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GENERAL DESCRIPTION OF THE BARREL SHIFTER EVENT BUILDING METHODS

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Abstract

At High Energy Physics experiments, parallelism allows scalable, high-bandwidth event building systems. On-line event building of physical events is only feasible by using switch-based event builders. The Barrel Shifter is a well-known event building method providing a simple rotating interconnection pattern. A computational method based on matrix operations is introduced for a distributed traffic control. The general form of the transformation matrix allows to define several different traffic control schemes that may be divided into two classes. Buffering requirements and modification of the transformation matrix are also examined.

Keywords: event building, traffic control, interconnection network, matrix operation.

1. Introduction

High Energy Physics (HEP) is a special field of particle physics where charged particles are accelerated and collided. When particles interact in a detector and the interaction satisfies certain conditions, the detector electronics produces a lot of data, which is called an *event*. Events are composed of several event fragments. Each event fragment is produced by a detector segment. The aim of the event building process is to collect the separated, parallel event fragments of the same event in one destination device for off-line processing.

At High Energy Physics experiments, data flow is essentially unidirectional, i.e. from the detector subsystems to a farm of processors or storing devices. Since data volume to be transmitted can reach a few Gigabytes per second [1][2][4], data acquisition systems based on a single shared bus cannot be used any more due to the limited bandwidth. Parallelism is the only solution to eliminate the bandwidth limitation. The use of multiple interconnection results in a scalable, high-throughput event builder, which itself may constitute a small data acquisition system or may be a component of a large, multilayered system. Several implementations of an interconnection network are possible, such as multiple busses, multiport memories or a switching fabric. Both the multiple bus and the multiport memory architectures still have the problem of realization if the number of data sources and data destinations is great. For large event builders, only switched networks based on high-speed serial links seem to be feasible. The most efficient utilization of the switch occurs when several events are simultaneously built, and the event fragments of different events are distributed uniformly in time and space over the switch.

2. The Barrel Shifter Event Building Method

The Barrel Shifter [3,6] is a well-known event building method in data acquisition systems of High Energy Physics experiments. The Barrel Shifter operates in a switched communication network and provides a simple rotating interconnection pattern to connect source and destination nodes. After one round rotation of the interconnection pattern, the system works in a steady state. Operation of the Barrel Shifter requires the following assumptions:

1. the numbers of the source nodes and destination nodes are equal;
2. the size of the event fragments is constant;
3. the interarrival time of the event fragments is equal to the transmission time of one event fragment.

If the above conditions are fulfilled, the Barrel Shifter will convert the parallel event fragments to assembled event streams with no loss of user bandwidth. *Fig. 1* illustrates the operation of the classical[1] Barrel Shifter in a 4×4 system. In the figure, sources are identified by capitals, whereas events by integers. Identifiers in light gray show event fragments being transmitted.

The Barrel Shifter method is an easy-to-implement traffic control scheme in HEP data acquisition systems. There is no need of central control: the traffic control can be distributed over the source nodes. Regularity of the interconnection pattern allows to describe the state transitions of the traffic control by using matrices.

3. Description of the Traffic Control Scheme of the Classical Barrel Shifter

In this section, we suppose a classical Barrel Shifter with n source nodes and n destination nodes. The lower index of the vectors and matrices indicates their dimension.

[1] first published in [3]

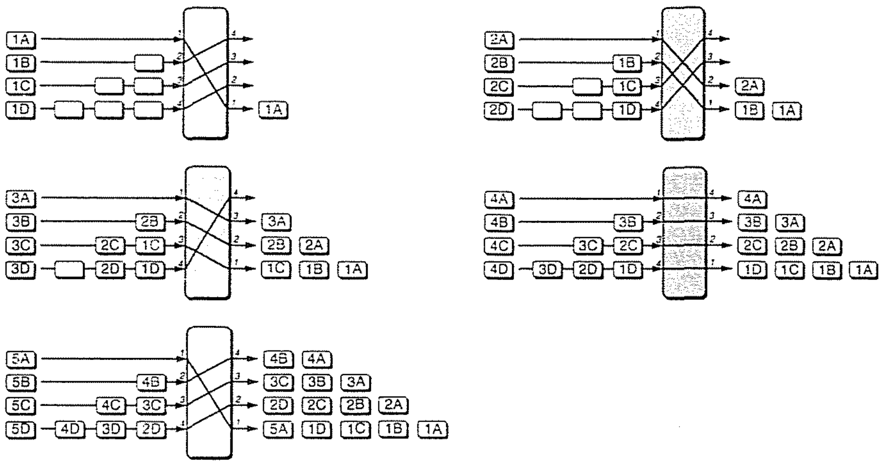

Fig. 1. The classical Barrel Shifter in a 4×4 system

Let us denote the state of all the sources after the kth rotation with

$$\mathbf{s_n}[k] = \begin{bmatrix} s_1 \\ s_2 \\ \vdots \\ s_n \end{bmatrix}, \tag{3.1}$$

where s_i is the serial number of the event fragment to be transmitted by the ith source. $\mathbf{s_n}$ is called *source vector*.

Lets now define the kth *state vector* of the traffic control with

$$\mathbf{x}[k] = \begin{bmatrix} \mathbf{s_n}[k] \\ \cdots \\ 1 \end{bmatrix}. \tag{3.2}$$

In this case, the $(k+1)$th state vector can be obtained by the following multiplication:

$$\mathbf{x}[k+1] = \mathbf{T} \cdot \mathbf{x}[k], \tag{3.3}$$

where the transformation matrix $\mathbf{T}$ is a hypermatrix:

$$\mathbf{T} = \begin{bmatrix} \mathbf{R_n^{(1)}} & \vdots & n\mathbf{e_n^{(1)}} \\ \cdots\cdots & . & \cdots\cdots \\ 0 & \vdots & 1 \end{bmatrix}. \tag{3.4}$$

Let us now examine the blocks of the transformation matrix. The upper-left block $\mathbf{R_n^{(1)}}$ is a once-rotating matrix that rotates the elements of the source vector $\mathbf{s_n}[k]$ downward by one element:

$$\mathbf{R_n^{(1)}} = \begin{bmatrix} 0 & \vdots & 1 \\ \cdots\cdots & . & \cdots\cdots \\ \mathbf{E_{n-1}} & \vdots & 0 \end{bmatrix}. \tag{3.5}$$

$\mathbf{R_n^{(1)}}$ is responsible for the rotating interconnection pattern. After one rotation of the source vector, another fragment of a given event is sent by the logically neighbouring source.

The upper-right block is a vector of which first element is the number of sources and its all other elements are zero. This block increments the serial number of the new event in each rotation phase. The $\mathbf{e_n^{(1)}}$ vector is a unit vector in which the first element (indicated by the upper index) is 1, whereas other elements are zero. In general, the ith unit vector is defined as:

$$\mathbf{e_n^{(i)}} = \begin{bmatrix} 0 \\ \vdots \\ 0 \\ 1 \\ 0 \\ \vdots \\ 0 \end{bmatrix} (i). \tag{3.6}$$

The lower-right block determines which source sends first the event fragment of the new event. Since this block is one-dimensional, the first event fragment of each new event is sent by the logically first source.

The lower-left block has no function and therefore it is always a block of zeros.

Now we can determine any state of the traffic control by the formula:

$$\mathrm{x}[k] = \underset{(k)}{\mathrm{T}} \cdot \underset{(k-1)}{\mathrm{T}} \cdot \ldots \underset{(2)}{\mathrm{T}} \underset{(1)}{\mathrm{T}} \mathrm{x}[1] = \mathrm{T}^k \cdot \mathrm{x}[1], \tag{3.7}$$

where

$$\mathrm{x}[1] = \begin{bmatrix} \mathbf{s_n}[1] \\ \cdots\cdots \\ 1 \end{bmatrix} \tag{3.8}$$

and

$$\mathbf{s_n}[1] = \begin{bmatrix} 1 \\ 0 \\ -1 \\ \vdots \\ 3-n \\ 2-n \end{bmatrix}. \tag{3.9}$$

During the initial transient, certain elements of the source vector are negative values or zero. Since no event is identified by negative value or zero, we formally introduce the function

$$\Psi(s_i) = \begin{cases} s_i & \text{if} \quad s_i \geq 1 \\ 0 & \text{if} \quad s_i < 1 \end{cases} \tag{3.10}$$

If $\Psi(s_i) = 0$, source i sends no event fragment, otherwise it sends the event fragment of event s_i. Thus the *modified source vector* is

$$\mathbf{s}_\mathbf{n}^*[k] = \Psi(\mathbf{s}_\mathbf{n}[k]) \tag{3.11}$$

which is already valid during the initial transient, too.

4. Generalization of the Classical Barrel Shifter

Examining the source buffer requirements of the classical Barrel Shifter, we can see that the buffer size of a source depends on the logical place of the source. The first source needs a buffer for only one event fragment, whereas the last source needs a buffer for n event fragments if there are n sources in the system. That property is due to the fact that the first event fragment is always sent by the same source, i.e. by the first source at the classical Barrel Shifter. If we keep changing the source which first sends the event fragment of a new event, the buffering requirements may be distributed more evenly amongst the sources. This idea has led to a general form of the transformation matrix. According to the general transformation matrix, a lot of other traffic control schemes can be defined that work under the same condition as the classical Barrel Shifter. The difference between the several Barrel Shifter methods appears in the interconnection pattern and the buffering requirements. Some methods provide evenly distributed buffer requirements that reduces memory expenses. Those methods mean cost-effective alternatives to the classical Barrel Shifter.

The basic idea is to periodically change the source, which sends the first event fragment of a new event. This results in a rotating selection pattern of the sources from the point of view of the events.

The general transformation matrix is defined as

$$\mathbf{T} = \begin{bmatrix} \mathbf{R}_\mathbf{n}^{(\mathbf{p})} & n\mathbf{E}_\mathbf{n} \\ \mathbf{0}_\mathbf{n} & \mathbf{R}_\mathbf{n}^{(\mathbf{q})} \end{bmatrix}, \tag{4.1}$$

where $\mathbf{R}_\mathbf{n}^{(\mathbf{p})}$ and $\mathbf{R}_\mathbf{n}^{(\mathbf{q})}$ are p-times and q-times downward rotating matrices, respectively. $\mathbf{R}_\mathbf{n}^{(\mathbf{p})}$ determines the position of the fragments of old events in the source vector, whereas $\mathbf{R}_\mathbf{n}^{(\mathbf{q})}$ determines which source should send the first event fragment of a new event. In general, the structure of a k-times downward rotating matrix is given by

$$\mathbf{R}_{\mathbf{n}}^{(\mathbf{k})} = \begin{bmatrix} \mathbf{0} & \mathbf{E}_{\mathbf{k}} \\ \mathbf{E}_{\mathbf{n-k}} & \mathbf{0} \end{bmatrix}, \tag{4.2}$$

where $\mathbf{E}_{\mathbf{k}}$ and $\mathbf{E}_{\mathbf{n-k}}$ are identity matrices and $\mathbf{0}$ is a block of zeros. The k-times upward rotating matrix is the transposed form of the downward rotating matrix:

$$\mathbf{R}_{\mathbf{n}}^{(-\mathbf{k})} = (\mathbf{R}_{\mathbf{n}}^{(\mathbf{k})})^{\mathbf{T}}. \tag{4.3}$$

The block $n\mathbf{E}_{\mathbf{n}}$ in the transformation matrix increments the serial number of the new events.

According to the general transformation matrix $\mathbf{T}$, the source vector $\mathbf{s}_{\mathbf{n}}[k]$ is now extended with an n-dimensional unit vector, thus the general state vector is:

$$\mathbf{x}[k] = \begin{bmatrix} \mathbf{s}_{\mathbf{n}}[k] \\ \mathbf{e}_{\mathbf{n}}^{(\mathbf{i})} \end{bmatrix}. \tag{4.4}$$

The $(k+1)$th state vector can be obtained from the kth or the first state vector according to (3.3) and (3.7), respectively. So we have

$$\mathbf{x}[k+1] = \mathbf{T} \cdot \mathbf{x}[k] = \mathbf{T}^{k+1} \cdot \mathbf{x}[1]. \tag{4.5}$$

The modified source vector is defined in the same way as in (3.11).

The general form of $\mathbf{T}$ assumes the following two conditions for the source vectors:

1. No event may get to the same position in the source vector within one rotation cycle.

2. A new event and any of the old events may not get to the same position in the source vector at any rotation phase.

From the first condition, p and n should be relative prime numbers. It means that the lowest common multiple of p and n should be their multiplication, that is

$$[p,n] = p \cdot n, \qquad p \neq 0. \tag{4.6}$$

From the second condition, $(p-q)$ and n should be relative prime numbers, that is

$$[(p-q),n] = (p-q) \cdot n, \qquad p \neq q. \tag{4.7}$$

When generating different $\{p;q\}$ pairs for a given n, the following identity rules should be respected:

$$\{p;q\} \Leftrightarrow \{(an+p);(bn+q)\}, \tag{4.8}$$

$$\{-p;-q\} \Leftrightarrow \{p;q\}^*, \tag{4.9}$$

$$\{p;0\} \Leftrightarrow \{(p+c);0\}, \tag{4.10}$$

where a, b and c are any integer. The identity (4.8) can easily be proved by the modulo calculus. In rule (4.9), the sequence of the switching samples of the interconnection pattern is inverted if both p and q are multiplied by -1, thus the traffic control does not essentially change. (The inversion is denoted by a *.) Rule (4.10) means that sources can be rearranged if the first fragment of each event is always sent by the same source.

The first rule results in the following reasonable intervals for p and q:

$$0 < p < n, \tag{4.11}$$

$$0 \leq q < (n-1), \tag{4.12}$$

$$p \neq q. \tag{4.13}$$

The $\{p;q\}$ pairs in which p and q satisfy relations (4.11-13) are called *base pairs*. Depending on whether p is greater or less than q, we define two classes of the Barrel Shifter methods. If $p > q$, we talk about α-type Barrel Shifter, otherwise the method is called β-type Barrel Shifter. *Table 1* summarizes the possible base pairs of p and q when the system contains 8 sources.

Table 1. $\{p;\ q\}$ pairs of a general 8×8 Barrel Shifter

	α-type Barrel Shifters							β-type Barrel Shifters					
p	1	3	5	5	7	7	7	1	1	1	3	3	5
q	0	2	2	4	2	4	6	2	4	6	4	6	6

From *Table 1*, we can see that the classical Barrel Shifter is a special case of the α-type Barrel Shifters, when $p = 1$ and $q = 0$, i.e. when the first event fragments are always sent by the same source. According to the identity rule (4.10), the $\{p;0\}$ pairs generate the classical Barrel Shifter at any value of p. If $p \neq 1$, sources can be rearranged and the interconnection pattern will look like in *Fig. 1*. The Inverse Barrel Shifter, which was first introduced in [5], is a special case of the β-type Barrel Shifters, when $p = 1$ and $q = 2$.

The initial source vector is different for the two types of Barrel Shifters. In the case of the α-type Barrel Shifters, the initial source vector is:

$$\mathbf{s_n}[1] = \begin{bmatrix} 1 \\ 0 \\ -1 \\ \vdots \\ 3-n \\ 2-n \end{bmatrix} \tag{4.14}$$

and for the β-type Barrel Shifters, the initial source vector is:

$$\mathbf{s_n}[1] = \begin{bmatrix} 1 \\ 2-n \\ 3-n \\ \vdots \\ -1 \\ 0 \end{bmatrix} . \tag{4.15}$$

The initial state vector of both types of Barrel Shifters is

$$\mathbf{x}[1] = \begin{bmatrix} \mathbf{s_n}[1] \\ \mathbf{e_n^{(q+1)}} \end{bmatrix} . \tag{4.16}$$

5. Buffer Requirements of the Barrel Shifter Methods

In case of the classical Barrel Shifter, each source sends the event fragments in their arrival order. Thus a simple FIFO memory can be used in the sources to buffer the event fragments. However, the buffer size of a source depends strongly on the logical place of the source. If the logical sequence of the sources may change during the operation, all buffers should be designed to be capable of buffering n event fragments.

At all the other Barrel Shifter methods, the buffering requirements are distributed more or less evenly amongst the sources. In optimal case, every source has to maintain a buffer for $(n/2+1)$ event fragments. (This occurs, for example, at the $\{1;2\}$ base pair.) How this distribution depends on the values of p and q, requires further, more detailed analysis. Although the evenly distributed buffering requirements reduce the maximum buffer size in the system, event fragments are sent out of their arrival order, and therefore only random access memory can be used as source buffer.

6. Modification of the General Barrel Shifter Methods

If condition (4.7) is not satisfied, the general transformation matrix should be changed. In order to avoid contention of old and new event fragments at the output of the sources, one possible solution is to modify blocks $\mathbf{R_n^{(p)}}$ and $n\mathbf{E_n}$. In the special case of $\{p;q\} = \{2;1\}$ and $n = 2k\,(k \in \mathrm{N})$, the transformation matrix may be modified as follows:

$$\mathbf{T} = \begin{bmatrix} \tilde{\mathbf{R}}_\mathbf{n}^{(2)} & n\tilde{\mathbf{E}}_\mathbf{n} \\ 0 & \mathbf{R_n^{(1)}} \end{bmatrix} , \tag{6.1}$$

where

$$\tilde{\mathbf{R}}_{\mathbf{n}}^{(2)} = \begin{bmatrix} 0 & \mathbf{E}_2^{-1} \\ \mathbf{E}_{\mathbf{n}-2} & 0 \end{bmatrix} \tag{6.2}$$

and

$$\tilde{\mathbf{E}}_{\mathbf{n}} = \begin{bmatrix} \mathbf{E}_{\mathbf{n}-1} & \mathbf{e}_{\mathbf{n}-1}^{(1)} \\ 0 & 0 \end{bmatrix}. \tag{6.3}$$

The initial source vector and state vector is given by (4.14) and (4.16), respectively, because this scheme is derived from an α-type Barrel Shifter. However, this traffic control scheme cannot be regarded as a Barrel Shifter since its transformation matrix does not follow the general form as given in (4.1).

7. Summary

In this paper, a computational model for the traffic control of the Barrel Shifter event building methods was introduced. As a first step, we described the state transitions of the classical Barrel Shifter by using a state vector and a transformation matrix. In the second step, we extended the transformation matrix and the state vector that can be used to produce several different traffic control schemes if certain conditions are satisfied. We also examined the buffering requirements of the different schemes. Finally we presented a possible solution to a special case when conditions of the general Barrel Shifter are not satisfied.

As a conclusion we can say that the general transformation matrix is available to produce a lot of different traffic control schemes in the same switched interconnection network, provided that event fragments have equal size and the transmission time of an event fragment is equal to one time slot. Some traffic control schemes result in evenly distributed buffering requirements, unlike the classical Barrel Shifter at which the buffer size depends on the source's logical place.

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