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Analog circuit design space description based on ordered clustering of feature uniqueness and similarity

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A B S T R A C T

This paper presents a symbolic technique to create ordered feature clustering schemes that express the main similarities and differences between analog circuits. Four separation scores, based on entropy, item characteristics, category characteristics, and Bayesian classifiers, were studied to produce clustering schemes that offer insight about the uniqueness and importance of specific design features in setting AC performance as well as the limiting factors of the designs. The experiments consider a set of 50 state-of-the-art amplifier circuits. The paper offers a detailed discussion on using the insight obtained from circuit feature clustering for topology synthesis and refinement.

1. Introduction

Circuit macromodels express the main characteristics of analog circuits, e.g., the mathematical dependency of voltages and currents at circuit nodes on design variables, e.g., transistor dimensions [1,2]. Models also describe the relations between performance attributes and circuit design variables [3,4]. Existing modeling methods successfully address a large variety of performance attributes, like small-signal AC performance [1,3], weakly nonlinear distortion [5,6], and large-signal analysis [4]. The used techniques include regression analysis [2], symbolic analysis [1], piecewise-linear approximation [7], and model-order reduction [8,9]. Circuit models are used for fast performance evaluation, circuit design and synthesis, and getting insight into circuit operation for verification.

There are few modeling methods that characterize a population of circuits to indicate the similarities and differences in their topological and behavioral features as well as their impact on performance. However, descriptions of circuit populations can offer a comprehensive presentation of the design space covered by the design set, the flexibility of design features when used under various constraints, and the uniqueness of features in tackling specific requirements. Such insight results by comparing circuits to find common and unique design features, e.g., the similar and distinct symbolic terms of pole and zero expressions. The comparison helps understanding the performance advantages and limitations of a circuit topology compared to another, the performance impact of circuit nodes and their structural connections to other nodes, the conditions under which alternative circuits offer similar performance, and the design aspects that boost or limit the performance of a circuit compared to alternatives. The obtained insight is useful to synthesize topologies, or refine existing circuits to incorporate useful features from other designs or to identify common characteristics that can be reused for broad sets of performance requirements.

This paper presents a symbolic technique for creating models, called ordered node cluster representations (ONCR), that express the main similarities and differences between a set of analog circuits with common functionality. The insight obtained from the representations are the similar and dissimilar circuit features, including the related topological structures and their symbolic expressions. The modeling method includes three main steps: (i) identifying the possible separation criteria, (ii) analyzing the criteria with respect to their potential of grouping the circuits, and (iii) building ONCRs such that the separation of dissimilar circuits is maximized. In addition, the method performs two initial steps that create the symbolic circuit descriptions used for analysis. The paper studies four separation scores: entropy, item characteristics, category characteristics, and Bayesian classifiers. A preliminary version of the paper was presented in [10]. This paper introduces three new separation scores, and a comprehensive study for two sets of state-of-the-art amplifier circuits: one using ten circuits and the other having fifty circuits. A detailed discussion of the application of ONCRs for topology synthesis and refinement is also offered.

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The paper has the following structure. Section 2 defines the discussed problem. Section 3 describes the proposed algorithm for generating ONCRs. Section 4 presents experimental results and a discussion of the applications of ONCRs. Conclusions and future work end the paper.

2. Problem description

Given a set of circuits C_1, C_2, …C_n, the problem requirement is to build a symbolic description (model) that presents the main similarities and differences between circuits (in a population of circuits) with respect to their structural features and influence on performance. A good description scheme must easily distinguish the circuits, e.g., there should be a minimum number of criteria that separate a circuit from the other circuits in the set with respect to their topological features and performance attributes.

Fig. 1 illustrates the theoretical formulation of the problem. Three circuits C_i are shown in the figure. Each circuit is described by the set of its nodes $V_{i,k}$. This captures the circuit structure, which is important to understand how similarities and differences correlate to the circuit topologies. Nodes are characterized by functions P_k to express the node poles and $F_{k,p}$ to describe the coupling between nodes. The symbolic functions are related to AC performance, like pole positions and separation, and magnitude and phase response. Expressions P_k and $F_{(k,p)}$ are continuous functions in the s-domain. Functions $F_{(k,p)}$ describe the AC domain coupling between nodes and correspond to the arc labels in Fig. 1(a). Functions $P_k = R_k/(1+sR_kC_k)$ characterize the poles at each circuit node, where R_k and C_k are the symbolic expressions for the resistive and capacitive components, respectively.

Producing a feature clustering scheme for the set of circuits C_i must (i) identify the nature of criteria used in finding similarities and differences between the circuits and (ii) find the topological features that realize the similarities and differences. As shown in Fig. 1(c), the two objectives create a scheme in which the ordered levels correspond to the identified criteria and the node groups (G_i) at each level represent clusters of nodes with similar features. In addition, a reliable separation metric must be available to produce clusters that characterize the amount of dissimilarity between circuits.

There are always more criteria sets possible to distinguish circuits. For example in Fig. 1(a), the characteristics of the nodes $V_{1,i}$, $V_{2,i}$ and $V_{3,i}$ along curve D_1 can be used for distinguishing the circuits. Alternatively, nodes $V_{1,i}$, $V_{2,j}$ and $V_{3,j}$ along curve D_2 could be used for clustering. The two curves lead to finding different common features for the circuits, e.g. similar symbolic expressions for their poles and coupling. In the first case, node $V_{1,i}$ in circuit C_1 forms a different cluster as it has different coupling to its subsequent node. Note that all possible criteria sets (corresponding to a curve D_k) define the space for clustering. Fig. 1(b) illustrates all circuit nodes with similar features identified for the curves D_k. The similar nodes are circled together and form a group G_i of similar features, with respect to their pole and coupling to other nodes expressions.

The representation in Fig. 1(c) aggregates the feature similarity and dissimilarity information for all nodes in the three circuits. This representation is called ordered node cluster representation (ONCR). ONCRs are directed graphs, similar to concept variety [11]. The upper levels of ONCRs correspond to curves D_k with high similarity of the corresponding node features. The low levels represent nodes with dissimilar features. For example, the output nodes of the three circuits have similar features as their pole expressions are matched. The input nodes are dissimilar as their coupling is different. If a circuit has nodes at different levels of the scheme, then the levels and corresponding groups are joined by a directed edge to indicate the ordered nature of the representation with respect to feature similarity.

The common and dissimilar node features presented in the representation are related to the relevant performance attributes $Perf_i$. For example, for AC domain, the shared node features represent the common symbolic expressions of the poles at the nodes, and the analyzed performance $Perf_i$ defines the position of the common pole on the magnitude and phase response of the circuit.

Example: The impact of a node depends on the nodal poles and coupling to all other nodes in the circuit, e.g., all functions $F_{(k,p)}$ through which the node is connected to the rest of the circuit. For example, the impact of node $V_{1,i}$ of circuit C_1 in Fig. 1(a) is characterized by functions P_i (pole expression) and $F_{1,3}$, the coupling to node V_{out}, and functions $F_{1,1}$ and $F_{1,2}$, the coupling from node V_{in}. The AC performance impact of the node includes the dependency of the circuit's magnitude and phase responses on functions P_i, $F_{1,3}$, $F_{1,1}$ and $F_{1,2}$.

The quality of an ONCR depends on the relevance of the common and distinguishing criteria, including their impact on performance and insight on circuit design, e.g., uniqueness of a criterion in controlling a certain performance attribute and brevity of the related expression [12]. Good distinguishing criteria have short mathematical expressions (which makes them easy to understand), and are

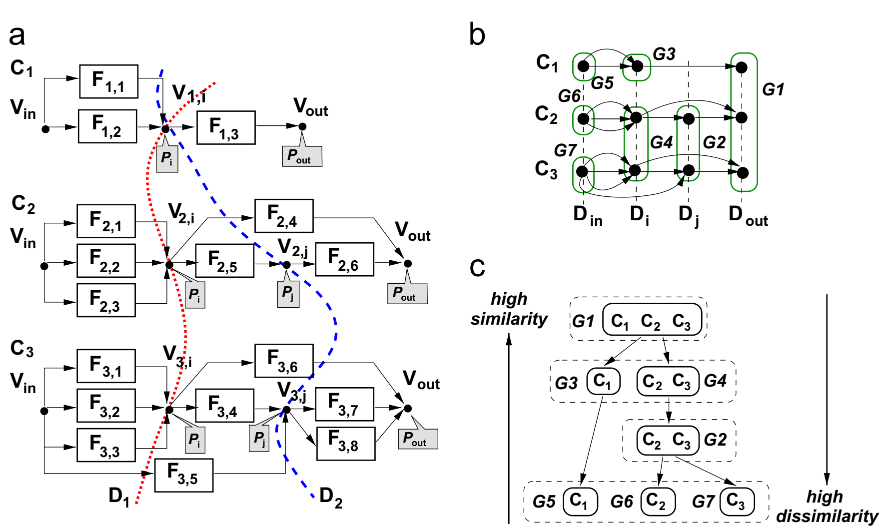

Fig. 1. Theoretical description of the circuit feature clustering problem.