Beam-forming Schemes for the Mexican IPS Array

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1 Introduction :

The Mexican IPS array is a planar array comprising of an Ease-West row of 64 nos. of full-wave dipoles and a North-South column of 64 rows. Dipoles are spaced $1\,\lambda$ apart and the E-W rows are spaced $0.5\,\lambda$ apart. The Project document of the Instituto de Geofisica,UNAM,Mexico mentions about Butler Matrices for beam-forming and yet is silent about the data capture/recording/analysis after beam- formation.

The primary aim of this report to show two schemes - viz.one being the digital beam-scanning method and the other is conventional Butler–matrix plus data processing back-ends. Cost comparison is done towards the concluding section.

2 Beam-forming Techniques :

Beam-formers are complex networks used to precisely control the phase and amplitude of RF power passing through them. In receiving systems, similar to the Mexican IPS Array, they are constructed between the antenna arrays and the receiver to shape the relative spatial sensitivity of the system to RF signals originating in its field of view. The result is to effectively 'focus' the receiver system on a specific region of space.

2.1 Butler–matrix :

In a phased-array construction,similar to the Mexican Array, the Butler–matrix can generate mulitiple simultaneous beams covering a large sector of space. For the same beam-pointing direction, each beam has the gain of a single-beam array of the same size and illumination. A separate beam terminal is provided for each beam of the Butler–matrix output.
This network uses quadrature couplers (viz.,directional couplers that have a 90° phase-shift property) and fixed phase shifters. A signal injected at any one of the beam input terminals excites all the radiating elements equally in amplitude with phase differentials of odd mulitples of π/N , where N is the total number of radiating elements or beam terminals. A Butler–matrix requires 2^{n-1} couplers at each of its n levels, where $N = 2^n$. Thus the total no. of couplers will be,

$n{\cdot}2^{n-1}$ or
$N/2 \cdot \log_2(N)$.
For a 32- element matrix of Mexican array, $n = 5$ and 80 nos. of quadrature couplers will be required.

2.2 Digital Beam-forming :

Arrays employing digital beam-forming has a distinct advantage of multi-functionality with programmable interfaces while compared to analogue methods. All the amplitude and phase-shifting functions, as well as beam-forming are done digitally. True time-delay for steering the beam can also be implemented. Unlike the previous scheme, this technique offers a single beam which can be steered to any region on the celestial sphere (for Mexican Array). The advent of high-speed ADCs and Digital Down-conversion Converters (DDCs) has reduced the complexity of designing one such Digital Beam-former.

3 Scheme 1: Digital Beam-forming

A functional block diagram of this completely digital beam-former, (more appropriate term would be - beam scanner) is shown in Fig.1.

Every aspects and nuances of the Mexican Array has been taken into consideration for this design.

- The amplified outputs from all the E-W rows 1 to 64 are passed through a bank of band-pass filters, so as to get the RF signals in the required band centered around 139.65 MHz with a bandwidth of 1.5 MHz.[1]
- Filtered RF signals are given as inputs to 32 nos. of DDCs, whose digitised outputs are interfaced with a FPGA based Adaptive Digital Beam-former.
- The ADBf processes the 64 digital inputs from the DDC bank,along with the computed 'weights' (for a plane wave front incident on the array, $\Delta\phi_i\,; i = 1..64$) and produces a scanning beam on the array-aperture.

  The weights computation in real-time/off-line, as the user demands it, can be carried out by the data acquisition PC.See Appendix-A for $\Delta\phi_i$ computations.

[1]

[1] `Vide.Fig.1 of the Tech.Note: G.Sankar,''Matching Network for the Mexican IPS Array - New Development'', MxA/TR/2k2--02,Aug.2002`

- The 64-digital beam-outputs are porcessed next by the DAS-Data Acquisition System by the user selection of any two beam-outputs (like Beam 1 and Beam 33), correlate and record the data in the PC.

- The DAS PC - any P4 processor with high dynamic memory should even handle multiple beam (more than 2) correlation and analysis; for post-processing as well as the phase-weights computations MATLAB 6.0 (or above) is recommended.

The device identified for this DDC operation is a Dual Channel (analog inputs) Reconfigurable Digital Receiver – Model 304 FlexReceiver PMC of Red River Inc.,TX.. The architecture features a dual channel digitizer tightly coupled to a Xilinx FPGA and a PCI Bus Master supports 64-bit (66 MHz) data transfer. The built-in FPGA can support the ADBf operations as envisaged above as well as the PCI bus eliminates the need for an independent DAS. **Hence this functions as the combined blocks of DDC, ADBf and DAS**.

If we were to implement this, an additional IF block must be introduced in Fig.1 - between the BPF and DDC blocks. Since this device/ card handles a maximum data sampling rate of 105 Msps, a down-conversion from 140 MHz to less than 50 MHz is mandatory.

For the 64-inputs from Mex.Array, 32 nos. of this Card are required. The PC plus MATLAB can handle the PCI output and process the data in a seamless fashion.Drivers for Linux, being provided with the Cards, are another cost-effective solution.

4 Scheme 2: Analog Beam-forming

Here, a balance is struck between the conventional anlog method with the modern DDC blocks. Fig.2 shows the overall block diagram. As conceived earlier, two Butler matrices of 32 -element each are employed. The complexity of building a 32-element matrix is minimised by selecting off-the-shelf products, as illustrated in the following section.

- North and South array Butler matrices are the first blocks. The dipoles rows 1 to 32 form the inputs to the N-array matrix, while rows 33 to 64 are the inputs to S-array matrix.

- The 32-beam simulataneous beams are coupled to a RF switch, such that any one beam from N-array and another from S-array can be correlated. The 32-to-1 RF switch is the 2nd block. The switches are interfaced with a Fibre-optic Receiver to facilitate beam-selection. Based on the Mex.Array site's topogrphy, the Fibre-optic Receiver was chosen; an RF interface will require amplifiers/IF mixers.

- The selected beam-output from the switch is band-pass filtered next; a pair of filters are required.

- Through a low-loss RF cable the beam outputa are brought to the Rx/Control room.

- An identical block of DDCs and DAS, follows (minus ADBf) next; If one were to use the same FlexReceiver PMC 304 card, a **single card is sufficient**.

- PC + MATLAB is the final block. Beam selection/control info. is passed on to a Optical Transmitter. Data acquisition is simpler from the PCI bus outputs of the FlexRx.PMC 304 card.

- A plastic fibre to link the OTx and ORx circuits. The length of fibre can be $\sim$ 200 m. and 1310 nm. wavelength will be used for communication.

5 Butler Matrix Construction :

The 32-element Butler matrix will require 80 nos. of quadrature couplers and 64 nos. of fixed phase-shifters, as shown in Fig.3. Passive Quad.couplers are available which can be soldered to a PCB. MACOM's JHS-121 is one-such coupler. Similar PCB-mountable phase shifters (like trim pots) are also available - viz., Merrimac's PSS-2B Series. The Ref.links as indicated by '0' phase-shift in Fig.3 can be custom-made by semi-rigid cables of equal electrical length and 64-nos. of coaxial connectors (SMAs/N-type) would complete one full-matrix for 32 elements.

The required beam formation can be easily realised as per the above construction plan, since reliable products are identified and minimal help is required from skilled-technical hands while fabricating the unit.

6 Comparison of the Schemes :

On technical aspects both schemes are comparable; the first one, has an edge over the other because of the limitless flexibility in usage of the array despite the availability of 2 or more beams for correlation. The hardware can be configured quickly for user-requirement and can be restored back to default conditions through the FPGA programming. With the exponential improvement in computing power, the future of the array usage may extend beyond radio astronomy.

The second scheme has the advantage of simultaneous availability of multiple beams. This makes it feasible to conduct simultaneous observations of two different regions of the sky,implying that we have two independent DDC + DAS blocks. Future upgradation of the facility is simply adding up the DDC + DAS blocks so that the multiple beams of the Butler matrix are utilised to a fuller extent.

Multiple beams **can** be realised in the first scheme too **without adding any additional hardware** components; The FPGA coding can ensure multiple beams simultaneously.

6.1 Hardware Costs :

Scheme 1

Let us refer to Fig.1. Item-wise costs (in US $) are indicated below:

No.	Functional Blocks	No.of units	Cost/ unit	Net Cost
1	Band-pass filters	64	10 $	640 $
2	DDC + ADBf + DAS	32	2000 $	64000 $
3	PC + MATLAB	1	2000 $	2000 $
4	Connectors + Misc.	—	2000 $	2000 $
	Total cost			**68640 $**

Scheme 2

Refer Fig.2. The cost for a single Butler matrix must be estimated first.

`32-element Butler matrix` - Components

No.	Functional Blocks	No.of units	Cost/ unit	Net Cost
1	Quad.couplers	80	10 $	800 $
2	Fixed phase shifters	64	5 $	320 $
3	Connectors	128	7 $	896 $
4	Semi-rigid cables	64	1.5 $	96 $
5	PCB,Chassis,Misc.	—	200 $	200 $
	Total cost			2312 $

Coming back to the overall system,

No.	Functional Blocks	No.of units	Cost/ unit	Net Cost
1	Butler Matrix	2	2312 $	4624 $
2	RF switch blocks	2	130 $	260 $
3	BPFs	2	10 $	20 $
4	Low-loss RF cable	2	600 $	1200 $
5	Accessories of (4)	1	670 $	670 $
5	DDC+DAS+Software	1	4000 $	4000 $
6	Fibre,OTx,ORx	1	100 $	100 $
7	Misc.	—	1000 $	1000 $
	Total cost			**11874 $**

Scheme 2 is **cheaper by a factor of** $\sim$ **6** when compared to Scheme 1.

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Appendix – A
Adaptive Beam-forming – Computation of Phase Weights

If one considers the plane-wave front incident on the array at an angle θ, the only difference between the signals received at the different antennas is the phase shift induced by the path length differences.

The Beam-former concept is to adjust the individual delays so that the signal appears to be arriving at each antenna simultaneously.The required phase delay for each antenna n ($n = 0 \ldots N-1$) is given by,

$$\Delta\phi_n = 2\pi n \frac{d}{\lambda} \sin\theta$$

By adjusting the phase delays the array can "look" in a specified direction.As shown in the figure, the signal flow from each antenna, $x_n(t)$ can be expressed in a complex form:

$$x_n(t) = A\exp(j\omega t + \phi)\cdot\mathbf{s}$$

where,

$$\mathbf{s} = \begin{bmatrix} \exp(j\Delta\phi_0) \\ \vdots \\ \exp(j\Delta\phi_{N-1}) \end{bmatrix}$$

The array output,$y(t)$, with the weights incorporated (antennas can be considered as angle-of-arrival filters and the block diagram shown above is similar to adaptive filters...) will be

$$\begin{aligned} y(t) &= \mathbf{w}^H \; \mathbf{x}(t) \\ &= \sum_{n=0}^{N-1} w_n^* x_n(t) \\ &= A\exp(j\omega t + \phi) \sum_{n=0}^{N-1} w_n^* \exp(j\Delta\phi_n) \end{aligned}$$

For uniform amplitude weighting,in the summation term above all ws will be equated to unity and only the phase delays $\Delta\phi_n$ would matter. For precise side-lobe's suppression and interfering signal's ellimination in the array output non-unity weights must be considered.

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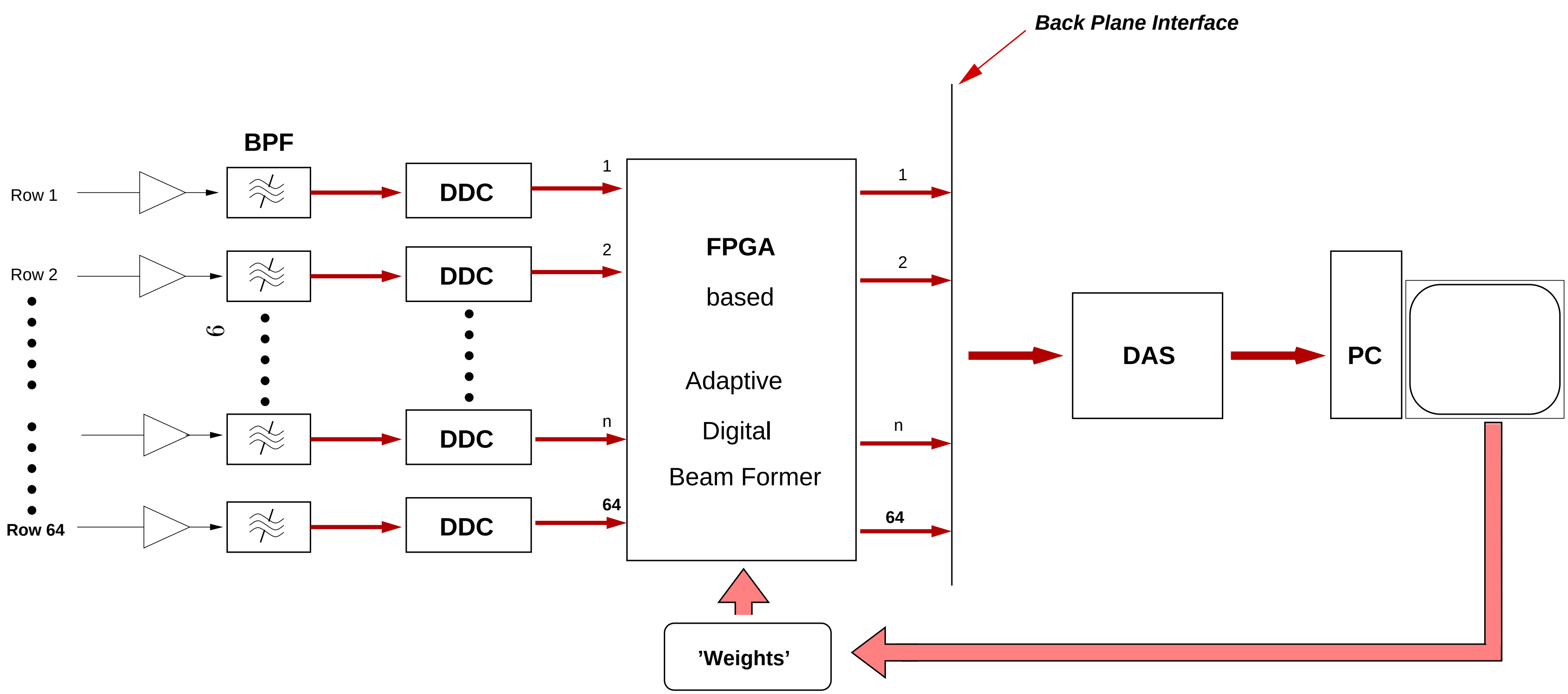


Fig.1 Digital Beam Forming Scheme for the Mexican IPS Array.

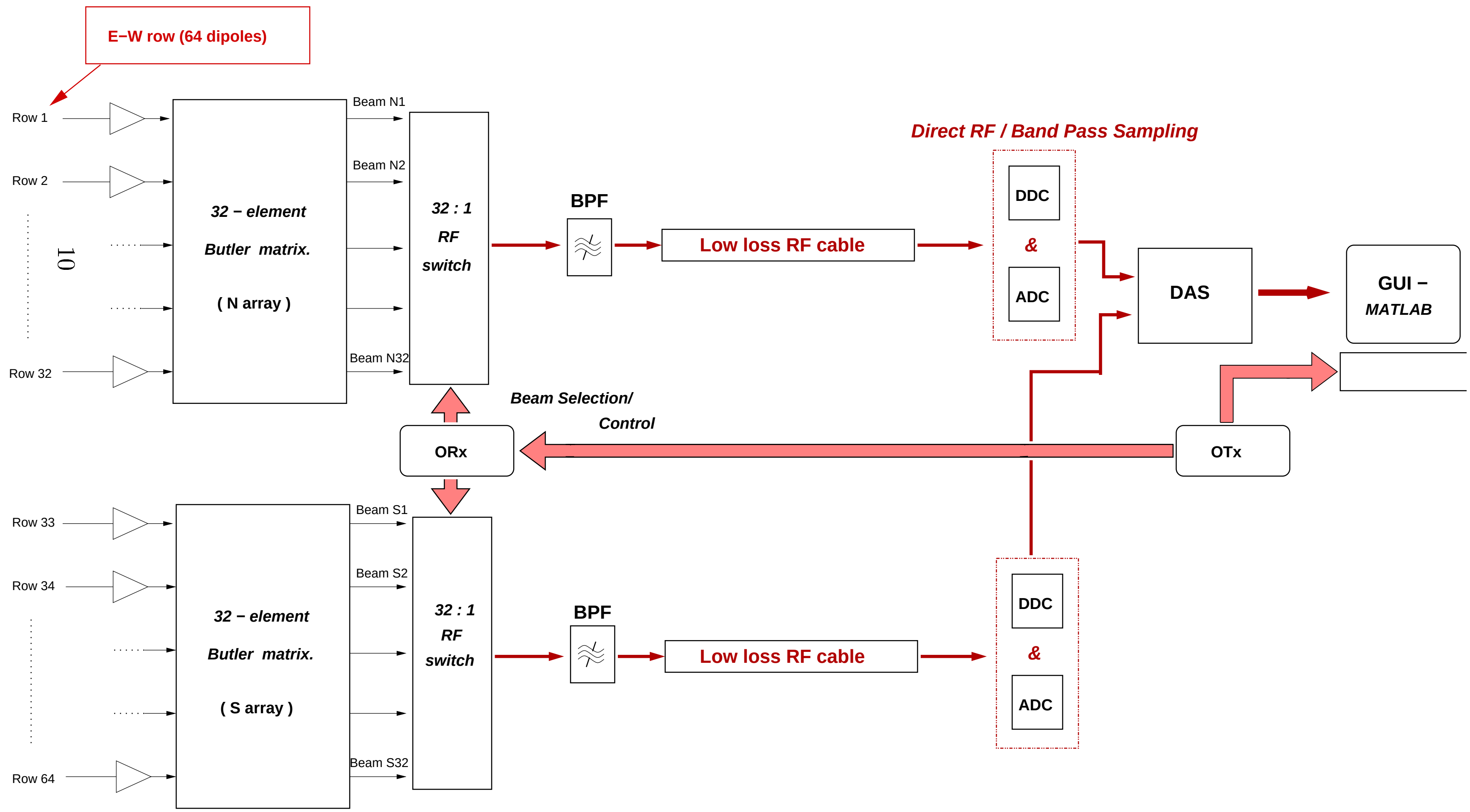


Fig.2 Analog Beam Forming Scheme for Mexican IPS Array.

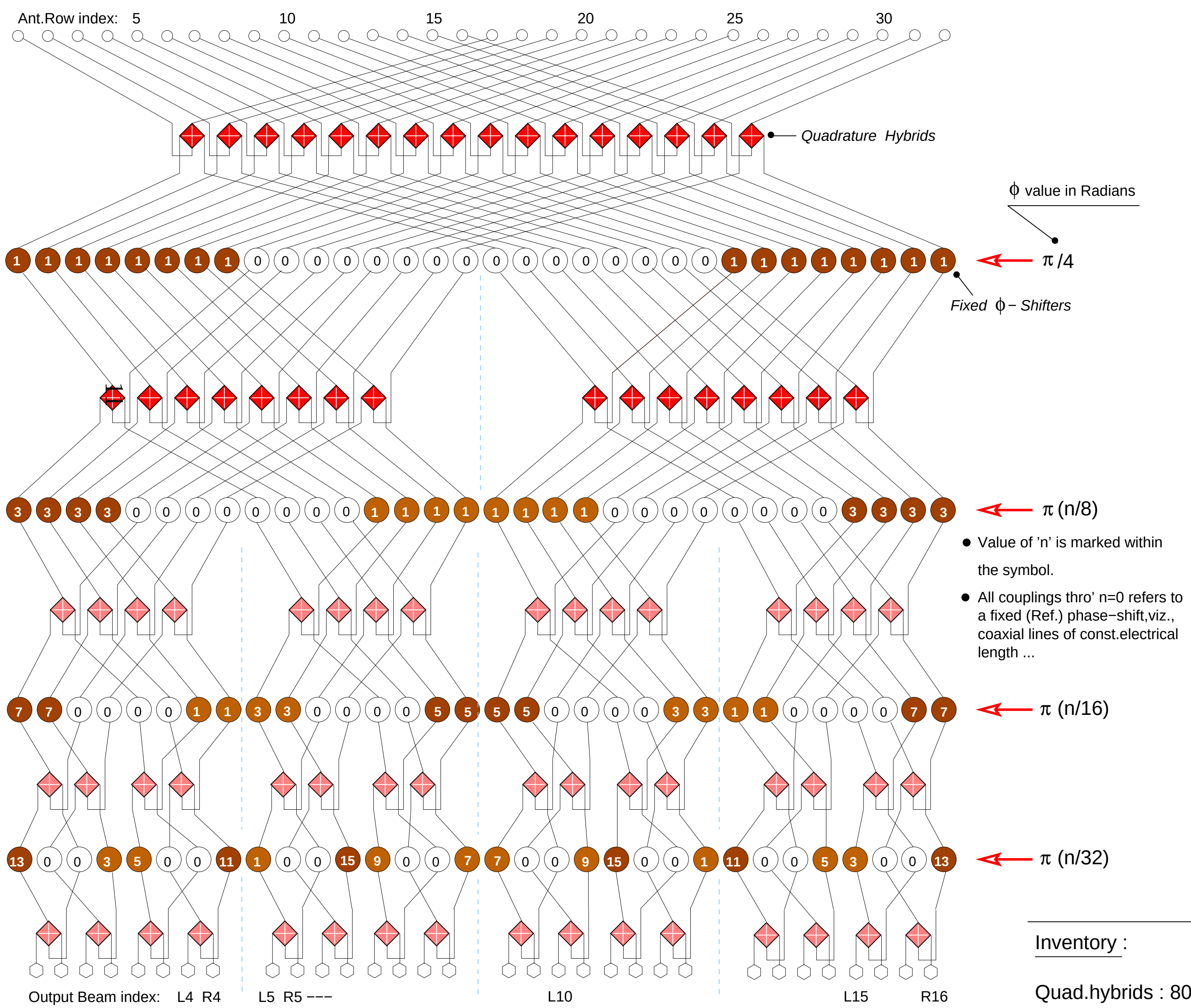
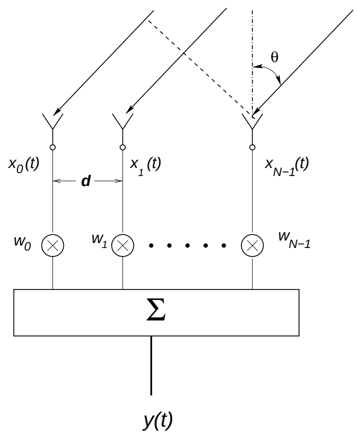


Fig.3 32−Element Butler Matrix.

Inventory :

Quad.hybrids : 80 Nos.

Phase shifters : 64 Nos.


θ
x0(t)
x1(t)
xN−1(t)
d
w0
w1
wN−1
Σ
y(t)