Accurate Calculation of Bit-Level Transition Activity Using Word-Level Statistics and Entropy Function

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1. ABSTRACT
Accurate models for the calculation of bit-level switching activity in data-path operators, by combining the dual-bit type model with the entropy based calculation are presented. Given the input statistics the conditional entropy per bit is estimated by means of a sigmoidal model. A polynomial approximation to the entropy of the sign bits has been developed. Entropy and switching activity of primary inputs are used to estimate the output activity. The Triple-Bit Type (TBT) model is introduced to describe the behavior of the LSBs of the multiplier out-put, which do not behave as white noise. The error between the results of the proposed models and the measurements of entropy and switching activity is about 1% for signals with correlation factor less than 0.8.

2. INTRODUCTION
Power consumption has become a crucial factor in VLSI system design as technology improvement enables the production of ICs with continuously increasing density. Extensive research into various aspects of low-power system design has been performed during last years. Techniques for power estimation at the circuit and/or logic level giving accurate results do exist [5]. The establishment of methods permitting power estimation at the algorithmic and/or architectural level is desirable since the decisions can be taken in early design stages leading to cost reduction and shorter design cycles.

The dominant factor of power dissipation in CMOS circuits is the dynamic power dissipation, which is directly proportional to the signal transition activity. Different terms such as transition activity [8,9], transition density [6], switching activity and transition probability [3,4] have been proposed to express the number of signal transitions. The objective is to establish an accurate model to predict the bit-level switching activity from word-level statistics, thus permitting the estimation of the power consumption of a hardware implementation of the algorithm.

In [3] the signal activity is estimated by means of the signal entropy (and/or the informational energy). The mean entropy per bit of the inputs is calculated and the information scaling factor is introduced to estimate the signal activity at the outputs. A compositional technique is applied to complex data-flow graphs comprising of basic operators. A model is developed for the estimation of the average switching activity within each module, taking into account functional and/or structural information. The Dual Bit Type (DBT) model was introduced in [2] for modeling the power consumption of datapaths at the architectural level. The bits comprising a word of a data stream are not independent. The LSBs behave as white noise sequences, while the MSBs exhibit a non-random behavior, depending on signal magnitude and correlation factor. A data processing module is divided into parts characterized by different activities and the power consumption is estimated through the calculation of different capacitive coefficient vectors for each part of the module. The methodology proposed in [8,9] employs high-level signal statistics, a statistical signal generation model and the signal encoding for the estimation of transition activity. The DBT model is used and an accurate relation for transition activity is derived when the bit-level probability and correlation factor are known. Also, word-level signal statistics are propagated through DSP operators and transition activity is calculated for simple digital filter structures.

Although significant models for high-level power estimation have been proposed in [2,3,8,9], there are several drawbacks. In [3] it is assumed that the input and output of the modules have equal wordlength, that it is not true in all cases (e.g. multipliers). Also, the estimation of the mean entropy per bit completely ignores the DBT model. In [2] no estimation of the transition activity is given but only the breakpoints defining the LSB and MSB regions are calculated. In [8,9] the transition activity is computed using the bit-level correlation factor. Since in most cases the word-level correlation factor is known a method is required to calculate the bit-level one. Such an expression can be produced when the signal generation model is known and for simple models only, while the approximation that the bit-level correlation factor is equal to the word-level one is not accurate.

In this paper a novel method for the accurate calculation of bit-level switching activity based on the DBT model and the entropy function is proposed. First we combine the two techniques in order to estimate the switching activity of primary inputs, which are assumed to be described by Gaussian processes. The conditional entropy per bit is estimated by a sigmoidal model, using the word-level signal statistics. An accurate polynomial approximation to the conditional entropy of the MSBs is derived, permitting the calculation of the transition activity from the entropy function. The effects of basic data-path operators on signal statistics and entropy are studied and their output switching
activity is estimated. It was found that the LSBs of the product do not behave as white noise sequences and the Triple-Bit Type (TBT) model is introduced. The numerical results derived by the proposed models show satisfactory agreement with the analytical measurements in a variety of simulation examples.

In section 2 some basic definitions are given, the sigmoidal model of the conditional entropy is developed for the primary inputs and the polynomial approximation to the entropy of the MSBs is introduced. Section 3 is devoted to the calculation of signal statistics, entropy and switching activity of the outputs of elementary data-path operators and the TBT model. In section 4 numerical results based on the proposed models are produced and comparison to analytical measurements is performed. Finally, the conclusions are discussed in section 5.

2. ENTROPY MODEL

2.1 Definitions

Let \( x(n) \) be the input signal of a DSP system. In general this signal can be modeled by a random Gaussian process with mean value \( \mu \), variance \( \sigma^2 \), and correlation factor \( \rho \). The auto-correlation function \( R_{xx}(m) \), is defined as [7]:

\[
R_{xx}(m) = \sum_{n=0}^{\infty} x(n+m) \cdot x(n), m = 0,1,\ldots
\]

The variance and the correlation factor of \( x(n) \) are:

\[
\sigma^2 = R_{xx}(0), \quad \rho = \rho(1) = R_{xx}(1) / R_{xx}(0)
\]

Let \( b(n) \) be a binary signal and \( p_0 \) the probability of being 0 at time \( n \). Then the probability \( p_1 \) of being 1 is \( p_1 = 1 - p_0 \). Let \( p_{i0}, i=0,1 \) be the conditional probability of \( b(n) \) to be in state \( i \) given that \( b(n-1) \) was in state \( j \). The following relations hold between signal probabilities and conditional probabilities [4]:

\[
p_0 = \frac{p_{00}}{p_{01} + p_{00}} \quad \text{and} \quad p_1 = \frac{p_{01}}{p_{01} + p_{10}}
\]

The transition probability, \( p_{ij} \), is the probability of \( b(n) = i \) and \( b(n-1) = j \). Consequently, the switching activity, \( s_w \), of \( b(n) \) is given by:

\[
s_w = p_{01} + p_{10} = p_0 \cdot p_1 + p_1 \cdot p_0
\]

The concept of entropy is used to quantify the uncertainty of a random variable with discrete probability distribution. The entropy of a binary random variable is defined as [3,7]:

\[
H = -(p_0 \log p_0 + p_1 \log p_1),
\]

where \( \log \) denotes the base 2 logarithm function.

By definition the entropy function takes only positive values within the interval \([0,1]\). The minimum value 0 is obtained for \( p_0 \) or \( p_1 \) equal to 1, complete certainty, while the maximum value of 1 is obtained for \( p_0 = p_1 = 0.5 \), maximum uncertainty.

The conditional entropy between two successive time steps, \( H_c \), expressing the uncertainty of \( b(n=i) \) given that \( b(n-1=j) \) is [3,7]:

\[
H_c = -(p_{00} \log p_{00} + p_{01} \log p_{01} + p_{11} \log p_{11} + p_{10} \log p_{10})
\]

2.2 Sigmoidal entropy model

In the following we assume that \( \mu = 0 \) and two's complement number representation. The conditional entropy function exhibits a form similar to that of the transition activity and it can also be modeled by a DBT model, as it is shown in Fig.1. The significant difference is that correlated and anticorrelated signals having equal \( \rho \) (e.g., \( \rho = 0.95 \) and \( \rho = -0.95 \)) exhibit identical entropy functions. This is due to the fact that the uncertainty about the next signal value is the same in the two cases. The probability that the signal in two successive time steps will be of the same polarity for positive \( \rho \) is equal to that of being of the inverse polarity for negative \( \rho \).

The minimum value of the entropy, \( H_{\text{min}} \), of the MSBs can be expressed as a function of \( \rho \):

\[
H_{\text{min}} = 2\log_2(1-\rho^2)
\]

In [2] the breakpoints are given and a linear approximation to the transition region has been proposed. An accurate sigmoidal model for the conditional entropy per bit is proposed:

\[
H_c(i) = 2\log_2(1-\rho^2) + \frac{1-2\log_2(1-\rho^2)}{1+\exp\left(-0.5BP1 + BP0\right)}
\]

where BP0 and BP1 are given by:

\[
BP0 = \log(\sigma) + \log(\sqrt{1-\rho^2} + |\rho| / 8), \quad \text{and} \quad BP1 = \log(4\sigma)
\]

Relations (7) and (8) have been produced by curve-fitting to an average of entropy curves of 10 Gaussian signals having equal absolute values of \( \rho \). In Fig. 1 are shown the measured values of \( H_c \), as well as the plot of (8). The breakpoints of \( H_c \) depend on the signal variance and correlation factor. BP0 is identical to that of the transition probability given in [2], while BP1 is slightly moved towards the MSB. It should be noted that although for the calculation of BP1 in [2] \( \mu \) assumed to be non-zero the DBT model is correct only for \( \mu = 0 \). For example if \( \mu - 3\sigma > 0 \) then almost all of the signal values are positive and the MSBs have zero transition probability irrespective of \( \rho \).

Fig. 1. The sigmoidal conditional entropy model.

2.3 Calculation of switching activity

Given the signal statistics \( H_c \) can be calculated by (8) and (9). The objective is to express the switching activity as a function of \( H_c \). Such an analytical expression it is not possible to be produced due to the logarithms present in the RHS of (6). However, for a zero mean Gaussian process \( p_{00}p_{11} = 0.5 \) for all bits within the word. Therefore, (6) is simplified to:

\[
H_c = -0.5(p_{10} \log p_{10} + p_{11} \log p_{11} + p_{00} \log p_{00} + p_{01} \log p_{01})
\]

Moreover, since \( p_{00} \sim p_{11} \) and \( p_{00}p_{11} \sim p_{10}p_{01} \) (10) becomes:

\[
H_c = -(p_{10} \log p_{10} + (1-p_{01}) \log(1-p_{01}))
\]

Again (11) can not be solved analytically. Since \( 0 < p_{10} < 1 \) the RHS of (11) can be approximated by an eighth order polynomial

\[
R(p_{10}) = \sum_{j=0}^{4} 2^{-j} (p_{10} - 0.5)^{2j}
\]

By substitution of (12) into (11) we obtain:
The transformation \( (p_{10} - 0.5)^2 = u \) leads to:

\[
8u^4 + 4a^2 + 2a^2 + u + 0.5 = 2^{-H_x}.
\]  

(14)

In general (14) has four complex roots which lead to eight complex roots of (13). However since \( \frac{1}{2} \leq H_x \leq 0 \) there is always a real solution of (14) which leads to a value of \( p_{10} \) within the interval [0,1]. Actually the proposed approximation is valid for \( H_x \geq 0.134 \) where \( \Re(p_{10}) \geq p_{10} e^{(1-p_{10})} \). This is equivalent to 0.0185 < \( p_{10} < 0.9815 \) which is true for all real life signals, since the corresponding correlation factor is greater than 0.995 or less than 0.005.

3. BASIC OPERATORS

Having computed the transition activity of a signal the next step is to study the propagation of the statistics through basic operators and the modifications of the conditional entropy at the operator’s output. Three operators, common in DSP algorithms, are examined, namely adder, multiplier and delay unit. It is assumed that their primary inputs are mutually uncorrelated Gaussian processes with statistics \( p_1, \sigma_1, p_2, \sigma_2 \).

3.1 Adder

The output signal of an adder is also a Gaussian process. The statistics of the sum are described as functions of the input statistics by the following relations [7]:

\[
\mu_s = \mu_1 + \mu_2, \quad \sigma_s^2 = \sigma_1^2 + \sigma_2^2, \quad \text{and} \quad \rho_s = \frac{\rho_1 \sigma_1^2 + \rho_2 \sigma_2^2}{\sigma_1^2 + \sigma_2^2}
\]  

(15)

Assuming identical input and output wordlength and that no overflow occurs the conditional entropy per bit and the breakpoints of the sum can be computed by (8) and (9) using \( \mu_s, \sigma_s \) and \( \rho_s \) from (15). Moreover, the transition activity of the MSBs can be calculated from (14).

3.2 Multiplier

The statistics of the product are described as functions of the input statistics by the following equations:

\[
\mu_p = \mu_1 \mu_2, \quad \sigma_p^2 = \sigma_1^2 \sigma_2^2, \quad \text{and} \quad \rho_p = \rho_1 \rho_2
\]  

(16)

However, the product can not yet be described by a Gaussian process. Therefore, a different methodology is required for the calculation of the switching activity of the bits of the product. We assume that the output wordlength of an \( N \times M \) multiplier is \( N \times M \) bits. The effects of the multiplication on the LSBs and the MSBs of the product are examined separately, and the Triple-Bit Type (TBT) model is introduced to accurately describe the activity in the different regions of the product.

3.2.1 Least significant bit

The probability of the product to be an odd number is less than that of an even one. Assuming equally probable odd and even numbers in the input streams, the output probabilities are 0.25 and 0.75 respectively. Therefore, the LSB of the product exhibit less activity than that of the white noise. If \( p_{\text{odd}} \) and \( p_{\text{even}} \) are the probabilities of the odd numbers in the input streams the probability of odd and even numbers in the product are:

\[
p_{\text{odd}}^p = p_{\text{odd}}^n p_{\text{odd}}^2 \quad \text{and} \quad p_{\text{even}}^p = 1 - p_{\text{odd}}^n p_{\text{odd}}^2
\]  

(17)

In general, the probability of a product of \( m \) numbers to be odd, if \( p_{\text{odd}} = 0.5 \). A simple case is \( p_{\text{odd}}(k) = 2^{-m} \).

The transition probability, \( p_{\text{even}}^p \), of the LSB can be also calculated by the input probabilities. The transition probabilities of the LSB of the product are given by:

\[
p_{\text{odd}}^n = p_{00}^n + p_{01}^n p_{00}^2 + p_{10}^n p_{00}^2
\]

(19a)

\[
p_{01}^n = p_{00}^n p_{01}^2 p_{00} + p_{01}^n p_{10}^2 p_{00} + p_{11}^n p_{00}^2 p_{11}
\]

(19b)

\[
p_{10}^n = p_{11}^n p_{10}^2 p_{11} + p_{01}^n p_{10}^2 p_{11} + p_{11}^n p_{11}^2 p_{11}
\]

(19c)

\[
p_{11}^n = p_{11}^n p_{11}^2 p_{11}
\]

(19d)

The conditional probabilities used for the calculation of entropy can be obtained from the signal and transition probabilities according to (4).

The multiplication by a constant has similar effects. When one or more of the LSBs of the constant are zero the same number of LSBs of the product are also zero, i.e., they have zero signal and transition probability.

3.2.2 Most significant bits

The product of the two inputs can be represented as a positive or negative number by multiplication of two signals with \( p_{\text{odd}} = 0.9 \) and \( p_{\text{even}} = 0.1 \). The conditional entropy of the MSBs is defined by the following relations:

\[
p_{\text{odd}} = p_{\text{odd}}^n p_{\text{even}}^n + p_{\text{even}}^n p_{\text{odd}}^n + p_{\text{even}}^n p_{\text{even}}^n + p_{\text{even}}^n p_{\text{even}}^n
\]

(21a)

\[
p_{\text{even}} = p_{\text{odd}}^n p_{\text{even}}^n + p_{\text{even}}^n p_{\text{odd}}^n + p_{\text{even}}^n p_{\text{odd}}^n + p_{\text{even}}^n p_{\text{even}}^n
\]

(21b)

\[
p_{\text{even}} = p_{\text{odd}}^n p_{\text{even}}^n + p_{\text{even}}^n p_{\text{odd}}^n + p_{\text{even}}^n p_{\text{odd}}^n + p_{\text{even}}^n p_{\text{even}}^n
\]

(21c)

\[
p_{\text{odd}} = p_{\text{odd}}^n p_{\text{odd}}^n + p_{\text{even}}^n p_{\text{odd}}^n + p_{\text{even}}^n p_{\text{odd}}^n + p_{\text{even}}^n p_{\text{even}}^n
\]

(21d)

Eqs. (21a)-(d) hold for all bits higher than BP1. The activity of the MSBs of the product with correlation factor \( \rho_p \) depends not only on \( \rho_p \) but also on the transition activity of the inputs. This also affects the conditional entropy of the product, since there is no more one to one correspondence between entropy and correlation factor and therefore, eq.(8) can not be used. For example, according to (16) a signal with \( \rho_p = 0.9 \) can be produced by multiplication of two signals with \( p_{\text{odd}} = 0.94 \) and \( p_{\text{even}} = 0.96 \) having switching activities \( s_{\text{odd}} = 0.11 \) and \( s_{\text{even}} = 0.09 \), or \( s_{\text{odd}} = 0.05 \) and \( s_{\text{even}} = 0.14 \), respectively. From (21) the activity of the MSBs of the product is 0.182 and 0.168, while the conditional entropy is \( H_{\text{BP1}} = 0.685 \) and \( H_{\text{BP2}} = 0.655 \).

3.2.3 The Triple-Bit Type (TBT) Model

A triple-bit type (TBT) model is introduced for the description of the conditional entropy of the product. In Fig. 2 it is shown the entropy per bit for four different signals. The first one, (circles), is a Gaussian signal with \( \sigma = 128 \) and \( \rho = 0.9 \). The second and the third one, (triangles and squares), is the product of two signals with \( \sigma = 128 \) and \( \rho = 0.96 \) and \( \rho = 0.94 \) having switching activities \( s_{\text{odd}} = 0.11 \) and \( s_{\text{even}} = 0.09 \), or \( s_{\text{odd}} = 0.05 \) and \( s_{\text{even}} = 0.14 \), respectively. Finally, the fourth one, (diamonds), is the product of three signals with \( \sigma = 128 \) and \( \rho = 0.95 \), \( \rho = 0.99 \), and \( \rho = 0.96 \). While in all cases \( \rho = 0.9 \) the entropy of the MSBs is different as predicted by (21).

![Figure 2. The Triple-Bit Type model](image-url)
The breakpoints $BP_0$ and $BP_1$ defining the sign-bit region of the entropy function, if the product are defined again by (9) taking into account (16). From Fig.2 it is also evident that not only the LSB of the product is affected by the multiplication, but there is a region of LSBs exhibiting lower activity. Assuming that a signal is a product of an arbitrary number, $n_m$ of Gaussian processes, i.e., $p(n) = \prod_{i=1}^{n_m} p(x_i)$, $n_m \geq 2$, the third breakpoint, $BP_2$, defining the LSB region was found to be:

$$BP_2 = 2(n_m + 1)$$  \hspace{1cm} (22)

From (19) and (6) the conditional entropy of the LSB becomes:

$$H^c_i(0) = -2^{-n_m} \log 2^{-n_m} + (1 - 2^{-n_m}) \log(1 - 2^{-n_m})$$  \hspace{1cm} (23)

The entropy within the LSB region ($i \leq BP_2$) can be well approximated by an exponential function of the form:

$$H^c_i(i) = H^c_i(0) - (1 - H^c_i(0)) \exp(0.5 + 0.5^{-n_m})$$  \hspace{1cm} (24)

The effect of the multiplication on the LSBs tends to disappear when a product is used as one operand of another operation. It has been observed that the TBT model holds also for a multiply/accumulate unit implementing FIR filters. However, this problem is quite different since the one input of the multiplier is a periodic sequence and the other input is a non-periodic sequence. Using the concept of the Dual-Bit Type model a sigmoidal model for the conditional entropy has been proposed for signals described as random Gaussian processes. A polynomial approximation to the entropy, which allows the direct calculation of switching activity, has been introduced. The propagation of input statistics to the output of basic data-path operators has been studied. A novel Triple-Bit Type model, has been introduced to describe accurately the behavior of the LSBs of the product. Analytical relations for the calculation of the bit-level switching activity of the product bits directly from the combination of the activities of the input signals have been produced. The numerical results show satisfactory agreement between analytical measurements and the proposed models for both entropy and switching activity.

### 3. Delay unit

The statistics and the conditional entropy function of the output of a delay unit are identical to those of its input.

### 4. EXPERIMENTAL RESULTS

For the evaluation of the proposed models a number of experiments have been performed aiming to the determination of the error between measured and estimated values of both entropy and switching activity. Different random Gaussian signals with known correlation factor varying from $-0.95$ to $0.95$ have been produced and analyzed. The entropy and switching activity has been calculated by detailed counting over one million of signal values. Also the same measures have been estimated using eqs (7) and (14), respectively. The difference between real and estimated values has been also computed. In Table 2 are shown typical values for the measured and estimated values of conditional entropy and switching activity of the sign bits, as well as the relative error. The maximum error in entropy, which in all cases is less than 10%, is present only to highly correlated or anti-correlated data streams. As it is shown the error decreases significantly to almost 1% for $\rho \leq 0.8$, which is true for most of the real-life signals. The behavior of the error in switching activity is similar to that of the entropy. Although for highly correlated data streams the relative error seems to be high, the absolute error is quite small since the value of switching activity approaches to zero. Moreover, the relative error of both conditional entropy and transition activity within the transition region is for all cases less than 10%.

For the evaluation of the TBT model, a variety of signals with specific $\rho$ have been produced by different combinations of two or more primary inputs. The error values obtained for the sign-bits and the transition region of the product behave exactly as those of the primary inputs. The error in the LSB region was found to be less than 2% for all bits less than $BP_2$.

### 5. CONCLUSIONS

A new methodology has been developed for the estimation of bit-level switching activity from the high-level signal statistics and the conditional entropy. Using the concept of the Dual-Bit Type model a sigmoidal model for the conditional entropy has been proposed for signals described as random Gaussian processes. A polynomial approximation to the entropy, which allows the direct calculation of switching activity, has been introduced. The propagation of input statistics to the output of basic data-path operators has been studied. A novel Triple-Bit Type model, has been introduced to describe accurately the behavior of the LSBs of the product. Analytical relations for the calculation of the bit-level switching activity of the product bits directly from the combination of the activities of the input signals have been produced. The numerical results show satisfactory agreement between analytical measurements and the proposed models for both entropy and switching activity.

### Table 1. Measured, estimated, and error values of sign-bit conditional entropy and switching activity for different $\rho$.

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<th>ENTROPY</th>
<th>TRANSITION ACTIVITY</th>
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<td>MEAS.</td>
<td>EST.</td>
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<td>0.4418</td>
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### 6. REFERENCES


