IV-7. APPLICATION OF THE BUTLER MATRIX TO HIGH-POWER MULTICHANNEL SWITCHING

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This paper describes a technique for multichannel switching of high microwave power levels, based on an application of waveguide hybrid circuits such as the well known Butler matrix.* It operates on the basic principle of dividing the high power input into a number of lower-power parts, then phase shifting these lower-power components to cause them to recombine into any one of the multiple output channels. The number of channels is any binary number, $N = 2^n$, and the total power which can be switched is equal to N times the power handling capability of the phasing components used.

To introduce the technique, simple four-channel switch configurations will be discussed, but the principle can readily be extended to 8, 16, 32 and higher binary numbers. The N = 4 configuration not only avoids excessive complexity in the discussion, but is a very practical configuration in its own right for array systems using four antennas to obtain hemispheric coverage.

Butler Matrix Switch. The well known Butler matrix is an arrangement of 3 db hybrids and fixed phase shifters which has heretofor been applied to multiple-beam array antennas. Power introduced into any one of its input ports is divided equally among the output ports, but with various phase delays, such that when the output ports are connected to a linear array of antenna elements, a tilted beam is radiated.

If instead of radiating the divided output power, we feed it into an identical Butler matrix, attached back-to-back as shown in Figure 1, the power will be recombined in the second matrix and

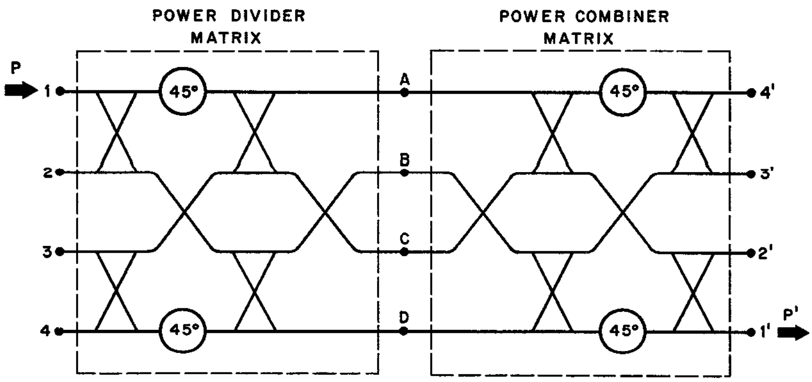
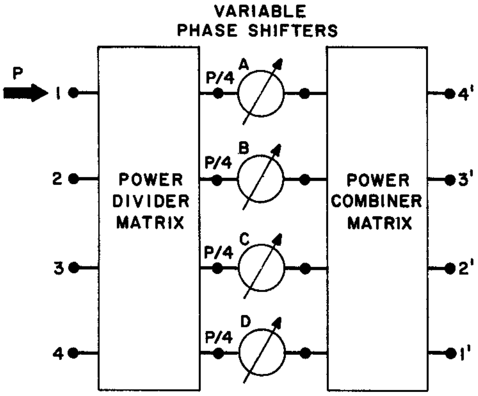


Figure 1. Back-to-Back Butler Matrices

*This type of matrix was also developed independently by Willey and Shelton. (See Reference 1, 2, and 3.)

the total power will appear at a single port diagonally opposite the input port. If we now introduce variable phase shifters between the back-to-back Butler matrices as shown in Figure 2, we can cause the power to combine into any of the other output ports by properly adjusting the phase shifters. For the four-channel example, power from input port 1 can be switched into the four output terminals, 1', 2', 3', or 4' by providing the phase values A, B, C, D given in the table of Figure 2.

Notice that all required phase shifts are in discrete multiples of 90 degrees, which allows the variable phase shifters to be digital rather than analog. Also note that each phase shifter is exposed to only one-fourth the total power being switched. By extending the principles illustrated in this four-channel example to higher order matrices, the technique can be used for switching correspondingly higher power levels.



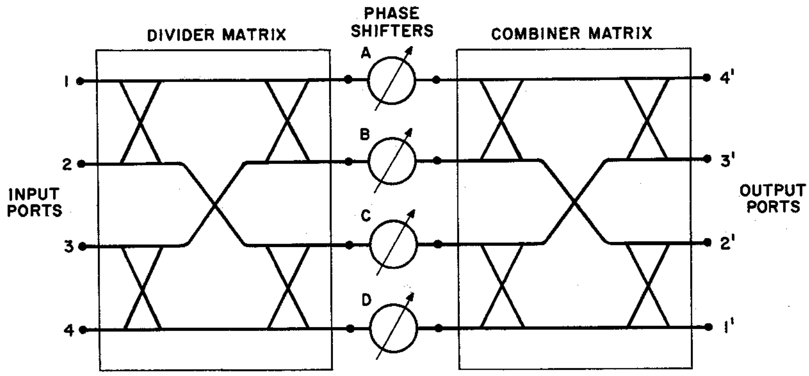
INPUT 1 TO OUTPUT	PHASE SHIFT			
	A	B	C	D
1'	0	0	0	0
2'	-180°	0	-180°	0
3'	-180°	-270°	0	-90°
4'	-270°	-180°	-90°	0

Figure 2. Four-Channel Butler Matrix Switch

Hybrid-Coupler Matrix Switch. The Butler matrix includes fixed phase-shifters and some crossed lines which are necessary only for its original antenna application, but are not necessary for the switching application. A simpler matrix switch can be devised as illustrated in Figure 3.

Not only does this simpler arrangement eliminate the fixed phase shifters, but it can be shown that the variable phase shifters need to have only two values of phase shift, namely 0 and 180 degrees, whereas up to three multiples of 90 degrees are required in the Butler matrix configuration. The values of phase shift required in this simplified arrangement, and the corresponding switch paths established, are shown in the accompanying table of Figure 3.

One possible mechanical configuration for an N = 4 channel waveguide hybrid matrix switch is illustrated in Figure 4 (a). The one-bit (0 to 180 degrees) digital phase shifters shown are compact latching ferrite phase shifters developed at Westinghouse, which are capable of peak powers of over 20 kw at C-band, with an insertion loss of between 0.3 and 0.5 db. Improvements in ferrite materials currently under way offer the promise of doubling the power capability with no increase in loss. Assuming short slot hybrids with an insertion loss of 0.10 db, the overall insertion loss of an ideal four-channel matrix switch would be the sum of the phase shifter loss plus four times the hybrid loss, or between 0.7 and 0.9 db. An ideal switch is defined as one having identical hybrids and phase shifters with zero relative amplitude or phase errors.



SWITCH PATHS ESTABLISHED	PHASE SHIFT			
	A	B	C	D
1↔1', 2↔2', 3↔3', 4↔4'	0	0	0	0
1↔2', 2↔1', 3↔4', 4↔3'	0	0	−180°	−180°
1↔3', 2↔4', 3↔1', 4↔2'	0	−180°	0	−180°
1↔4', 2↔3', 3↔2', 4↔1'	−180°	0	0	−180°

Figure 3. Four-Channel Hybrid Matrix Switch

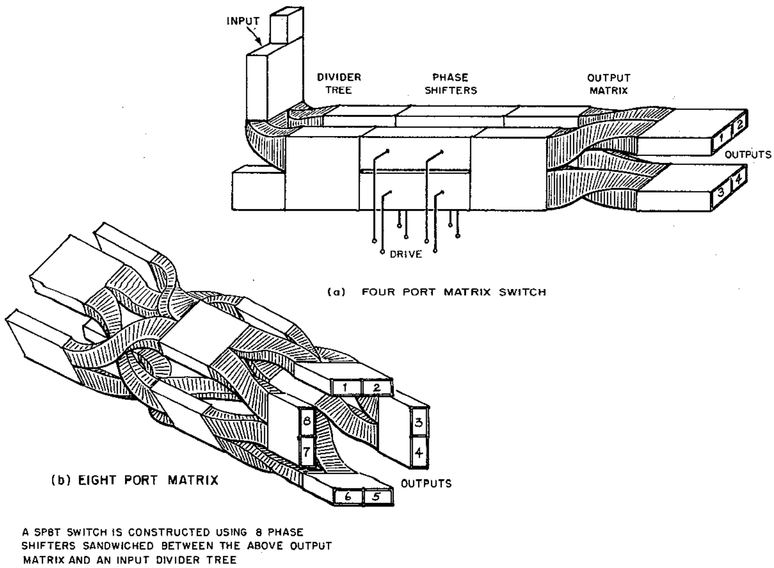


Figure 4. Four and Eight Port Matrix Switch

For higher-order ($N = 2^n$) hybrid matrix switches, the overall insertion loss (in db) increases in proportion to the exponent n, which represents the number of levels of hybrids required in the power divider and combiner matrices. The phase shifter insertion loss, however, which represents the lossiest single component, still appears only once no matter what the value of n. One possible mechanical configuration of an N = 8 channel waveguide hybrid switch matrix is shown in Figure 4 (b). This is a "cylindrical" configuration, as distinguished from the alternative and more familiar Butler matrix "flat" configuration

Effects of Phase and Amplitude Errors. For a practical matrix switch, it is desirable to examine the effects of imperfect components. An error analysis was performed using matrix algebra with the ideal switch matrix providing the base for the error analysis Errors in the form $(1 + \delta) e^{j\beta}$ were applied to the hybrids and phase shifters in the ideal matrix equation to compute resulting errors in the output channel signals.

Some special cases were analyzed to demonstrate the effects of various possible errors. Three of the cases considered were:

1 Equal amplitude errors δ in a fraction F of the N phase shifters

2 Equal phase errors β in a fraction F of the N phase shifters

3 Small random phase errors in both the phase shifters and the combiner matrix hybrids.

The results of this analysis are shown in Figure 5. A statistical error analysis involving both amplitude and phase errors (tolerance) is in process, and results are forthcoming.

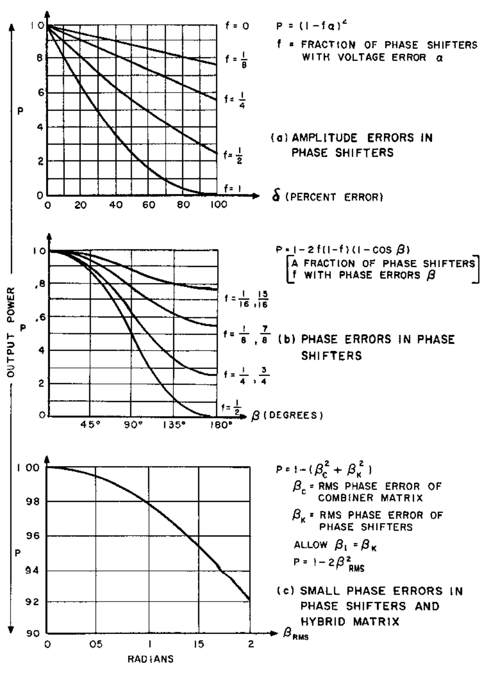


Figure 5. Normalized Power for Various Errors

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