EFFICIENT TEST GENERATION FOR BUILT-IN SELF-TEST BOUNDARY-SCAN TEMPLATE

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Abstract—An analysis and design of a pseudorandom pattern generator, PRPG, (based on a linear recurrence) for built-in self-test (BIST) boundary scan design is presented. We present for the case when $r \geq s$, a design of an s-stage PRPGs capable of producing 2^s-1 distinct r-bit patterns within 2^s-1 clock pulses independent of the hardware realization of the PRPG. Next, we present for the case when $r<s$; the expected number $\bar{N}(T)$ of clock pulses, (over an ensemble of different pseudorandom sequences generated by different PRPGs and their initial states), such that a PRPG will produce $T \leq 2^r$ r-bit test patterns, and $\bar{T}(N)$ the expected number of distinct patterns given the number of clock pulses N. In this analysis, $\bar{N}(T)$ and $\bar{T}(N)$ are derived based on randomly drawing (without replacement) of test patterns and shown to be very close to the experimental average number $\bar{N}_{ex}(T)$ of PRPG clock pulses obtained for s = 24, r = 14, 18 and 22 ($r<s$). Thus, the value $\bar{N}(T)$ or $\bar{T}(N)$ can be used as a benchmark for evaluating the efficiency of the test genration with respect to minimal test application time.

1 Introduction

Boundary-scan-design templates, (Fig. 1), have been proposed in [1]-[3] as standard components for design of testable VLSI chips. For these templates, the test generation procedure for the built-in self-test (BIST) mode can be described as follows. The boundary input register is switched to function as a pseudorandom test pattern generator (PRPG). The PRPG is implemented by a maximal-length-sequence linear sequential circuit, [4]-[6], capable of generating at most 2^s-1 different s-bit patterns where s is the number of flip-flops in the PRPG. Furthermore, a test pattern at any moment consists of r = n + m bits in which n consecutive bits are the contents of the PRPG flips-flops connected to the primary inputs (PIs) and other m consecutive bits are obtained from scanning-in the content of the last PRPG flip-flop to the m-bit interior scan register via the scan path, (see, Fig. 1).

Our goal is to provide for an efficient test generation technique for the BIST boundary-scan design proposed in [1]-[2]. With respect to test application time, an efficient test generation implies that the PRPG produces for every clock pulse, (state transition), a test pattern which has not previously appeared. Efficiency of the test generation can be defined as the number of distinct r-bit test patterns generated divided by the number of clock pulses applied.

In Section 2, we will show for the case when $r \geq s$, that an efficient test generation is achieved if the connections for the PIs are from the last n PRPG filp-flops, (e.g., see Fig. 1, 2, 3, and 4). In Section 3, we will derived for the case when $r<s$, r = n+m, the expected number of clock pulses $\bar{N}(T)$ for an s-stage PRPG producing $T \leq 2^r$ distinct r-bit patterns, and the expected number $\bar{T}(N)$ of distinct patterns generated within a given number N of clock pulses. The derivation of $\bar{N}(T)$ and $\bar{T}(N)$ will be based on the assumption that the test generation procedure is a repeated experiment of randomly drawing, without replacement, an r-bit pattern out from the pool initially containing 2^s r-bit patterns

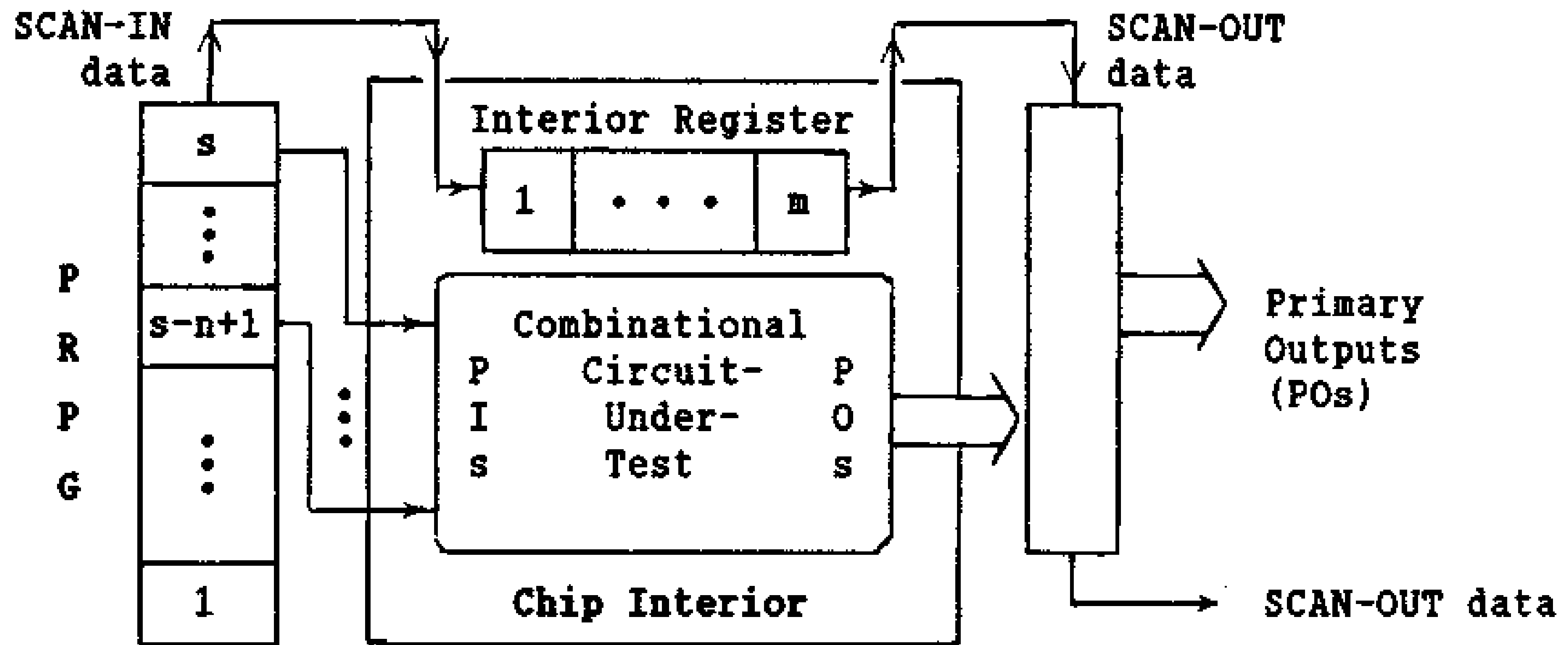

Fig. 1. Built-in Self-test Boundary Scan Design

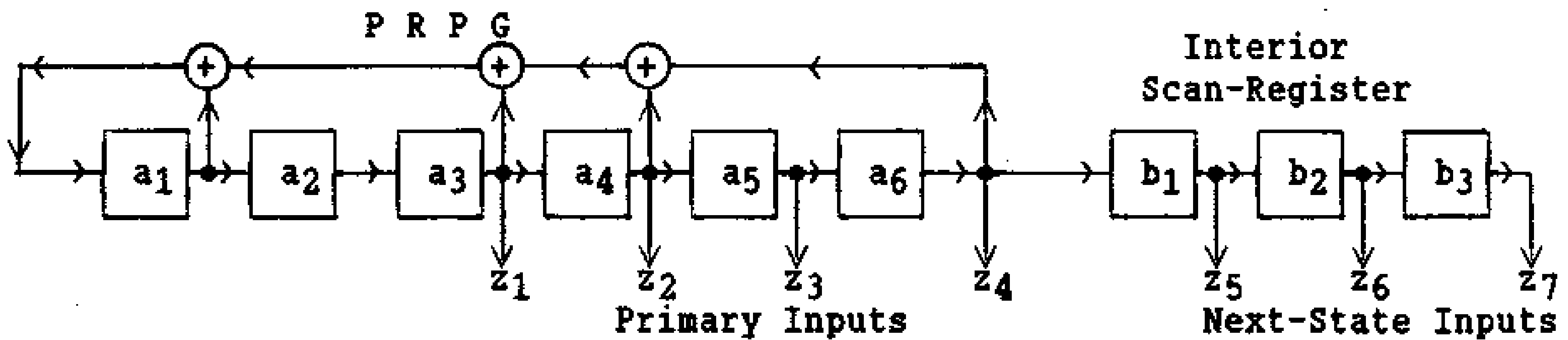

Fig. 2. An example of Efficient Test Generation: (s,n,m)=(6,4,3), r=n+m=7, with External XOR-Gate LFSR Realization of the PRPG.

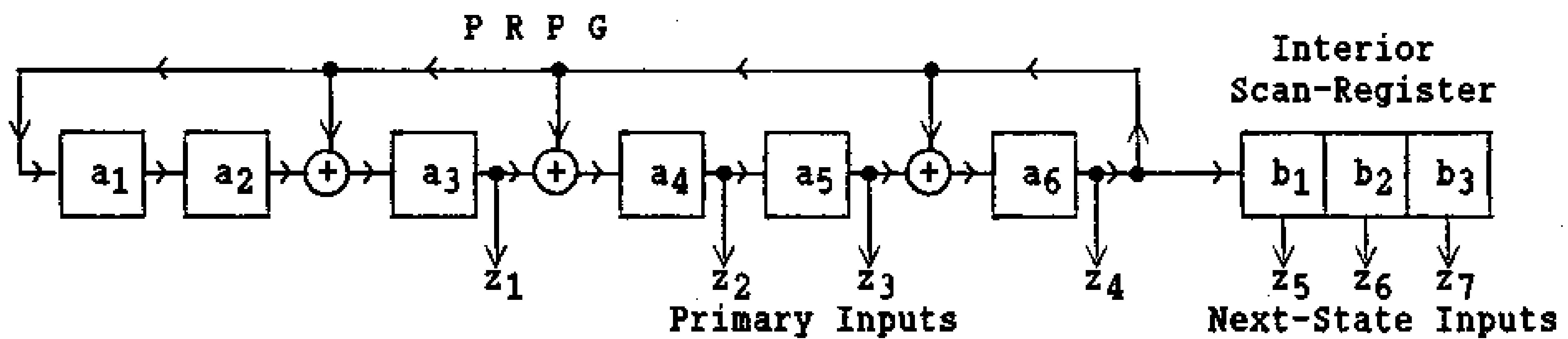

Fig. 3. An example of Efficient Test Generation: (s,n,m)=(6,4,3), r=n+m=7, with Internal XOR-Gate LFSR Realization of the PRPG.

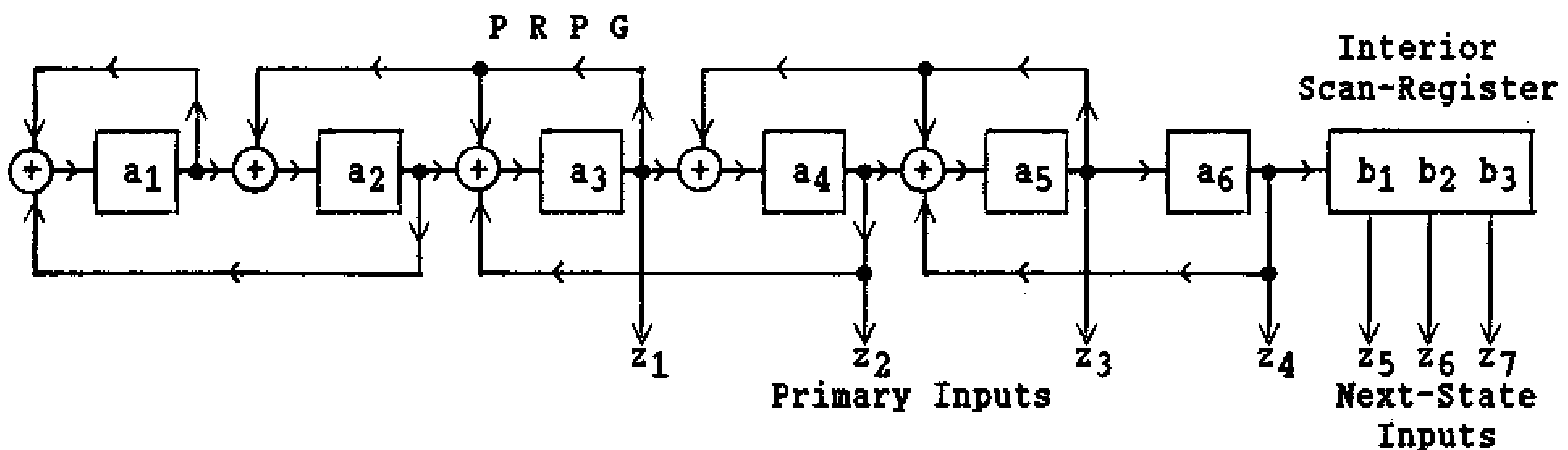

Fig. 4. An example of Efficient Test Generation: (s,n,m)=(6,4,3), r=n+m=7 with Cellular Automata Register (CAR) Realization of the PRPG.

distributed uniformly (every r-bit pattern has 2^{s-r} copies). We will further show that $\bar{N}(T)$ is close to the experimental average $\bar{N}_{ex}(T)$, (obtained by simulation), for s = 24, r = 14, 18 and 22, (see Fig. 6).

The number of clock pulses required for an s-stage PRPG to generate $T \le 2^r$ distinct r-bit patterns is important for design of built-in self-test chips and boards [7]. For a PRPG with a given number of flip-flops s and fixed feedback taps, the test application time can be minimized by a proper choice of the number of clock pulses applied. Thus, the proposed $\bar{N}(T)$ and $\bar{T}(N)$ can then serve as a benchmark on minimal number of clock pulses required for test generation.

2 Efficient Test Patterns Generation for the Case When $r \ge s$

In this section, we will show that, for the case when $r \ge s$, 2^s-1 distinct nonzero r-bit test patterns can be generated by shifting the PRPG at most $s-n+2^s-1$ times, provided that the contents of the last n consecutive cells in the PRPG are the test patterns to PIs and the content of the rightmost cell is scanned into the interior scan register,(e.g., see Fig. 2, 3 and 4).

Consider a general block diagram of the proposed test generation for BIST boundary scan design (Fig. 5). The system consists of an autonomous linear sequential circuit (ALSC) without feed-forward cascaded with a scan register, (e.g., see Fig 2, 3 and 4, where the ALSC is an LFSR and a CAR). We will show that for such a system there exists a one-to-one correspondence between $\underline{a}(t-k)$, the states of the ALSC at moments $t-k$ $(t \ge k)$, and $\underline{y}(t)$, the contents of the first s consecutive bits of the r-bit test pattern at moments $t \ge k$, where $r \ge s$, $r=n+m$, and the initial state of the ALSC is denotes as $\underline{a}(0)$.

More specifically, the following theorem holds:

<u>Theorem</u> 1. For any ALSC without feed-forwards cascaded with a scan register

$$\underline{y}(t+k) = C\underline{a}(t), \qquad (1)$$

where $t \ge k$, $\underline{a}(t), \underline{y}(t) \in V_s$ (V_s denotes the s-dimensional vector space over $\{0,1\}$), and C is an $(s \times s)$ nonsingular triangular matrix over GF(2), the Galois Field of two elements $\{0,1\}$ where the addition is the exclusive OR.

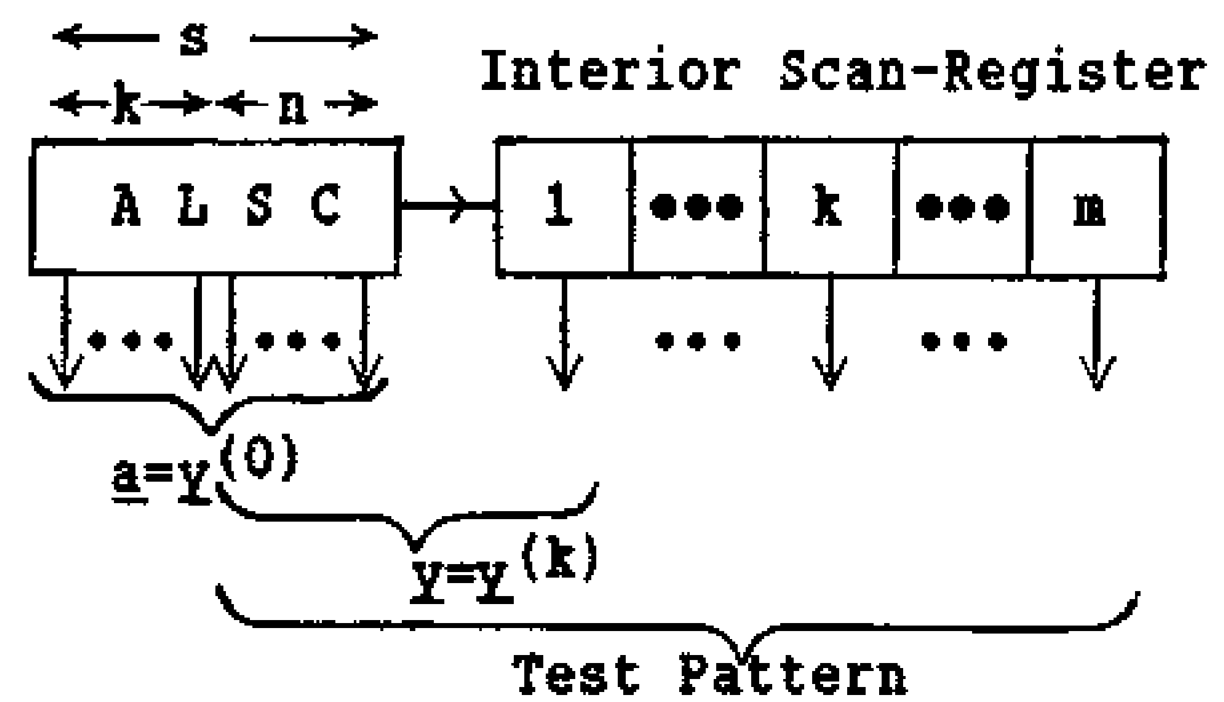

Fig. 5. Block Diagram of Test Generation for Boundary Scan

<u>Proof</u> Denote by $\underline{y}^{(i)}(t)$, $i \in \{0,1,\ldots,k\}$, $\underline{y}^{(i)}(t) \in V_s$) the s-dimensional binary vector formed by the contents of the s-i last (rightmost) consecutive cells of the ALSC and i first (leftmost) cells of the scan register.

Let t be the initial moment of time. By definition, $\underline{y}^{(0)}(t) = \underline{a}(t)$. It is easy to see that for the moment of time t+i the vector $\underline{y}^{(i)}(t+i)$ is uniquely determined by the vector $\underline{y}^{(i-1)}(t+i-1)$. Namely,

$$\underline{y}^{(i)}(t+i) = C^{(i)}\underline{y}^{(i-1)}(t+i-1), \qquad (2)$$

where $C^{(i)}$ is a triangular matrix with diagonal elements equal to one.

Indeed, denote by $y_j^{(i)}(t+i)$ the <u>jth</u> component (from left to right) of the vector $\underline{y}^{(i)}(t+i)$. Then, because of the absence of feedforwards, $y_j^{(i)}(t+i)$ is determined only by the components $y_g^{(i-1)}(t+i-1)$ with $g \ge j$. Moreover, $y_j^{(i-1)}(t+i-1)$ always contributes to $y_j^{(i)}(t+i)$ for the ALSC considered. Hence, by recursive substitution,

$$\underline{y}(t+k) = \underline{y}^{(k)}(t+k) = C\underline{a}(t), \quad (k=s-n), \tag{3}$$

where $C = C^{(k)}C^{(k-1)}\cdots C^{(1)}$, and C is also a triangular matrix with all the diagonal elements equal to one. Thus, C is a nonsingular matrix. Therefore, $\underline{a}(t)$ is uniquely determined by $\underline{y}(t+k)$

$$\underline{a}(t) = C^{-1}\underline{y}(t+k), \tag{4}$$

which implies that for different states $\underline{a}(t)$ of the ALSC the corresponding s-bit patterns $\underline{y}(t+k)$ are also different.

Since all the 2^s-1 successive states of a PRPG with nonzero initial state (implemented as an ALSC) $\underline{a}(t)$, $t=0,\ldots,2^s-2$, are different, it follows from Theorem 1 that all the 2^s-1 successive r-bit patterns generated at the moments of time $t = k, k+1, \ldots, k+2^s-2$ are also different. Thus, after $k+2^s-1$ clocks the system will generate the maximum possible number of 2^s-1 different test patterns.

Example 1. Consider the case $(s,n,m) = (6,4,3)$, i.e., $r=7$ and $k=2$. Fig. 2, 3 and 4 show diagrams of three different realizations of PRPGs. For the case of the PRPG implemented by the external XOR-gates LFSR (see Fig. 2), it is obvious that the leftmost six-bit block of the test pattern $(z_1,\ldots,z_6)$ is the state of the PRPG delayed by $k=2$. This relation establishes the one-to-one correspondence.

For the PRPG being implemented by the internal XOR-gate LFSR (see Fig. 3), we have, $\underline{y}^{(0)}(t) = \underline{a}(t)$, and

$$\underline{y}^{(1)}(t+1) = \begin{pmatrix} y_1^{(1)}(t+1) \\ y_2^{(1)}(t+1) \\ y_3^{(1)}(t+1) \\ y_4^{(1)}(t+1) \\ y_5^{(1)}(t+1) \\ y_6^{(1)}(t+1) \end{pmatrix} = \begin{pmatrix} a_2(t+1) \\ a_3(t+1) \\ a_4(t+1) \\ a_5(t+1) \\ a_6(t+1) \\ b_1(t+1) \end{pmatrix}$$

$$= \begin{pmatrix} 100000 \\ 010001 \\ 001001 \\ 000100 \\ 000011 \\ 000001 \end{pmatrix} \begin{pmatrix} y_1^{(0)}(t) \\ y_2^{(0)}(t) \\ y_3^{(0)}(t) \\ y_4^{(0)}(t) \\ y_5^{(0)}(t) \\ y_6^{(0)}(t) \end{pmatrix} = \begin{pmatrix} 100000 \\ 010001 \\ 001001 \\ 000100 \\ 000011 \\ 000001 \end{pmatrix} \begin{pmatrix} a_1(t) \\ a_2(t) \\ a_3(t) \\ a_4(t) \\ a_5(t) \\ a_6(t) \end{pmatrix}$$

$$= C^{(1)}\underline{y}^{(0)}(t) = C^{(1)}\underline{a}(t). \tag{5}$$

$$\underline{y}^{(2)}(t+2) = \begin{pmatrix} y_1^{(2)}(t+2) \\ y_2^{(2)}(t+2) \\ y_3^{(2)}(t+2) \\ y_4^{(2)}(t+2) \\ y_5^{(2)}(t+2) \\ y_6^{(2)}(t+2) \end{pmatrix} = \begin{pmatrix} a_3(t+2) \\ a_4(t+2) \\ a_5(t+2) \\ a_6(t+2) \\ b_1(t+2) \\ b_2(t+2) \end{pmatrix}$$

$$= \begin{pmatrix} 100010 \\ 010010 \\ 001000 \\ 000110 \\ 000010 \\ 000001 \end{pmatrix} \begin{pmatrix} y_1^{(1)}(t+1) \\ y_2^{(1)}(t+1) \\ y_3^{(1)}(t+1) \\ y_4^{(1)}(t+1) \\ y_5^{(1)}(t+1) \\ y_6^{(1)}(t+1) \end{pmatrix}$$

$$= C^{(2)}\underline{y}^{(1)}(t+1) = C^{(2)}C^{(1)}\underline{a}(t). \tag{6}$$

For the PRPG implemented by the cellular automata register (CAR), (see Fig. 4), we have,

$$C^{(1)} = \begin{pmatrix} 101000 \\ 011100 \\ 001010 \\ 000111 \\ 000010 \\ 000001 \end{pmatrix}, \quad C^{(2)} = \begin{pmatrix} 111000 \\ 010100 \\ 001110 \\ 000100 \\ 000010 \\ 000001 \end{pmatrix},$$

$$C^{(3)} = \begin{pmatrix} 101000 \\ 011100 \\ 001000 \\ 000100 \\ 000010 \\ 000001 \end{pmatrix}, \quad C^{(4)} = \begin{pmatrix} 111000 \\ 010000 \\ 001000 \\ 000100 \\ 000010 \\ 000001 \end{pmatrix},$$

$$C^{(5)} = \begin{pmatrix} 100000 \\ 010000 \\ 001000 \\ 000100 \\ 000010 \\ 000001 \end{pmatrix}, \quad C^{(6)} = \begin{pmatrix} 100000 \\ 010000 \\ 001000 \\ 000100 \\ 000010 \\ 000001 \end{pmatrix}. \tag{7}$$

All $C^{(i)}$, ($i=1,\ldots,6$, in this example $k\le 6$, $s=6$), are nonsingular over GF(2).

In contrast, if the connection points to the PIs are taken from the first four cells of the CAR the state-dependence equation for the first s-bit block of the r-bit test patterns ($s=6$, $r=7$) is given by

$$\begin{pmatrix} z_1 \\ z_2 \\ z_3 \\ z_4 \\ z_5 \\ z_6 \end{pmatrix} = \begin{pmatrix} 100000 \\ 010000 \\ 001000 \\ 000100 \\ 111011 \\ 011111 \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \\ a_5 \\ a_6 \end{pmatrix}. \tag{8}$$

The above matrix over GF(2) is singular which implies that the 2^s-1

successive r-bit test patterns are not guaranteed to be all distinct. In fact, only 33% of the r-bit patterns generated by application of $s-n+2^s-1$ clock pulses were distinct, ([1] and [2]).

3 Efficient Test Generation for the Case When r<s

In the design of a specific chip, a designer may have to use a pre-design boundary-scan template in which the number of PRPG flip-flops s is greater than the number of bits r in the test patterns. The problem arises as how to efficiently generate, with a minimal number N of clock pluses, a desired number $T \leq 2^r$ distinct r-bit patterns using s-stage PRPG when r<s. (An inefficient technique is to clock the PRPG for $N=2^s-1$ times). The efficiency of a test generation (when s, r and T are given) depends on the choice of the initial state of the PRPG. For ramdomly chosen initial state, we can characterize the efficiency in terms of $\bar{N}(T)$, the expected number of clock pulses (over an ensemble of s-stage PRPGs and their initial states) such that a PRPG will generate $T \leq 2^r$ r-bit patterns, and $\bar{T}(N)$, the expected number of distinct r-bit patterns generated within N clock pulses. We note also that the problem of determining an initial state that results in a minimal number of clock pulses for a given s-stage PRPG generating $T \leq 2^r$ r-bit patterns is still open.

The proposed probabilistic model for the test generation procedure is a repeated experiment of randomly drawing, without replacement, an r-bit pattern out from the pool initially containing 2^s r-bit patterns distributed uniformly. The assumption made is that an r-bit pattern generated by PRPG at any moment of clock pulse is random (random draws). Moreover, since the r-bit patterns are the r consecutive bits of the s-bit patterns generated by the PRPG, it follows that, with 2^s-1 clock pulses every nonzero r-bit pattern appears 2^{s-r} times and the pattern of r zero's appears $2^{s-r}-1$ times, thus, the proposed model is assumed as a drawing without-replacement experiment. (The random without replacement drawing model has been used in [8] for estimating the number of pseudorandom patterns needed to achieve a given fault coverage for pseudorandom testing).

In the proposed model, let ν be a random variable defined as the number of draws (analogous to the number of clock pulses) and τ be a random variable defined as the number of distinct patterns appeared. We show in Theorem 2, below, the expected number $\bar{N}(T)$ of random draws such that T distinct patterns will appear for the first time. Moreover, the expected number $\bar{T}(N)$ of distinct patterns appeared in N draws ($\nu=N$) is given below in Corollary 1.

<u>Theorem</u> 2. Let $Q = 2^r$, $M = 2^{s-r}$ and ξ_i be a binary random variable defined as follows; $\xi_i=1$ if the pattern appeared at the $i\underline{th}$ draw has not previously appeared (distinct) and $\xi_i=0$ if the pattern has previously appeared. The conditional probability that exactly T distinct patterns will appear within N random draws satisfies the folowing equation:

$$\Pr\{\tau=T \mid \nu=N\} = \Pr\{\tau=T \mid \nu=N-1\}\Pr\{\xi_N=0\} + \Pr\{\tau=T-1 \mid \nu=N-1\}\Pr\{\xi_N=1\}, \quad (9)$$

where $\Pr\{\xi_N=0\} = \frac{MT-N+1}{MQ-N+1}$ and $\Pr\{\xi_N=1\} = \frac{M(Q-T+1)}{MQ-N+1}$.

The solution of the above functional equation is:

$$\Pr\{\tau=T \mid \nu=N\} = \frac{\binom{Q}{T}}{\binom{MQ}{N}} \sum_{\ell=0}^{T} (-1)^{T-\ell} \binom{T}{\ell} \binom{M\ell}{N}. \quad (10)$$

The conditional probability that N is a number of draws such that T, $1 \leq T \leq Q$, distinct patterns will appear for the

first time (minimal number of draws) is given by

$$\Pr\{\nu=N|\tau=T\}= \Pr\{\tau=T-1|\nu=N-1\}\Pr\{\xi_N=1\}, \quad (11)$$

and the conditional expected value for the number of draws given T, $(1\le T\le Q)$, is

$$E\{\nu|\tau=T\} = \bar{N}(T) = (MQ+1)\left[1-\prod_{k=Q-T+1}^{Q}\left(1+\frac{1}{Mk}\right)^{-1}\right]. \quad (12)$$

A good approximation for $\bar{N}(T)$ when $Q\gg 1$ can be given by:

$$\bar{N}(T) \approx \begin{cases} (MQ+1)\left[1-\left(\frac{Q}{Q-T}\right)^{-1/M}\exp\left(\frac{1}{2M(Q-T)}-\frac{1}{2MQ}\right)\right], T<Q; \\ (MQ+1)\left[1 - Q^{-1/M}\exp(-\gamma M^{-1})\right], T=Q; \end{cases} \quad (13)$$

$\gamma\approx 0.577$ is the Euler's constant, [9].

Proof. In (9), $\Pr\{\tau=T|\nu=N\}$ is expressed as a sum of two probabilities: $\Pr\{\tau=T|\nu=N-1\}\Pr\{\xi_N=0\}$, the probability that T distinct patterns appear before the Nth draw and $\Pr\{\tau=T-1|\nu=N-1\}\Pr\{\xi_N=1\} = \Pr\{\nu=N|\tau=T\}$, the probability that in N draws T distinct pattern appear for the first time, (see, (11)). It can be verified that $\Pr\{\tau=T|\nu=N\}$ given in (10) satisfies (1) and the initial condition $\Pr\{\tau=1,\nu=0\} = 0$, $\Pr\{\tau=1,\nu=1\} = 1$.

The expected value $\bar{N}(T)$ given in (12) is obtained from

$$\bar{N}(T) = \sum_{N=0}^{MQ} N \Pr\{\tau=T-1|\nu=N-1\}\,\frac{M(Q-T+1)}{MQ-N+1}$$

$$= (MQ+1)\left[1 - \frac{Q!\,\Gamma(Q-T+1+1/M)}{(Q-T)!\,\Gamma(Q+1+1/M)}\right], \quad (14)$$

$\Gamma(x)$ is the Euler Gamma-function, [9].

For $Q\gg 1$, the term, (see, (12)),

$$\prod_{k=Q-T+1}^{Q}\left(1+\frac{1}{Mk}\right)^{-1} \ge \exp\left(-\frac{1}{M}\sum_{k=Q-T+1}^{Q} k^{-1}\right)$$

$$= \exp\left(-\frac{1}{M}\left[\psi(Q+1)-\psi(Q-T+1)\right]\right), \quad (15)$$

where $\psi(x) = d\ln\Gamma(x)/dx$, [9]. Finally, the approximations (13) are obtained from (15) using a series expansion for $\psi(x)$, [9]. □

Corollary 1. The conditional expected value for the number of distinct patterns given $\nu = N$,

$$E\{\tau|\nu=N\} = \bar{T}(N) = Q-Q\binom{MQ}{N}^{-1}\binom{MQ-M}{N}. \quad (16)$$

Proof Let $\{\nu_i,\ i=1,\dots,Q\}$ be a set of random variables defined as the number of times the patterns from the pool of Q patterns will appear in N draws, $(\nu_1+\nu_2+\dots+\nu_Q = N,\ \nu_i\ge 0)$, then, we have,

$$\Pr\{\nu_i\ge 1\} = 1 - \binom{MQ}{N}^{-1}\binom{MQ-M}{N}. \quad (17)$$

Further, let us define a set of binary random variables, $\{\zeta_i:\ \zeta_i=1 \text{ iff } \nu_i\ge 1,\ i=1,\dots,Q\}$, then, the expected value, $E\{\zeta_i\} = \Pr\{\nu_i\ge 1\}$. Finally, (16) is obtained by

$$\bar{T}(N) = E\{\sum_{i=1}^{Q}\zeta_i\} = \sum_{i=1}^{Q}E\{\zeta_i\}$$

$$= Q\Pr\{\nu_i\ge 1\} = Q - Q\binom{MQ}{N}^{-1}\binom{MQ-M}{N}. \quad (18)$$

Note that, $\bar{T}(N)$ can also be found by taking the expectation of T,

$$\bar{T}(N) = \sum_{T=0}^{\min\{N,Q\}} T\Pr\{\tau=T|\nu=N\}, \quad (19)$$

where $\Pr\{\tau=T|\nu=N\}$ is given by (10). □

Fig. 6 shows a comparison of $\bar{N}(T)$ and the simulation results $\bar{N}_{ex}(T)$ for s = 24, r = 14, 18 and 22, respectively, where the characteristic polynomial of the PRPGs is $x^{24}\oplus x^7\oplus x^2\oplus x\oplus 1$. The average values $\bar{N}_{ex}(T)$ have been obtained from 20 randomly chosen initial states of the PRPG and three different realizations of the PRPG: the external XOR-gate LFSR, the internal XOR-gate LFSR, and the cellular automata register (CAR). The comparison of $\bar{N}_{ex}(T)$ and $\bar{N}(T)$ are shown in terms of the

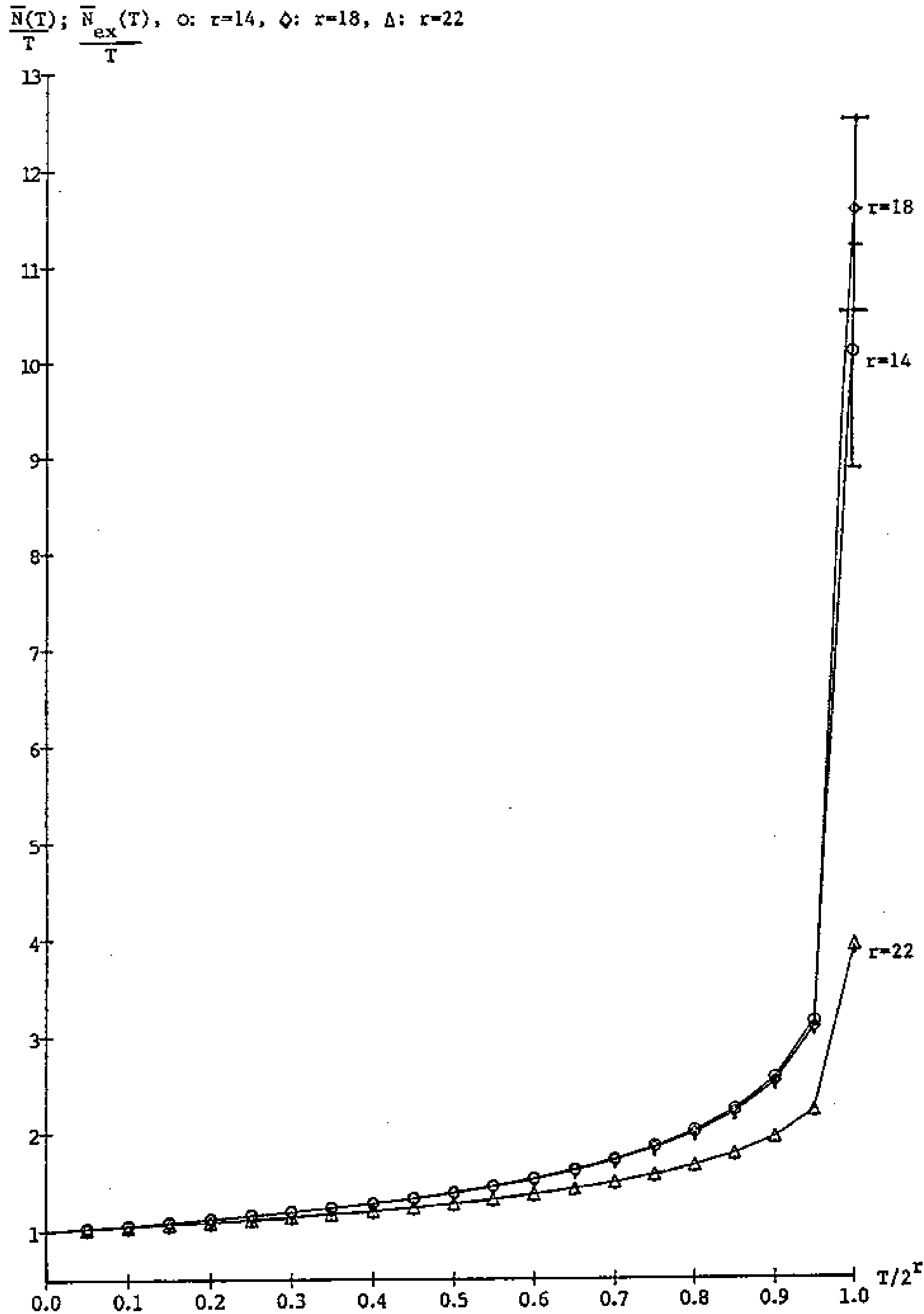

Fig. 6. $\bar{N}(T)/T$ (lines) and $\bar{N}_{ex}(T)/T$ (data points)—Comparison

efficiency for the test generation $\bar{N}_{ex}(T)/T$ and $\bar{N}(T)/T$ versus the normalized value $T/2^r$, furthermore, the function $\bar{N}(T)$ are shown in the solid and $\bar{N}_{ex}(T)$ are shown as data points, with different symbols for different r values. Note that the standard deviations of $\bar{N}_{ex}(T)/T$ are noticable in Fig. 6 only for the case of $T/2^r = 1$, and r = 14 and 18.

The experimental results, $\bar{N}_{ex}(T)$ indicate that, the proposed $\bar{N}(T)$ provides a good theoretical estimate for an average number of clock pulses over randomly chosen the initial states of the PRPG. We also observe that the exhaustive test generation of all 2^r r-bit patterns (i.e., $T/2^r = 1$) can be quite inefficient where as the cases of "near" exhaustive test generation

(e.g., $T/2^r = 0.95$) are reasonable.

Conclusions

We presented a modified internal connections of a BIST boundary scan design which ensures an efficient test generation for the case when $r \geq s$. The modification from the original circuitry is that, the connections for PIs are from the last n consecutive cells. It is important to note that, the proposed modification is independent on the choice of PRPG implementation.

For the case when $r<s$, the expected number $\bar{N}(T)$ of PRPG clock pulses required for generating $T \leq 2^r$ distinct r-bit patterns and the expected number $\bar{T}(N)$ of distinct patterns given a number N of clock pulses were presented. The proposed theoretical average $\bar{N}(T)$ was shown to be close to the experimental average values $\bar{N}_{ex}(T)$. Hence, the value $\bar{N}(T)$ or $\bar{T}(N)$ can be used as a benchmark for evaluating the efficiency of a BIST boundary scan test generation.

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