$  is an  $n$ -variate, so can be very large because every circuit element that affects the transfer function has process variations. Also, it is unclear which

realizations  $\theta$  should be selected from  $v$ . For example, to verify worst case system performance without detailed knowledge of the A/D architecture,  $2^n$  simulations have to be performed. (b) Noise effects are not modeled, so TSNR cannot be calculated.

In this paper we present a behavioral model[2] for the class of Nyquist rate A/D (Section 2) and some parameter extraction techniques for effects due to process variations (Section 3.1). Circuit designers benefit from using this model because there is a systematic and efficient way to compute from model parameters the important A/D error sources (Section 3.5), the distributions of INL and DNL (Section 3.2), and TSNR (Section 3.4). The efficiency is illustrated with an optimization example (Section 3.3). System designers benefit from using this model because the model statistically summarizes all relevant A/D non-idealities, speeding worst case and Monte Carlo system simulations (Section 4).

## 2 New behavioral model

### 2.1 Modeling process variations

The transfer curve of a Nyquist A/D plots the output code on the range against the input continuous value on the abscissa. (Figure 1). Assuming the nominal A/D has  $N$  bits of resolu-



Figure 1: Nyquist A/D transfer curve

tion, is designed to be monotonic and has no missing codes, the nominal transfer curve can be characterized by  $2^N - 1$  real numbers in a vector,  $\mu_i$ , representing the expected value of the transition points  $t_1, t_2, \dots$  shown in Figure 1. Thus,  $\mu_i$  represents the expected transitions with no process variations.

Due to statistical process variations, the transfer curve has statistical variations. The statistical variations can be conveniently represented by a distribution,  $v$ , which we can find by making the following assumptions. (1) *Process variations are the cumulative effects of many integrated circuit fabrication steps. Thus, according to the Central Limit Theorem in probability theory, the distribution of the process variations,  $v$ , is approximately multivariate normal.* (2) *In general, an A/D is designed to be insensitive to process variations which are relatively small. Thus, the transition points,  $t_i$ , change relatively little with respect to process variations. So, to a good approximation,  $t$  changes linearly with respect to the process variations.*

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