Low Overhead Fault-Tolerant FPGA Systems

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***Abstract*— Fault-tolerance is an important system metric for many operating environments, from automotive to space exploration. The conventional technique for improving system reliability is through component replication, which usually comes at significant cost: increased design time, testing, power consumption, volume, and weight. We have developed a new fault-tolerance approach that capitalizes on the unique reconfiguration capabilities of field programmable gate arrays (FPGA's). The physical design is partitioned into a set of tiles. In response to a component failure, a functionally equivalent tile that does not rely on the faulty component replaces the affected tile. Unlike application specific integrated circuit (ASIC) and microprocessor design methods, which result in fixed structures, this technique allows a single physical component to provide redundant backup for several types of components. Experimental results conducted on a subset of the MCNC benchmarks demonstrate a high level of reliability with low timing and hardware overhead.**

***Index Terms*—Field programmable gate array (FPGA), fault-tolerance.**

I. Introduction

A. Motivation

WHILE once Field programmable gate arrays (FPGA's) were mostly applied to prototyping, logic emulation systems, and extremely low volume applications, they now are used in a number of high-volume consumer devices. FPGA's are also now being used in more exotic applications. For example, the Mars Pathfinder mission launched in 1996 by NASA relies on Actel FPGA's for some system services. Unlike early applications, these high-volume and mission-critical systems tend to have stringent reliability requirements [1]. Thus, there is a drive from the user community to improve reliability through some level of fault-tolerance.

Unfortunately, current technology trends tend to make FPGA's less reliable. FPGA vendors have been moving down the same path of smaller device size as the rest of the semiconductor industry. Electronic current density in metal traces will increase as device feature size shrinks from 0.5 to 0.35 μm and smaller, which results in a greater threat of electromigration. As transistors shrink, the amount of charge required to turn them on reduces, which also makes the components more susceptible to gamma particle radiation. At the same time, FPGA vendors are moving to larger and larger dies in order to deliver more logic gates to their customers. The larger dies introduce more opportunities for failure and bigger targets for gamma particles.

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Engineers traditionally respond to these threats through redundancy, such as replicating components (e.g., microprocessors and ASIC's) or replicating logic internal to a component [e.g., built-in self-repair (BISR)]. However, replication is a particularly unattractive approach for FPGA systems given the common customer complaint that devices cost too much and do not provide enough equivalent logic gates. A better approach is to leverage the flexible nature of FPGA devices to provide replication at a much finer level. Conceptually, if a single logic block fails, it is often possible to find an alternate circuit mapping that avoids the fault. Most vendor place and route tools provide an option for reserving resources, and in the face of a fault, the tool could be invoked to search for a new placement which only uses functional components. The resulting system could provide reliability with very low overhead, i.e., by reserving only a few percent of the resources as spares for fault recovery. Unfortunately, this approach results in significant system downtime. Thus, the technique will not be sufficient for mission-critical applications with hard real-time constraints. This approach also requires that the end user have the vendor place and route tools, which is usually not possible. It seems unlikely that the end consumer will wish to even know about an embedded FPGA, let alone worry about generating a new configuration for one. Finally, because each fault is distinct, each component would possibly require a unique circuit placement. These three factors combine to make the approach impractical.

We instead propose a technique for increasing FPGA system reliability with very low overhead. The target architecture for demonstration is a Xilinx 4000EX part, which is composed of an array of configurable logic blocks (CLB's). Nonetheless, we believe that this technique is applicable to a wide range of FPGA architectures. The place-and-route computer-aided design (CAD) tool maps a circuit netlist onto the array of CLB's and interconnect components. We propose partitioning the physical design into a set of tiles. Each tile is composed of a set of physical resources (i.e., CLB's and interconnect), an interface specification which denotes the connectivity to neighboring tiles, and a netlist. Reliability is achieved by providing multiple configurations of each tile. Furthermore, by using locked tile interfaces, the effects of swapping a tile configuration do not propagate to other tiles, thus reducing the storage overhead.

B. Motivational Example

Consider the Boolean function $Y = (A \wedge B) \wedge (C \vee D)$, which might be implemented in a tile containing four CLB's as shown in Fig. 1. This configuration contains one spare CLB, which is available if a fault should be detected in one of the

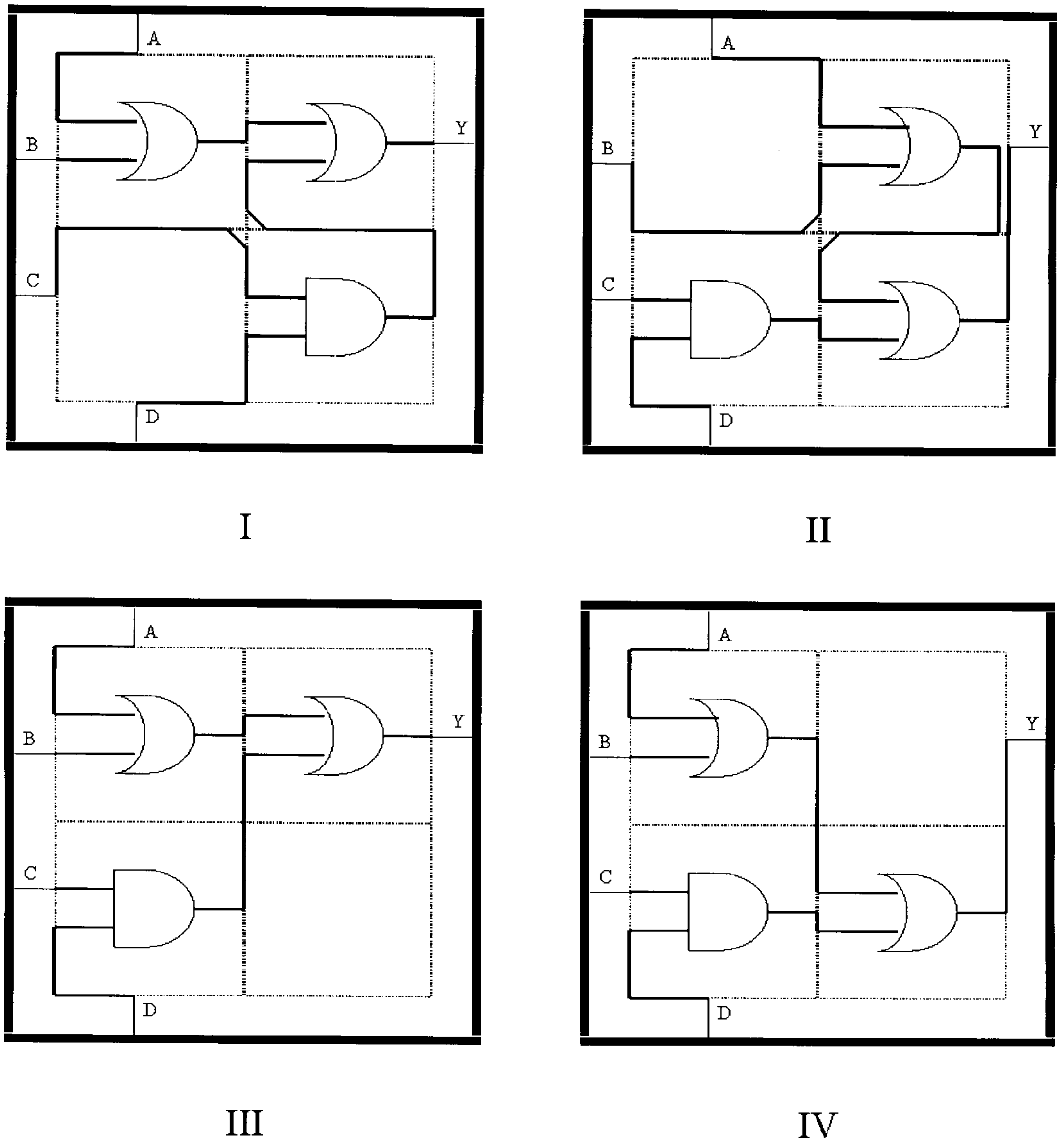

Fig. 1. Motivational example.

occupied CLB's. Upon detecting such a fault, an alternate configuration of the tile is activated which does not rely on the faulty CLB. Each implementation is interchangeable with the original, as the interface between the tile and the surrounding areas of the design is fixed and the tile's function remains unchanged. The timing of the circuit may vary, however, due to the changes in routing.

This approach has three main benefits compared to redundancy-based fault-tolerance: very low overhead, the option for runtime management, and complete flexibility. The overhead required to implement this fine-grained approach, which can be measured in both physical resources on the FPGA (CLB's, I/O blocks, and routing) and timing, is extremely low compared to redundancy. Run-time management can be a very valuable feature of a system, particularly for mission-critical applications. This fault-tolerance approach handles runtime problems on-line, minimizing the amount of system downtime and eliminating the need for outside intervention. The flexibility that this approach provides allows for application specific solutions. The degree of fault-tolerance can be changed based on timing constraints, resource limitations, or presumed CLB reliability.

C. Paper Organization

The following two sections discuss background information, approach restrictions, and work related to fault-tolerance and FPGA's. Section IV describes the details of the approach and implementation, and Section V introduces the formulas used to calculate the data for the experimental results in Section VI. Section VII discusses future work on this topic, and the paper closes with some remarks summarizing the benefits of this fault-tolerance approach.

II. Preliminaries

In this section, we survey the relevant background material for the proposed approach. We present the targeted FPGA architecture, the fault model assumed, and techniques envisioned for supporting the testing and fault diagnosis steps of the approach.

A. FPGA Architecture Model

The new fault-tolerance approach is demonstrated using the Xilinx XC4000EX family as the target architecture, specifically the XC4028EXBG352 [2]. However, neither the general concept nor the optimization algorithms are specific to the 4000EX family, or even Xilinx architectures. Any FPGA architecture supporting the ability to reconfigure a large number of times could be used, such as the Altera 10K and the GateField flash memory devices. The approach is not applicable to antifuse systems, such as the Actel architecture, as they cannot be reprogrammed.

B. Fault Model, Testing, and Diagnosis

The proposed approach requires fault detection and a diagnosis method as a preprocessing step. We assume a widely used single stuck at, open, or short fault model [3]. It is interesting to note that our strategy actually covers many simultaneous faults as long as each tile (see Sections IV and V) has at most one faulty CLB. In its current form, our approach does not address interconnect faults. Note that for local interconnects, faults will be expressed as a fault of the CLB to which it connects.

A number of schemes have been developed for detecting faults in FPGA's through exhaustive testing of the device architecture. Most of these approaches can be classified as off-line. For example, with built-in self-test (BIST) [4]–[7], the FPGA is loaded with a small testing circuit that is restricted to a specific physical region of the device, which is then used to test another portion of the device. The test circuit is moved across the device in a systematic manner until the entire device is thoroughly tested. The downside of these approaches is that they require the device to be taken off-line, which may not be practical in highly fault-sensitive, mission-critical applications. Fault-detection latency also increases as a result of an off-line approach. Recently, an online testing scheme has been developed for bus-based FPGA's that avoids these problems [8].

III. Related Work

Related work can be traced along the following three lines of research: FPGA synthesis, fault-tolerant design, and FPGA yield enhancement.

A number of different FPGA architectures and synthesis techniques have been proposed and demonstrated [9], [10]. Conceptually, our fault-tolerance approach is closest to BISR techniques. The main targets for BISR are systems that are bit-, byte-, or digit-sliced. These types of systems include SRAM and DRAM memories [11], as well as systems designed using a set of bit planes and arithmetic logic units (ALU's), assembled from ALU byte slices [1]. By far the most important use of bit-sliced BISR is in SRAM and DRAM circuits [12]–[14]. The bit-sliced BISR in memories significantly increases memory production profitability and is regularly used in essentially all modern DRAM designs. Among other BISR bit-sliced devices, the most popular and well addressed, from both a theoretical and practical point of view, are programmable logic arrays (PLA's) [15]–[18]. A simple, yet powerful methodology for the implementation of ALU byte slices was proposed by Levitt *et al*. [19].

Howard *et al*. [20] and Dutt *et al*. [21] have proposed using similar regularly structured BISR techniques for improving FPGA yield. Spare resources are allocated, and a manufacturing step is used to swap spare CLB's for faulty components. Altera uses this approach, along with on-chip fuses, to increase production yield on the 10K parts. Mathur and Liu have proposed using modified place-and-route tools to reroute part of the netlist in the vicinity of a faulty CLB [22].

Our approach is completely transparent to the existing computer-aided design (CAD) tool chain and exists as an intermediate step that is used in conjunction with exiting synthesis and place-and-route tools. Unlike the BISR techniques used in manufacturing, we are able to dynamically tolerate faults in the field. Finally, unlike Mathur and Liu, we are able to make timing guarantees (which is critical for real-time systems), require less system downtime, and do not require the end user to have access to FPGA CAD tools.

IV. Approach

The key element of our approach to fault-tolerance is partially reconfiguring the FPGA to an alternate configuration in response to a fault. If the new configuration implements the same function as the original, while avoiding the faulty hardware block, the system can be restarted. The challenging step is to identify an alternate configuration efficiently. In this section, we elaborate on the key elements of our approach.

A. Tiles and Atomic Fault-Tolerant Blocks

We reduce the amount of configuration memory required by reducing the size of the component that is reconfigured. This is enabled by logically partitioning a design in a way that components can be independently reconfigured without impacting the rest of the design. In comparison to other alternatives, this approach also reduces the down time for devices that support partial reconfiguration and, more importantly, significantly increases the level of fault-tolerance with only nominal hardware and timing overhead. The key concepts for implementing the new approach are tiles and atomic fault-tolerant blocks (AFTB's).

Definition 1: A *tile* is composed of three elements: a set of CLB's and interconnect resources, a netlist which must be placed on those CLB's and routed across the interconnect, and a specification of how to interface the tile to adjacent tiles.

Definition 2: An *atomic fault-tolerant block* (AFTB) is one instance of a tile and has at least one spare CLB that serves to "cover" the faulty CLB(s).

Because each tile is associated with both physical resources and portions of the complete netlist, the design can only be partitioned into tiles after the complete netlist has gone through place-and-route once. By fixing the interfaces between the tiles, we create the opportunity to produce multiple partial configurations that satisfy the functional specification for a

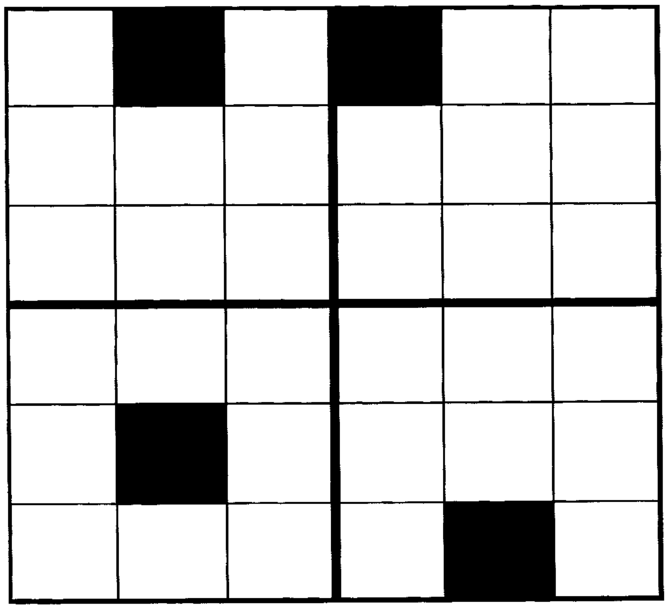
Fig. 2. A 6 × 6 CLB design partitioned into four 3 × 3 tiles.

given tile, independently from the remainder of the design. Fault-tolerance is achieved by introducing spare resources into each AFTB so that, once a fault in a particular CLB is detected, a configuration of the tile's functionality that does not utilize the faculty CLB can be activated.

Each tile has a set of AFTB's. An AFTB is independent from all AFTB's associated with other tiles by virtue of the fixed tile interface. Thus, selecting one AFTB for each tile can assemble a complete configuration, under the condition that none of the AFTB's rely on a faulty component.

Tiling provides many advantages in the implementation of fault-tolerant FPGA systems. First, the amount of memory needed to store the set of AFTB's is smaller than the amount required to store a set of complete configurations. For example, consider a design that must be able to tolerate any single CLB fault and which maps into a 6 × 6 CLB array It may be possible to divide the design into four 3 × 3 tiles (Fig. 2). Assuming that one configuration of the complete 6 × 6 design requires X bytes of memory, the nontiled approach would require 36*X of memory for fault-tolerance: one configuration for each CLB that is at risk. With our method, each tile would require nine AFTB's. However, since each tile (X/4 storage bytes) is independent, the entire storage is only 9*X, a 75% reduction from the nontiled approach.

Tiling also increases reliability. For this example, the nontiled approach could tolerate only one faulty CLB in the entire device. The tiled approach, however, is capable of tolerating any single fault in a tile but up to four faulty CLB's in the entire device.

The cost of increased fault-tolerance and reduced configuration memory is the possible introduction of more spare resources. For this example, the nontiled approach reserves 2.7% of the CLB's to protect against a single fault, while the tiled approach reserves 11%. However, tiling opens up the opportunity to explore a rich design space. By choosing the tile size and amount of spare resources that are appropriate for system requirements, tiling provides a powerful tool to the designer.

One remaining issue involves circuit timing. While timing analysis tools are not completely reliable for FPGA devices, the Xilinx XACT Step software has proven to be reasonably accurate. We use this tool to determine the timing estimate of the initial configuration before tiling. Furthermore, because each individual AFTB is generated as a modification to the original configuration we have good timing estimates for any single failure. However, it is difficult to know what the circuit timing will be once multiple AFTB's have been activated in response to failures in more than one tile. In particular, the critical path for the entire FPGA could pass through several AFTB's without falling on the longest path within any of them.

B. Synthesis Methods

The synthesis approach is organized in an iterative top-down manner. We start with a nonfault-tolerant base design and recursively partition it into tiles and AFTB's. We next check the feasibility of all fault scenarios in decreasing estimated level of difficulty. The idea is to determine as early as possible those base designs that will not result in a feasible solution. We also calculate early the final reliability figures, so that the designer has an option of terminating the current search and starting one that has a higher reliability potential.

The synthesis is summarized in the following pseudocode:

```
1.  while (!(complete || design possibilities exhausted )) {
2.      create initial non_ft_design;
3.      extract timing and area information;
4.      calculate design reliability;
5.      while (!(complete || tiling possibilities exhausted)) {
6.          partition design into tiles;
7.          if (!meet area criteria) break;
8.          while (!(complete || AFTB possibilities
                    exhausted)) {
9.              partition tiles into AFTBs;
10.             calculate AFTB reliability;
11.             if (!meet reliability criteria) break;
12.             order tiles by ft realization difficulty;
13.             order AFTB's by ft realization difficulty;
14.             for  $(j = 1; j <= \#$ of tiles; decreasing
                    difficulty) {
15.             for  $(i = 1; i <= \#$ of AFTBs; decreasing
                    difficulty) {
16.             create ft_design $(i, j)$;
17.             if (!(success && meet timing criteria))
                    break;
18. } } } } }
```

Lines 2–4 initialize the synthesis process for one instance of the base design. The place and route tool creates the base nonfault-tolerant design, and the relevant design characteristics are recorded. The procedure for the calculation of reliability is explained in Section V.

Line 5 starts the synthesis algorithm and dictates that the loop will terminate upon the creation of a fault-tolerant design that meets all of the user specifications, including overhead (area and timing), level of fault-tolerance, and available memory. The loop will also terminate if the algorithm reaches the end of its exhaustive tile partitioning search, thus revealing that the specifications cannot be met for the given FPGA architecture and design generated in line 2. In this case, the complete algorithm will be repeated using a different base design with increased spare resources throughout the FPGA.

Line 6 partitions the design into tiles, as described in Section IV-A. The placement and shape of the tiles are determined by the following three key factors listed in decreasing order of importance: amount of interconnect across the tile interface, tile logic density, and tile size. Our reliability calculation (see Section V) indicates that large tiles result in higher reliability. If the tiling attempt does not meet the user area specifications, the algorithm returns to the beginning of the tile partitioning loop for another tiling attempt. Hard macros (and fast carry chains) also affect the placement and shape of tiles, as efforts are made to keep macros intact.

Line 8 begins the AFTB partitioning algorithm, which terminates upon the successful creation of a fault-tolerant design meeting all user specifications or upon the exhaustion of all AFTB partitioning possibilities. If the latter occurs, the algorithm returns to line 5 for retiling.

Line 9 lays out the various AFTB's within a tile. The number of AFTB's for a given tile depends on the desired level of fault-tolerance, the number of free CLB's in the tile, and the malleability and density of the logic. The criteria used for partitioning the design into tiles are also used for this AFTB partitioning.

Line 10 ensures that the tile and AFTB partitions meet the user reliability specifications, and line 11 returns the algorithm to the beginning of the AFTB partitioning loop if they are not met. If upon such a return the AFTB partitioning possibilities have been exhausted, the design must be retiled, returning the algorithm to line 5.

Lines 12 and 13 facilitate early synthesis process failure detection. Tiles and AFTB's that are less likely to successfully place and route should be attempted first, thus efficiently returning the algorithm to the beginning of the loop if a fault-tolerant design meeting user specifications is not possible with the current tile and/or AFTB partitioning. The tile and AFTB characteristics causing them to be more difficult to realize include the criteria used in tile and AFTB partitioning. The presence of macros, and therefore reduced logic malleability, may also impact the assigned order of realization difficulty.

Lines 14 and 15 enforce the order defined by the two previous steps, as line 16 attempts to configure the various tiles and AFTB's. If the design can not be configured or if the configuration does not meet user timing specifications, the algorithm returns to the beginning of the AFTB partitioning loop (line 8) or, if AFTB partitioning is exhausted, to the beginning of the entire synthesis algorithm for retiling (line 5). The next iteration of line six partitions the design so as to give more slack (i.e., free CLB's) to the area of the previous iteration's failing tile. If no other tiling possibilities exist, the algorithm must return to line 1 for the creation of a new base design. If no base design possibilities remain, the algorithm terminates as unsuccessful.

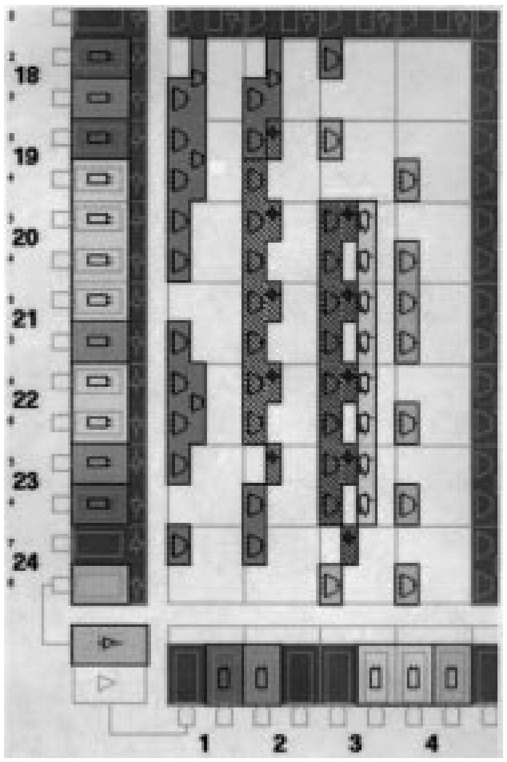

Fig. 3. Initial floorplan for PREP 5 benchmark.

The synthesis approach is illustrated using the PREP 5 benchmark shown in Figs. 3–5. Fig. 3 shows an implementation of the PREP 5 benchmark on the Xilinx 4000 architecture, a configuration that occupies rows 18–24 and columns 1–4. Only the CLB's in the defined area are used in the tiled design; the remaining CLB's are prohibited from use in any of the AFTB's.

Tile A covers rows 18–24 and columns 1–2, and tile B covers rows 18–24 and columns 3–4. Tiling was restricted by the occurrence of hard macros in each tile.

After partitioning the design into a set of tiles, the tiles are ordered by their implementation difficulty. In Fig. 3, the tiles are ordered A first and B second, primarily because the logic in tile A is denser.

Next we create a set of AFTB's for each tile, which are sorted in decreasing order of implementation difficulty. The tiles in Fig. 3 are assigned AFTB's that are composed of two adjacent CLB's. Each CLB is covered only once, making the total number of AFTB's per tile seven. For each AFTB, a complete configuration, i.e., one AFTB for each tile, is passed through the place and route tool. Although the placement and routing of the logic in the tile can be quite different for each AFTB, variations within a tile do not propagate to other tiles (other than timing). This is possible because, for each fault-tolerant configuration, only the tile in question is changed. All other tiles remain the same as in the original configuration.

After all of the AFTB's are stored in memory and the circuit begins operation, the system runs normally with the original configuration until a fault is detected. Upon detection, the circuit ceases functional mode until the proper reconfiguration can be made. As already mentioned, we assume that the fault-detection system is able to identify the faulty resource

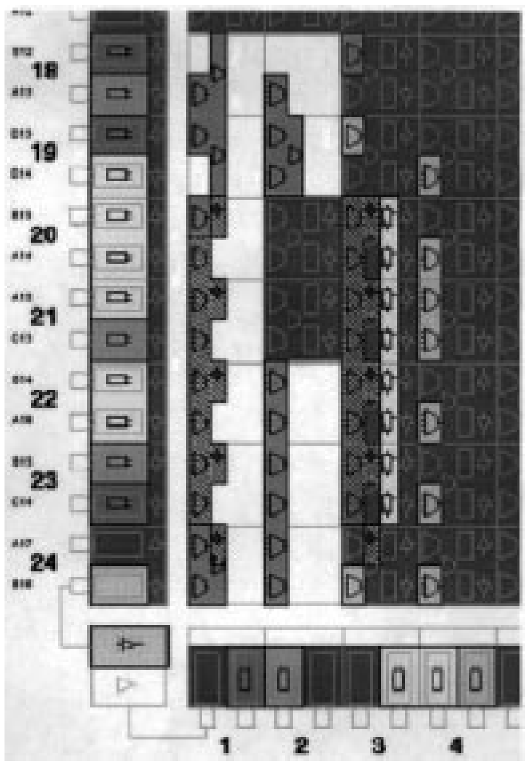

Fig. 4. PREP 5 after tiling with one AFTB identified.

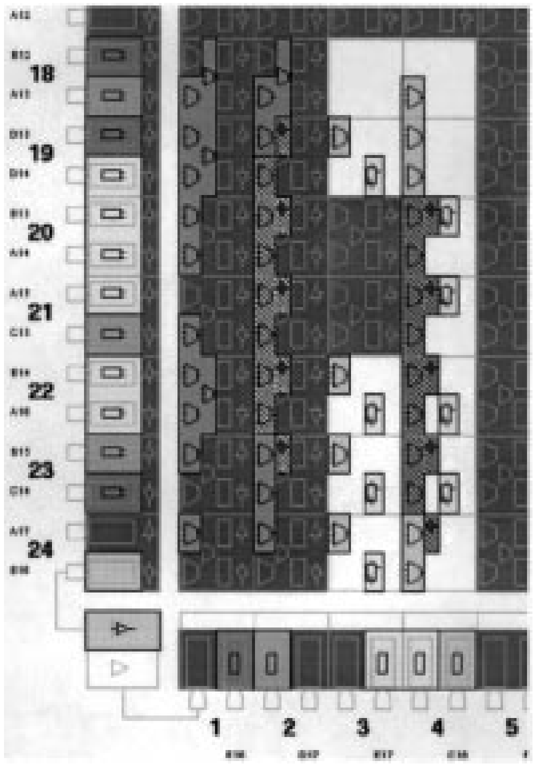

Fig. 5. System at runtime after swapping the AFTB in tile B due to fault at (20, 3).

in an architecture map. This information allows the system to retrieve the appropriate AFTB's from the configuration memory. The time needed for this memory access depends on normal access factors: access size, memory bus width, memory size, etc.

The last step involves the actual reconfiguration of the FPGA device. Once the AFTB is retrieved from memory, two options are possible depending on the capabilities of the FPGA architecture. If the device supports partial reconfiguration, the AFTB's of the affected tiles can be used in isolation to directly update the configuration. Otherwise, the AFTB's must be merged with the active and functioning AFTB's, thus providing the necessary data for a total chip reconfiguration. For example, if the CLB at row 20, column three failed in the design of Fig. 3, the proper configuration for tile B would be fetched from memory and configured onto the FPGA. The result is shown in Fig. 5. Note that the interface between tiles A and B is unchanged.

The time required to update a tile with a new AFTB depends on the complete set of tiles, the device architecture and the surrounding computer system. However, in all cases, it is bounded and can be used to provide a measured level of system availability. After updating the affected tile, the device is reset and the system resumes operation as before the fault. The only possible change could be in the timing of the circuit, as the routing in the altered tiles has likely changed. Timing numbers are generated with each AFTB, and the system can operate under worst case assumptions. Another, technically more demanding, option is the use of a programmable clock. If new faults occur later, the process repeats itself until more than one fault occurs in a tile for which there is no available AFTB that has all faulty CLB's as unused.

V. Reliability Calculation

The first step in calculating reliability is the selection of fault models. There are two major sources of logic faults in FPGA systems: cosmic radiation and manufacturing/operating imperfections.

Since the size of radiation particles is usually small when compared to the size of modern FPGA CLB's, we selected a cosmic radiation fault model that follows uniform distribution of independent (noncorrelated) failures. Extensive terrestrial efforts to accurately model the rate of such soft faults indicate high variance (several orders of magnitude) depending on factors such as seasonal solar activity, altitude, latitude, device technology, and device materials. Even for the same chip from the same manufacturer, variations by a factor higher than 200 are not uncommon [23]. Experiments indicate that in FPGA-like devices at an altitude of 20 km, error rates significantly higher than once per 1000 h are common [24]. Also, as circuit devices become smaller, they become more sensitive to soft faults [23]. If one considers the multiyear life of computing devices and other sources of potential errors (e.g., power surges), the need for fault-tolerance in devices which implement critical functions becomes apparent.

The second class of faults is related to manufacturing imperfections. These defects are not large enough to impact initial testing, but after a longer period of operation they become exposed. Design errors can also cause a device to stop functioning in response to rate sequences of inputs (e.g., due to a power density surge in a small part of design). For this type of model, we follow the gamma-distribution Stapper fault model [25]. The model is applicable on any integrated

TABLE I
TIMING BOUNDS DUE TO ROUTING VARIATION AMONG AFTB'S FOR EACH TILE

Design	Initial (ns)	Fastest (ns)	Slowest (ns)	Median (ns)	$\frac{\text{Slowest - Fastest}}{\text{Fastest}}$
9sym	71.6	71.6	82.0	76.8	0.15
c499	104.9	104.9	130.0	113.6	0.24
c880	110.8	110.8	126.4	117.3	0.14
duke2	87.9	87.9	118.8	96.4	0.35
rd84	50.2	50.2	72.8	58.6	0.45
planet1	145.0	145.0	194.9	166.1	0.34
styr	150.6	150.6	189.8	167.2	0.26
s9234	135.0	135.0	183.6	153.2	0.36
sand	97.6	97.6	117.7	103.8	0.21

circuit with regular repetitive structure, including memories and FPGA devices.

In the remainder of this section, we elaborate on technical details related to the two fault models' reliability calculations.

A. Independent Uniformly Distributed Faults

Suppose that a design is partitioned into t tiles. Furthermore, assume that tile i has a total of c_i AFTB's. The total number of used CLB's in the initial design is t_n. For the sake of clarity and simplicity, we limit our discussion to the case where each AFTB consists of three or fewer CLB's. We denote by m_{1i}, m_{2i}, m_{3i} the number of AFTB's of size one, two, and three CLB's, respectively, in tile i. We also denote their weighted sum $m_i = m_{1i} + 2^* m_{2i} + 3^* m_{3i}$.

Finally, we assume that the probability of a CLB being faulty is $(1 - P)$, i.e., the probability that a CLB is fault free is P. It is easy to see that the probability P_{init} that the original design is fault free is $P_{\text{init}} = P^{tn}$.

It is also easy to verify that the probability that a tile i in the optimized design is fault free Pft_i is given by the following formula:

$$\begin{aligned} Pft_i = & P^{m_i} + m_i * P^{(m_i-1)}(1-P) + (m_{2i} + 3 * m_{3i}) \\ & * P^{(m_i-2)} * (1-P)^2 + m_{3i}P^{(m_i-3)} * (1-P)^3. \end{aligned}$$

The first term corresponds to the scenario where all CLB's are fault free. The last three terms correspond to the scenarios where one, two, and three CLB's are faulty, respectively. The probability (Pft) that the optimized fault-tolerant design is functional is

$$Pft = \prod_{i=1}^{t} Pft_i.$$

B. Stapper's Fault Model

To calculate reliability for correlated faults, we started from the following formula [25]:

$$\begin{aligned} \overline{Y}_{mn} = & \binom{n}{m} \overline{Y}_1^m \left(\prod_{i=0}^{m-1} \frac{\mu + i}{\mu + i\overline{Y}_1} \right) \times (1 - \overline{Y}_1)^{n-m} \\ & \cdot \left(\prod_{j=0}^{n-m-1} \frac{\mu + j\overline{Y}_1/(1-\overline{Y}_1)}{\mu + m\overline{Y}_1 + j\overline{Y}_1} \right). \end{aligned}$$

TABLE II
VARIATION OF RESOURCES USED AMONG AFTB'S FOR EACH TILE

Design	Original # of CLBs	Final # of Club's	$\frac{\text{Final - Original}}{\text{Original}}$
9sym	46	49	.065
c499	94	96	.021
c880	110	115	.045
duke2	93	100	.075
rd84	27	28	.037
planet1	95	100	.053
styr	78	81	.038
s9234	195	206	.056
sand	82	90	.098

(Note that we have fixed a small typographical error in the original published formula.)

The formula calculates the probability that exactly m out of n identical modules operate correctly for a given value of the variability parameter μ and single CLB reliability $\overline{Y}_1$. The parameter μ indicates the assumed or the measured probability of clustered faults. Small values of μ imply high levels of clustering. As μ tends toward infinity the formula reduces to the case of independent uniformly distributed faults.

Stapper's formula is used to calculate the probability that at least m out of n modules operate correctly by a direct summation of relevant terms.

VI. EXPERIMENTAL RESULTS

We conducted an evaluation of the proposed approach and optimization algorithms in two phases. In the first, we applied the approach to nine MCNC designs. In the second phase we studied expected reliability improvement trends as a function of the number of used CLB's in a design.

Tables I and II show timing and cost (area) metrics, respectively, of the designs before and after the application of the new approach for reliability enhancement. The first column in both tables indicates the name of a design. The next four columns in Table I show the initial delay, and the best, worst, and median delay of the optimized designs. The rightmost column indicates the timing overhead as a result of enhanced reliability. For all nine designs, the largest timing overhead was in the range from 14 to 45%.

A number of factors complicate the task of calculating the physical resource overhead. The place-and-route tools will indicate the number of CLB's that are used for a particular

TABLE III
RELIABILITY OF THE ORIGINAL VERSUS TILED DESIGNS AGAINST CLB RELIABILITY

CLB P	.900		.950		.990		.995		.998		.999		.9999	
Design	Orig.	Tiled	Orig.	Tiled	Orig.	Tiled	Orig.	Tiled	Orig.	Tiled	Orig.	Tiled	Orig.	Tiled
9sym	1.2	16.9	11.6	56.2	65.6	95.7	81.0	98.4	91.9	99.5	95.9	100	99.2	100
c499	0.01	1.63	3.2	37.5	43.0	89.0	65.6	95.6	84.5	98.6	91.0	99.3	99.2	100
c880	0.0	0.6	1.8	31.7	37.3	91.2	61.2	97.6	82.2	99.6	90.7	99.9	99.0	100
duke2	0.01	0.7	2.8	31.9	41.3	90.8	64.3	97.5	83.8	99.6	91.6	99.9	99.1	100
rd84	7.2	38.6	27.7	74.7	77.8	98.5	88.2	99.6	95.1	99.9	97.5	100	99.8	100
planet1	0.02	5.4	11.5	32.6	41.7	94.1	64.7	98.4	84.0	99.7	91.7	99.9	99.1	100
styr	0.01	2.9	2.5	31.4	48.5	93.8	69.7	98.3	86.6	99.7	93.0	99.9	99.2	100
s9234	0.0	0.003	0.01	3.17	16.1	82.0	40.2	94.8	69.5	99.1	83.3	99.8	98.2	100
sand	0.03	1.53	1.83	2.50	45.7	92.4	67.6	97.9	85.5	99.7	92.5	99.9	99.2	100

TABLE IV
RELIABILITY OF ORIGINAL AND TILED DESIGNS USING STAPPER'S CORRELATED FAILURE MODEL WITH CLB RELIABILITY OF 90%/99%

	1		2		5		20	
	Orig.	Tiled	Orig.	Tiled	Orig.	Tiled	Orig.	Tiled
9sym	62.6/95.8	72.0/97.2	48.5/93.5	62.8/96.4	28.5/89.0	40.1/94.9	8.77/79.6	29.7/94.1
c499	57.9/95.1	68.2/96.5	41.6/92.2	54.8/95.5	19.9/86.1	36.2/94.1	2.76/71.6	14.5/88.7
c880	55.9/94.9	65.7/96.3	40.2/91.9	53.2/95.2	18.3/85.4	33.8/93.3	2.08/69.8	11.2/87.2
duke2	57.6/95.0	67.9/96.3	41.1/92.1	54.2/95.4	19.4/85.9	25.9/93.9	2.54/71.0	14.3/88.4
rd84	66.4/96.3	76.7/97.7	54.3/94.5	70.1/96.3	36.9/91.1	56.4/95.6	18.0/85.1	52.8/95.1
planet1	57.7/95.0	67.9/96.3	41.3/92.2	54.2/95.4	19.5/86.0	25.9/93.9	2.59/71.2	14.3/88.4
styr	58.9/95.2	68.1/96.9	43.0/92.5	56.2/95.8	21.6/86.8	39.6/94.4	3.63/73.4	15.4/89.8
s9234	53.1/94,3	64.4/95.6	35.1/90.9	58.9/93.5	13.1/82.9	28.4/89.6	0.63/62.5	5.32/83.6
sand	58.4/95.1	68.0/96.6	42.3/92.3	55.3/95.6	20.7/86.4	32.1/94.2	3.15/72.3	14.8/89.2

placement. However, these utilized CLB's rarely are packed into a minimal area. Unused CLB's introduce flexibility into the place-and-route step that may be essential for completion or good performance. For example, the initial c880 design possesses a concave region that contains 42 utilized CLB's but also 10 unutilized CLB's (19%). Therefore, we will report overhead in terms of the area used by the fault-tolerant design minus the total area of the original design, including unused CLB's such as the 19% measure above. The area overhead is presented in Table II, using the same format as Table I. The average, median, and worst case area overheads were 5.4, 5.3, and 9.8%, respectively.

Table III shows reliability improvements for the MCNC benchmarks under the uniform random fault model. The first column indicates the assumed probability (p) that a CLB is fault free. The next two columns show the probability that the original and fault-tolerant design of a particular benchmark is functioning properly. For example, for 9sym, with $p = 0.995$, the probability of the initial design and tiled design being functional is 81.0 and 98.4%, respectively.

Table IV shows the reliability figures for the same set of designs (original and tiled) with four different variability factors μ assuming the probability that a CLB is fault free is 90 and 99%. Table V is, in a sense, the strongest indication of the effectiveness of the proposed approach for reliability improvement. The second column of this table indicates the area overhead of tiled designs. The next four columns provide reliability data under two selected fault models for the duplication-enhanced fault-tolerant original and for the tiled designs. For both models, the tiled designs have significantly lower area overhead and always higher reliability than the conventional fault-tolerant designs.

TABLE V
COMPARISON OF RELIABILITY AND OVERHEAD FOR THE ORIGINAL DESIGN WITH COMPLETE REDUNDANCY (I.E., 100% OVERHEAD) VERSUS TILED DESIGN FOR CLB RELIABILITY OF 90% AND $\mu = 20$

	CLB Overhead for Tiling	Random Fault Model		Stapper's Fault Model	
		Orig.	Tiled	Orig.	Tiled
9sym	6.5%	2.4	16.9	16.8	29.7
c499	2.1%	0.02	1.6	5.4	14.5
c880	4.5%	0.00	0.6	4.1	11.2
duke2	7.5%	0.02	0.7	5.0	14.3
rd84	3.7%	13.9	38.6	32.8	52.8
planet1	5.3%	0.04	5.4	5.1	14.3
styr	3.8%	0.02	2.9	7.1	15.4
s9234	5.6%	0.00	0.003	1.3	5.32
sand	9.8%	0.06	1.5	6.2	14.8

Finally, Table VI calculates reliability improvement trends as the size of designs increase. It is assumed that all designs are partitioned into tiles of five AFTB's each consisting of two CLB's and requires an average hardware overhead (i.e., ~5.4%). Table VI indicates the potential of the proposed approach for reliability enhancement. For example, in the case of a 5000 CLB design, with $p = 0.999$, the probability of the initial design being functional is less than 1%, while the probability of the tiled design being functional is 98%. Fig. 6 graphs the reliability results for the 5000 CLB design.

VII. FUTURE WORK

Many of the highest volume FPGA devices tend to be dominated by interconnect resources, e.g., the Xilinx 4000 and the Altera 10K families. On the Xilinx 4000EX series, the majority of configuration bits are used to program the state of the interconnect rather than the CLB's, and it is likely that

TABLE VI
RELIABILITY OF TRADITIONAL DESIGN METHODS VERSUS TILED APPROACH AGAINST CLB RELIABILITY FOR LARGE FPGA'S

CLB	100 CLB design		1000 CLB design		5000 CLB design	
Reliability	Orig.	Tiled	Orig.	Tiled	Orig.	Tiled
.9500	0.005921	0.444669	0.000000	0.000302	0.000000	0.000000
.9750	0.079551	0.800119	0.000000	0.107534	0.000000	0.000014
.9800	0.132687	0.864375	0.000000	0.232820	0.000000	0.000684
.9850	0.220739	0.919633	0.000000	0.432660	0.000000	0.015161
.9900	0.366277	0.962643	0.000043	0.683364	0.000000	0.149026
.9950	0.606224	0.990317	0.006704	0.907280	0.000000	0.614762
.9980	0.819220	0.998429	0.136145	0.984404	0.000047	0.924414
.9990	0.905528	0.999608	0.370696	0.996091	0.007000	0.980610
.9995	0.951999	0.999903	0.611453	0.999028	0.085470	0.995153
.9999	0.990868	0.999995	0.912346	0.999952	0.632119	0.999762

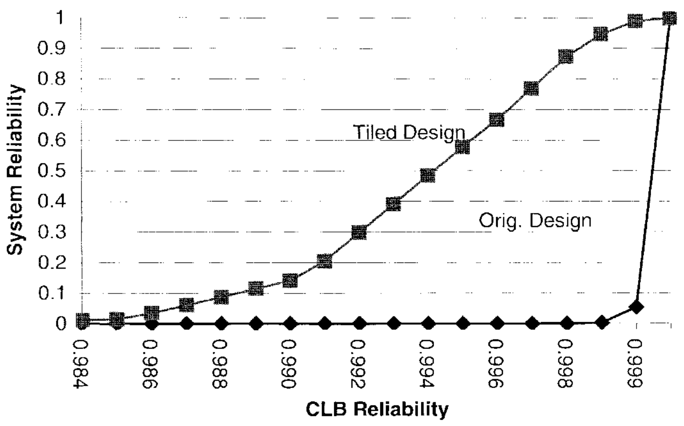

Fig. 6. Reliability of traditional methods versus tiled methods for a hypothetical 5000 CLB FPGA.

these interconnect resources are more susceptible to faults. The fault-tolerance methodology presented above addresses faults in interconnect resources directly dedicated to specific CLB's because they appear as CLB faults. Unfortunately, the vast majority of interconnect resources pass through higher level hierarchical switch structures that are not covered by unique CLB faults. Some of these routing resources will remain unused in each AFTB, thus providing some additional fault-tolerance. However, since this benefit comes as a byproduct of the approach rather than as a primary goal, we currently cannot make any specific claims on interconnect fault-tolerance.

VIII. CONCLUSIONS

Fault-tolerant techniques have recently emerged as an important design consideration for FPGA-based systems due to the rapid progress in FPGA integration and the growing market for these devices. In order to address this problem, we have developed the first fault-tolerance approach to work at the level of physical design. Our hierarchical fault-tolerance technique partitions designs into tiles and atomic fault-tolerant blocks. The approach scales systematically through an exploration of the design solution space at the physical level. The approach is constructed of four phases: design partitioning, tile partitioning and ordering, AFTB partitioning and ordering, and reliability calculation.

Experimental results conducted on a subset of the MCNC benchmarks for large CLB FPGA's indicate that the technique is effective with low hardware overhead.

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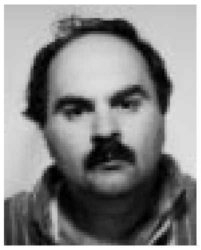

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