ABSTRACT
We propose a new BDD-based method for decomposition of multi-output incompletely specified logic functions into netlists of two-input logic gates. The algorithm uses the internal don’t-cares during the decomposition to produce compact well-balanced netlists with short delay. The resulting netlists are provably non-redundant and facilitate test pattern generation. Experimental results over MCNC benchmarks show that our approach outperforms SIS and other BDD-based decomposition methods in terms of area and delay of the resulting circuits with comparable CPU time.

1. INTRODUCTION
Decomposition of Boolean functions consists in breaking large logic blocks into smaller ones while keeping the network functionality unchanged. Decomposition plays an important role in logic synthesis. Research in this area started in the 1950s [1,2]. Recently, there has been a revival of interest in disjoint decomposition (called also disjunctive decomposition) [3,4,5].

Decomposition methods are classified as follows:
1) Each block of the resulting network has a single binary output, or may have multiple binary outputs (Ashenhurst and Curtis decomposition, respectively).
2) Supports of the blocks may overlap, or never overlap (disjoint decomposition).
3) Each block has two or less inputs (bi-decomposition), or the number of inputs may be larger than two.
4) Decomposition is performed as technology mapping for FPGAs, as a technology-independent transformation of logic circuits, or as a specialized mapping technique.
5) The decomposed structure is derived by splitting the larger blocks into the smaller ones, or the decomposition structure is assembled by iteratively adding small components until the network is equivalent to the initial specification.
6) BDDs are used in the decomposition algorithm, or not. If yes, BDDs are used to represent functions and store intermediate results, or BDDs are used as the essential data structure directing the decomposition process.
7) Decomposition shares blocks across outputs (logic cones) or decomposes each output (logic cones) independently.
8) The algorithm allows for don’t-cares or not.

This classification can be extended using other criteria such as methods for variable partitioning, methods for deriving the decomposed functions, cost functions used to evaluate the results of decomposition, etc. In terms of the above classification, the algorithm proposed in this paper is characterized as follows:
1) Each decomposed block has a single binary output.
2) Blocks may have overlapping supports.
3) Each resulting block has two or less inputs.
4) It is a technology-independent decomposition.
5) Larger components are split into smaller ones.
6) BDDs are used to store functions.
7) Blocks are shared across outputs and internal logic cones.
8) Incompletely specified functions are allowed; the more don’t-cares, the more efficient is the algorithm.

According to the above classification, the closest matches to our algorithm are its previous versions [6,7,8,9] and the recent approach [10,11]. As evidenced by our experiments, the present version of the algorithm outperforms its previous versions and compares favorably to [10,11]. A more detailed analysis of the differences of these approaches is given in Section 8 of the paper.

The paper is organized as follows: Section 2 introduces the notations and the decomposition models. Section 3 gives necessary and sufficient conditions for AND-, OR-, and EXOR-bi-decomposition. Section 4 gives the formulas for deriving the decomposed functions. Section 5 presents the variable grouping strategy. Section 6 presents hashing techniques. Section 7 discusses the decomposition algorithm. Section 8 presents experimental results. Section 9 summarizes the paper.

2. PRELIMINARIES
Let f: B^n → B, B∈{0,1}, be a completely specified Boolean function (CSF). The variable set X, on which f depends, in called support of f. Support size is denoted |X|. Let F: B^n → {0,1,-} be an incompletely specified Boolean function (ISF) given by its on-set (Q) and off-set (R). It is easy to convert the on-set/off-set
representation of an ISF into the interval specifying the set of permissible CSFs: \((Q, R)\). A CSF \(f\) is compatible with the ISF \(F = (Q, R)\), if\(\forall Q \leq f \leq R\).

This paper discusses bi-decomposition (called grouping in [12]), or decomposition of ISFs into netlists of two-input logic gates. One-step bi-decomposition is schematically represented in Fig. 1. Block C is an AND, OR, or EXOR gate, while components A and B are arbitrary ISFs. The support X of the initial function is divided into three parts: variables \(X_A\) that feed only into block A, variables \(X_B\) that feed only into block B, and the common variables \(X_C\). By definition, sets \(X_A, X_B,\) and \(X_C\) are disjoint. If \(X_A\) or \(X_B\) is empty, the resulting bi-decomposition is called weak. Otherwise it is a strong (or non-weak) bi-decomposition. In this paper, we consider both types of bi-decomposition and use the term “bi-decomposition” to denote strong bi-decomposition.

![Figure 1. Schematic representation of the two types of bi-decomposition: strong (left) and weak (right).](image1)

Notice that before decomposition function \(F(X)\) in Fig. 1 (right) has five inputs. The weak bi-decomposition creates five-input component A and three-input component B. The advantage of this decomposition consists in increasing the number of don’t-cares of component A and three-input component B. The advantage of this method is bi-decomposability remains essentially the same: if Property holds for all cells of all the Karnaugh maps, the function is OR-bi-decomposable. Therefore in the theorems below, there is no restriction on \(X_C\), meaning that it can be either empty or non-empty. We refer the reader to [6,7] for a detailed discussion.

Bi-decomposability of ISFs can be checked by applying the existential quantification to \(Q\) and \(R\), representing the on-set and the off-set, because the existential quantification over variables representing columns (rows) consists in adding up all the 1’s contained in the rows (columns).

**Theorem 1**: \(F(X) = \{Q(X), R(X)\}\) is OR-bi-decomposable with variable sets \((X_A, X_B, X_C)\) iff \(Q \& \exists X_A R \& \exists X_B R = 0\).

Due to the duality of AND and OR operations, the formula for checking AND-bi-decomposition can be derived by replacing on-set \(Q\) by off-set \(R\) in the above formula. For this reason, the rest of the paper considers only OR and EXOR bi-decomposition. Formulas for checking OR-bi-decomposability of strong and weak types are summarized in Table 1.

### 3.2 Bi-decomposition with an EXOR-gate

Because checking for EXOR-bi-decomposition is rather complicated, the following theorem is formulated for a simpler case of \(X_A\) and \(X_B\) including 1 and \(n\) variables respectively.

**Theorem 2**: \(F(X) = \{Q(X), R(X)\}\) is EXOR-bi-decomposable with variable sets \((X_A, X_B)\), such that \(|X_A| = 1\) and \(|X_B| = n\), iff \(Q_0 \& \exists X_B R_0 = 0\).
where \( Q_0 \) and \( R_0 \) are the on-set and off-set of the derivation of \( F \) w.r.t. the variable in \( X_A \):

\[
Q_0 = 3x_A Q & 3x_A R, \quad R_0 = \exists x_A Q + \forall x_A R.
\]

Checking EXOR-bi-decomposability with arbitrary non-overlapping sets \( X_A \) and \( X_B \) is performed by a specialized algorithm (Fig. 4). Procedure CheckExorBiDecomp() takes four arguments. The first two are the on-set (Q) and the off-set (R) of an ISF. The next two are variable sets \( X_A \) and \( X_B \). If an EXOR-bi-decomposition exists, the procedure returns the on-sets and off-sets of ISFs implementing components A and B, otherwise it returns zero BDDs.

Procedure CheckExorBiDecomp( bdd Q, bdd R, bdd XA, bdd XB) {
bdd QA = 0, RA = 0, QB = 0, RB = 0;
bdd QA = 0, RA = 0, QB = 0, RB = 0;
while ( Q != 0 ) {
    bdd Cube = SelectOneCube( Q );
    if ( qA & rA != 0 ) return (QA, RA, QB, RB);
    QA = QA + qA; \( R_A = R_A + rA \);
    if ( qB & rB != 0 ) return (QA, RA, QB, RB);
    QB = QB + qB; \( R_B = R_B + rB \);
}
return ( QA = QA + qA; \( R_A = R_A + rA \); QB = QB + qB; \( R_B = R_B + rB \);)
}

Figure 4. Algorithm for checking the existence of EXOR-bi-decomposition with arbitrary sets \( X_A \) and \( X_B \).

Internally called procedure SelectOneCube() returns a randomly selected cube. The Boolean function of the cube is quantified and projected in the directions of \( X_A \) and \( X_B \) to find one part of the EXOR-decomposable component, which is next added to the on-sets and off-set of the components A and B and subtracted from the initial on-set and off-set. If the on-set and off-set of components A and B are incompatible, CheckExorBiDecomp() returns zeros, otherwise the process is repeated as long as the given on-set is not empty. If at the end the off-set contains some minterms, they are added to off-sets of components A and B. For a detailed discussion of this algorithm, see [9].

4. DERIVING DECOMPOSED FUNCTIONS

This section presents formulas for deriving ISFs implementing components A and B (see Fig. 1). The case of an EXOR-bi-decomposition has been addressed in the previous section, because the decomposed functions in EXOR-bi-decomposition are derived as a result of the bi-decomposability check.

\begin{align*}
\text{Theorem 3: } & \text{Let } F(X) = \{ Q(X), R(X) \} \text{ be OR-bi-decomposable with variable sets } (X_A, X_B). \text{ The ISF } F_A = \{ Q_A(X), R_A(X) \} \text{ of the component A is:} \\
& Q_A = 3x_A Q & 3x_A R, \quad R_A = 3x_A R.
\end{align*}

\begin{align*}
\text{Theorem 4: } & \text{Let } F(X) = \{ Q(X), R(X) \} \text{ be OR-bi-decomposable with variable sets } (X_A, X_B) \text{ and a CSF } f_A \text{ belonging to the ISF } F_A \text{ is selected to represent component A. The ISF } F_B(X) = \{ Q_B(X), R_B(X) \} \text{ representing component B is:} \\
& Q_B = 3x_A Q - f_A, \quad R_B = 3x_A R.
\end{align*}

Formulas to derive ISFs representing components A and B are summarized in Table 1. Note that removing the existential quantifier w.r.t. \( X_A \) in the formulas for component A in the case of strong OR-decomposition leads to the corresponding formulas for weak OR-decomposition, because in the case of weak decomposition the variable set \( X_A \) is empty. Symbol ‘\(-\)’ stands for Boolean SHARP (A-B = A & B).

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|}
\hline
Type & Checking & Deriving A & Deriving B \\
\hline
OR & \( Q_A(\exists x_B R)(\exists x_A R) = 0 \) & \( Q_A = 3x_A(Q & 3x_A R) \) & \( Q_B = 3x_A(Q - f_A) \) \\
Weak & \( Q \cdot \exists x_B R \neq 0 \) & \( Q_A = Q & 3x_A R \) & \( Q_B = 3x_A(Q - f_A) \) \\
\hline
\end{tabular}
\caption{Checking OR-bi-decomposability and deriving ISFs for components A and B.}
\end{table}

5. VARIABLE GROUPING

An important task during the bi-decomposition is finding variable sets \( X_A \) and \( X_B \), for which the given type of bi-decomposition is feasible. This task is solved in two steps. First, \( X_A \) and \( X_B \) are initialized with a single variable. Next, attempts are made to add new variables to the sets while preserving the set sizes as close to being equal as possible.

Procedure FindInitialGrouping( bdd Q, bdd R, bdd S ) {
\{ for all \( x \in S \) {
\{ if \( x \) \in X_A \{ \}
\{ if \( y \) \in X_B \{ \}
\}
\}
return \( (X_A, X_B) \);
\}
}

Figure 5. Algorithm to find the initial sets \( X_A \) and \( X_B \).

Consider procedure FindInitialGrouping() implementing the first step of variable grouping (Fig. 5). It takes three arguments: the on-set Q, the off-set R, and the support S of an ISF. It returns two singleton sets, \( X_A \) and \( X_B \), if the function is strongly bi-decomposable with them, or two empty sets, if the function is not bi-decomposable in the strong sense with any variable grouping. The procedure CheckDecomposability() performs an OR-, AND-, or EXOR-bi-decomposability check, as discussed in Section 3, depending on what initial grouping is sought.

Procedure GroupVariables() (Fig. 6) implements the second step. The arguments and the return values are the same as in procedure FindInitialGrouping(). Having found a non-empty initial grouping, the procedure considers the remaining variables one by one and tries to add them to \( X_A \) and \( X_B \). Depending on sizes of \( X_A \) and \( X_B \), it tries to add the new variable to the smaller set first. The rationale is to keep the variable sets sizes close. Notice that the above greedy way of building \( X_A \) and \( X_B \) does not guarantee that they are the largest possible (meaning that the support sizes of components A and B are minimum). In practice, however, it gives a reasonably good trade-off between the size and the quality of the resulting variable sets and the computation time needed to evaluate the quantified formulas on each step of variable grouping. We tried a number of ways to increase the sizes of \( X_A \) and \( X_B \). For example, by excluding one variable at a time.
while trying to add others, and accepting the change only if excluding one variable led to the addition of two or more. This strategy reduced the netlist area by less than 3\% on average but the CPU time increased by 100\%.

procedure *GroupVariables* (bdd Q, bdd R, bdd S) 
{  (X_A, X_B) = FindInitialGrouping (Q, R, S);  
  if ( (X_A, X_B) == (\emptyset, \emptyset) ) return (\emptyset, \emptyset);  
  for all z \in S = (X_A \cup X_B)  
    if ( |X_A| \leq |X_B| )  
      // try adding the new variable z first to X_A, next to X_B  
      if ( CheckDecomposability (Q, R, X_A \cup \{z\}, X_B) )  
        X_A = X_A \cup \{z\};  
      else if ( CheckDecomposability (Q, R, X_A, X_B \cup \{z\}) )  
        X_B = X_B \cup \{z\};  
      else ... // similarly if ( |X_A| > |X_B| )  
      return (X_A, X_B); }

Figure 6. Procedure to find the variable grouping.

The above algorithm for variable grouping has another important consequence related to the testability of the netlist resulting from the bi-decomposition. Here we only formulate this result and refer the reader to [8] for details.

**Theorem 5:** If function F(X) = \{Q(X), R(X)\} is OR-, AND-, or EXOR-bi-decomposable with variable sets (X_A, X_B), that has been selected using the algorithm in Fig. 6, and the ISFs were derived using the formulas of Theorems 3 and 4, then the resulting netlist does not have redundant internal signals, i.e. it is completely testable for all stuck-at-0 and stuck-at-1 faults assuming the single stuck-at fault model.

### 6. Reusing Decomposed Blocks

The functions considered as input to the decomposition algorithm are incompletely specified (the on-set/off-set pairs) while the decomposed functions are completely specified. To enable efficient reuse of components across the netlist we developed an original caching technique, which allows checking that among the set of CSFs there exists a function F such that F (or it complement) belongs to the interval (Q_i, R_i). Theorem 6: Let an ISF F be given by on-set Q and off-set R. A CSF f is compatible with an ISF F iff

\[ Q \& \bar{f} = 0 \quad \text{and} \quad R \& f = 0. \]

The complement of f belongs to the ISF F iff

\[ R \& \bar{f} = 0 \quad \text{and} \quad Q \& f = 0. \]

Checking many functions for compatibility with the given ISF can be performed efficiently if the completely specified functions are sorted by support. This can be done by introducing a lossless hash table that hashes supports (represented as BDDs) into pointer to linked lists of CSFs (also represented as BDDs). In this case, checking reduces to getting the pointer to the linked list of all functions with the given support and walking through the list to determine whether one of them (or its complement) belongs to the given interval.

This technique turned out to be efficient in practice by achieving up to 30\% component reuse. The gain in area and CPU time is even more substantial, especially when a gate is reused on an early stage of the decomposition process, because in this case there is no need to generate the fanin cone of the given gate.

### 7. Bi-Decomposition Algorithm

This section presents the upper-level procedure performing one step of recursive bi-decomposition (Fig. 7).

procedure *BiDecompose* (bdd Q, bdd R) 
{  (Q, R) = RemoveEssentialVariables (Q, R);  
  if ( LookupCacheForCompatibleComponent (Q, R, S) ) {  
    F = GetCompatibleComponent (Q, R, S); return F;  
  }  
  if ( |S| \leq 2 ) {  
    (F_A, F_B, gate) = FindGate (Q, R);  
    F = AddGateToDecompositionTree (F_A, F_B, gate);  
    AddFunctionToCache (F);  
  }  
  bdd X_1 = OR, X_2 = AND, X_3 = OR, X_4 = EXOR, X_5 = BEST, X_6 = BEST,  
  (X_A OR, X_B OR) = GroupVariablesOR (Q, R, S);  
  (X_A AND, X_B AND) = GroupVariablesAND (Q, R, S);  
  (X_A EXOR, X_B EXOR) = GroupVariablesEXOR (Q, R, S);  
  (X_A BEST, X_B BEST) = FindBestVariableGrouping (  
    (X_A OR, X_B OR), (X_A AND, X_B AND), (X_A EXOR, X_B EXOR));  
  if ( (X_A BEST, X_B BEST) == (\emptyset, \emptyset) )  
    (X_A BEST, X_B BEST, gate) = GroupVariablesWeak (Q, R, S);  
  (Q_A, R_A) = DeriveComponent (Q, R, X_A BEST, X_B BEST, gate);  
  F_A = BiDecompose (Q_A, R_A);  
  (Q_B, R_B) = DeriveComponent (Q, R, X_A BEST, X_B BEST, gate);  
  F_B = BiDecompose (Q_B, R_B);  
  F = AddGateToDecompositionTree (F_A, F_B, gate);  
  AddFunctionToCache (F);  
  return F; }

Figure 7. The pseudo-code of bi-decomposition algorithm.

The arguments, Qi and Ri, are the initial on-set and off-set of the ISF to be decomposed. The return value is a CSF in the range (Qi, Ri) representing the resulting network of gates. At the beginning the support of the ISF is minimized by a simple greedy algorithm and a new ISF (Q, R) is created. In practice, support minimization occurs in less than 1\% of recursive calls for typical MCNC benchmarks. Next, a cache look up is performed. If it is successful, it means that the CSF in the given interval has already been implemented and can returned right away. If it is the terminal case, an appropriate two-input gate is added to the decomposition tree and to the cache before returning the gate’s CSF. Otherwise, the procedure calls three functions GroupVariables() to find sets X_A and X_B leading to a strong bi-decomposition with OR, AND, and EXOR gates.

Procedure FindBestVariableGrouping() considers the variable sets and determines the best one taking into account that X_A and X_B should be well-balanced. If variable grouping with non-empty variable sets X_A and X_B is not available (this happens in 20-30\% of recursive calls for typical MCNC benchmarks), procedure GroupVariablesWeak() finds the best variable grouping to perform weak AND/OR-bi-decomposition, which always exists.

Given the variable sets and the type of decomposition, the on-set and off-set Q_i and R_i of the ISF of component A are derived using the formulas of Section 4. Calling BiDecompose() recursively for component A returns the CSF f_A representing this component by a netlist of gates. The CSF f_A together with X_A and X_B are used to compute the ISF of the component B. Procedure BiDecompose() is again called recursively for component B. The CSF f of the netlist implementing the initial ISF is found using
CSFs $f_A$ and $f_B$ and the decomposition gate. Finally, the CSF $f$ is inserted into the cache and returned.

8. EXPERIMENTAL RESULTS

The algorithm has been implemented in the program BI-DECOMP written in platform-independent C++ using the BDD package CUDD [14]. The program has been tested on a 300Mhz Pentium II PC with 64Mb RAM under Microsoft Windows 98. The correctness of the resulting networks has been checked using a BDD-based verifier.

To demonstrate the optimization potential of bi-decomposition for both delay and area, we carried out two series of experiments. In the first one (Table 2), the bi-decomposition of MCNC benchmarks into two-input NAND/NOR/EXOR/NEXOR gates performed by BI-DECOMP is compared with similar results produced by SIS[15]. For SIS, the benchmarks have been preprocessed using script.rugged (with and without speed up) followed by a delay-oriented mapping into a subset of mcnc.genlib containing the above listed two-input logic gates.

Columns “gates” (“exors”) and “levels” give the number of (EXORS) gates and logic levels. Columns “area1” and “delay1” show results after running script.rugged and mapping. Columns “area2” and “delay2” show results if script.rugged is followed by speed up. SIS used at the most one or two EXOR gates per circuit. Column “time” gives the CPU time in seconds needed for BI-DECOMP to perform the decomposition and write the resulting BLIF file. The runtime for SIS was dominated by script.rugged and was one minute on average.

From Table 1 we see that BI-DECOMP produces larger area compared to SIS. This is because BI-DECOMP builds BDDs for the primary outputs and applies the bi-decomposition algorithm to them without any pre- or post-processing. However, the delay of the networks produced by BI-DECOMP is better because of the way the algorithm derives supports of the components resulting in a well-balanced bi-decomposition.

The second series of experiments (Table 3) shows that BI-DECOMP produces good results in terms of area for EXOR-intensive circuits. BI-DECOMP is compared with SIS[15] (script.rugged + area-oriented mapping into mcnc.genlib) and BDS, a BDD-based logic synthesis system [10]. (The results for SIS and BDS are taken from [11].) The number of gates after decomposition is shown in column “gates”. BDS outputs a netlist of 2/3/4-input (N)ANDs and (N)ORs, and 2-input (N)EXORS.

To make a fair comparison, we translated the two-input-gate output of BI-DECOMP into a set of gates comparable to the output of BDS. (This is why the gate count for 9sym in Table 3 differs from that of Table 2.) The column “area” shows the results of area-oriented mapping into mcnc.genlib.

One of the reasons why BI-DECOMP outperforms BDS on some test cases in that BDS does not make the most of the strong bi-decomposability of Boolean functions. The BDS algorithm does not guarantee that weak bi-decomposition is applied only when there is no strong bi-decomposition. Meanwhile, it is the strong bi-decomposition, with both $X_A$ and $X_B$ not empty (see Fig. 1), that leads to the fast reduction in the component size (smaller area) and creation of well-balanced netlists (shorter delay). Another difference between BDS and BI-DECOMP is in the use of don’t-cares. BDS uses them locally, to optimize the size of the BDD representation of one component. BI-DECOMP uses don’t-cares locally and passes don’t-cares (both external and locally generated) to the next decomposition steps by allowing the generic bi-decomposition procedure to work on ISFs.

9. CONCLUSIONS

We presented a new approach to decomposition of incompletely specified multi-output functions into netlists of two-input AND/OR/EXOR gates. The decomposition is based on Boolean formulas with quantifiers that can be evaluated using a standard BDD package. Our algorithm can be characterized as follows:

- The generated netlists are compact because it uses the EXOR gates for EXOR-intensive circuits, exploits external and internal don’t-cares, and achieves significant degree of component reuse by applying an original caching technique.
- The netlists are well-balanced, which significantly reduces the delay of the resulting circuit.
- The resulting netlists are 100% testable for single stuck-at faults [8]. Test pattern generation can be integrated into the decomposition algorithm with little if any increase in the complexity and runtime.

The future work includes extending the algorithm to work with arbitrary standard cell libraries, integration of ATPG into the process of decomposition, and generalization of the algorithm for multi-valued logic with potential applications in datamining [16].

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11. REFERENCES


Table 2. Comparison of delay-oriented decomposition results with SIS [15].

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