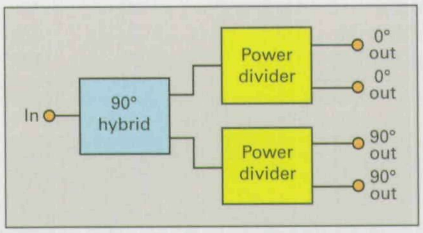
KEN GREENWOOD / DIRECTOR OF ENGINEERING

Understanding Passive Beamforming Networks

Passive beamforming networks can be constructed from a number of different high-frequency circuit technologies for precise control of antenna patterns over wide bandwidths.

Passive beamforming networks are widely used in military electronics systems, typically to control signal amplitude and phase with multiple antennas or radiating elements in such applications as jammers and phased-array radar systems. They can be used for both transmit and receive functions, and can be quite simple or complex, depending upon the number of signal beams to be processed. Beamformers have also been used to thwart the effects of jammers, but reconfiguring the antenna pattern from an array of radiating elements in both terrestrial and space-based communication systems. Early designs were typically fixed-beam architectures, although newer configurations include complex adaptive beamforming networks. Although beamforming networks can be formed with either active or passive configurations, this report will provide some insight into passive beamforming networks by providing several example topologies.

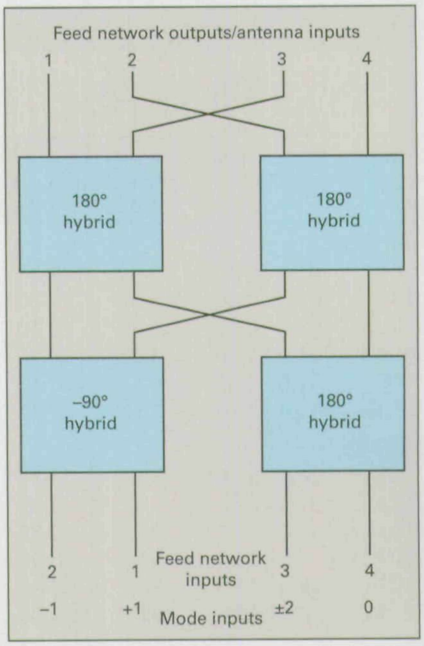
Beamforming networks may also be used to combine signals from a set of nondirectional antennas to simulate the behavior of a single, larger antenna (with higher gain). The feed network to the antennas allows beam steering without having to physically move the antennas. Early work leading to beamforming networks showed that multiple-beams could be produced from a linear array using a passive RF transmission line feed system.[1] The feed system was a passive circuit consisting of a network of hybrid junctions and fixed phase shifters. The numbers of beams equaled the number of inputs to the feed system being excited.[2]



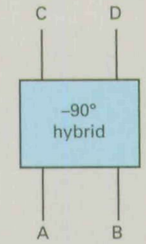
1. This simple 1 x 4 beamforming network is assembled from a quadrature hybrid coupler and a pair of power dividers. By using in-phase power dividers, the outputs of the dividers are offset 90° in phase relative to each other.

Separate findings around that same time[3] led to the development of a matrix feed network known as a Butler matrix. This work resulted in a formula for the phase difference between radiating elements, the number of hybrid junctions necessary to form N beams, and illumination techniques having other than uniform distributions, useful in reducing antenna sidelobe levels. While beamforming networks are commonly used in military electronics systems—such as electronic-intelligence (ELINT), electronic surveillance measures (ESM) radar, and signal-intelligence (SIGINT) systems—they are also employed in commercial communications systems, such as fourth-generation (4G) cellular communications systems that emply multiple-input, multiple-output (MIMO) antenna techniques to minimize the effects of interference and distortion.[4]

Beamforming networks operate by performing vector (amplitude and phase) manipulation on two or more input sig-

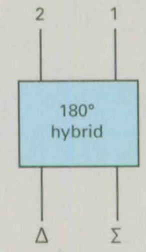


2. This 4 x 4 feed network consists of three 180° hybrids and a 90° hybrid.



	C	D
A	0°	–90°
B	–90°	0°

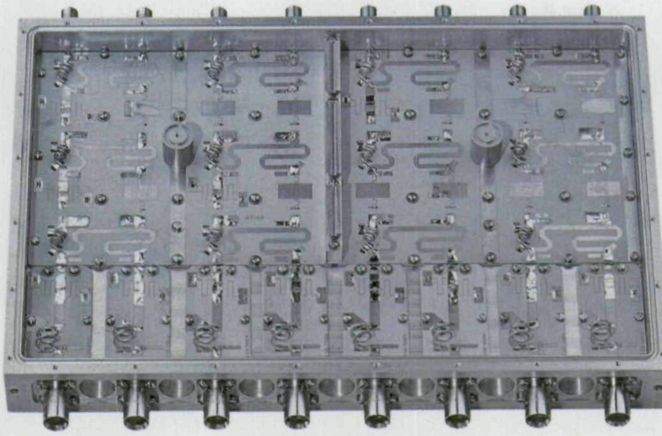
(a) –90° hybrid



	2	1
Δ	0°	180°
Σ	0°	0°

(b) 180° hybrid

3. These simple diagrams show the phase states at different ports for (a) a 90° hybrid coupler and (b) a 180° hybrid coupler.



4. This is a compact 8 x 8 Butler matrix fabricated entirely from passive components. [Photo courtesy of TRM Microwave (www.trmmicrowave.com).]

nals to create modified output signals. Because the amplitude and phase of input signals are being controlled, the design of a beamforming network implies tight control of the amplitude and phase characteristics of the passive components, such as phase shifters, employed in the beamforming network. When the output signals from a beamforming network are fed to an antenna array or array of antenna elements, those output signals result in electromagnetic (EM) field coordinates in three-dimensional space similar to what might be achieved by physically moving the antennas. Such antenna feed networks take advantage of antenna reciprocity, supporting both transmit and receive functions. In some cases, received RF signals are first down converted to intermediate-frequency (IF) signals before being applied to a beamforming network.

By controlling the amplitude and phase of signals fed to it for each antenna element in an array, a beamforming network can ultimately control the positions of the antenna system's main beam, as well as its sidelobe levels. In some systems, the beamforming network can even be used

BEAMFORMING NETWORK SERVES CUSTOM NEEDS

By application, most passive beamforming networks are custom in nature, designed according to the needs of an antenna array or electronic system. TRM Microwave (www.trmmicrowave.com) is a supplier of such custom beamforming network designs, for both military airborne and communications systems applications from 10 MHz to 18 GHz. The company has designed and produced multioctave beamforming networks based on ferrite, coaxial, and microstrip transmission-line technologies in package sizes as small as 2.0 x 3.5 x 0.7 in. **(see figure)**.

This compact beamforming network provides tightly controlled amplitude and phase characteristics from 500 to 2000 MHz in a package measuring just 2.0 x 3.5 x 0.7 in.

As an example of these compact passive beamforming networks developed for use in radar-warning receivers (RWRs), as well as in electronic-countermeasures (ECM) systems, a beamformer based on eight 0° power dividers, four 0° power dividers, four 180° power combiners, and 50-Ω coaxial delay lines was assembled for frequency coverage of 500 to 2000 MHz. Over that frequency range, the compact beamforming network achieves at least 18-dB isolation between ports with maximum insertion loss of 2.5 dB. The maximum input VSWR is 1.50:1 and the maximum output VSWR is 2.00:1.

Because the amplitude and phase performance of a beamforming network is so critical, great attention was paid to maintaining tightly controlled amplitude and phase characteristics

Table

Mode input	Feed network input	Feed network output			
		1	2	3	4
–1	2	0°	–90°	–180°	–270°
0	4	0°	0°	0°	0°
1	1	–90°	0°	–270°	–180°
±2	3	0°	±180°	0°	±180°

to steer antenna pattern nulls. Beamformers, which interface with an N array of antenna elements/apertures distributed as linear or circular arrays, are designed and analyzed by means of scattering (S) parameters. In a simple two-port network, such as a filter with input and output ports, the incident and reflected signals can be represented by four S-parameters:

S_{21} = the forward voltage gain,
S_{11} = the input port voltage reflection coefficient,
S_{12} = the reverse voltage gain, and
S_{22} = the output port voltage reflection coefficient.

Although S-parameters can be applied at any frequency, they are typically used for system, component, and device design at RF and microwave frequencies. When the simple two-port network is expanded into a four-port network more representative of a simple beamforming network, the S-parameters expand proportionally by the number of ports to include parameters for voltage gains and reflection coefficients at the different ports.

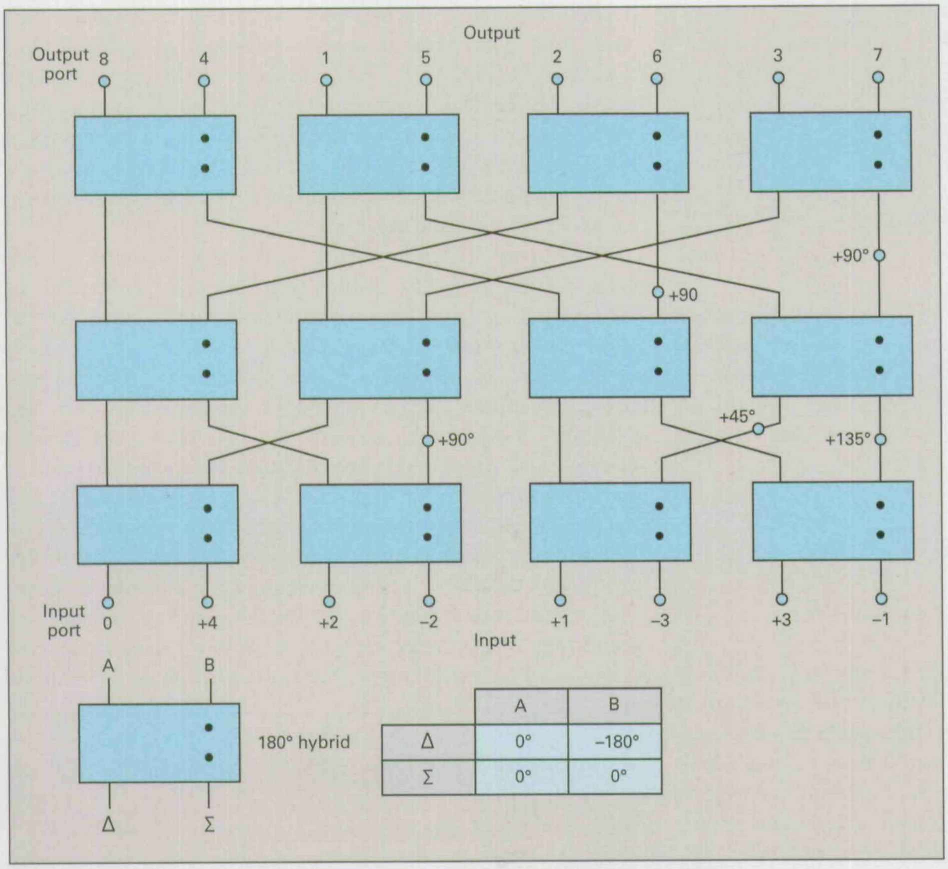
A passive beamforming network typically distributes signals by some combination of power dividers, hybrid circuits, and phase shifters, with a complex set of S-parameters representing the signal interactions between components. Combining such components into a compact integrated microwave assembly (IMA) involves many design challenges, including achieving optimum impedance matches among many separate circuits and components on a common printed-circuit board (PCB). As the circuit complexity and density increases, it becomes critical to use PCB substrates with dielectric constant and dissipation factor that are as consistent as possible as functions of frequency and temperature.

Because these circuits are typically integrated very close to an antenna array, they are usually designed for minimal weight and physical size. Compared to active beamforming networks, passive beamformers can be made electrically stable and reliable across a wide range of operating conditions, although a great deal of flexibility in the physical layout may be needed to accommodate a large variety of connector interfaces for different antenna arrays. In addition, as used in highly integrated, tightly coupled front-end structures, a successful beamforming network design must accommodate the electrical parasitics inherent in diverse physical layouts.

To better understand practical passive beamforming network design, it may be useful to study some examples. A beamforming network's performance is generally dictated by its intended application, specifically, the antenna array or system with which the beamforming network will be used. Numerous different passive RF/microwave design topologies are available when considering a beamforming network for a particular application. The examples presented below make use of ferrite material and planar transmission line implementations, including suspended stripline, stripline, airstrip, and microstrip technologies.

One example is the 1 x 4 beamforming network shown in **Fig. 1**, consisting of a 90° hybrid coupler and a pair of power dividers. The simple block diagram shows the the phase relationships of the output signals created from a single input signal, with two 0° outputs and two 90° outputs relative to the phase of the input

through all signal paths. The worst-case amplitude imbalance is ±0.5 dB while the worst-case phase imbalance is ±5°. The beamforming network, which is supplied with a chemical conversion coating finish per MIL-C-5541 Class 3 requirements, can handle input power levels to 1.5 W maximum and is designed to maintain accurate performance at operating temperatures from -55 to +85°C. All units were tested on a "go/no-go" basis, with full measurement data available upon request. *TRM Microwave*, 280 South River Road, Bedford, NH 03110; (603) 627-6000, *www.trmmicrowave.com.*



5. This block diagram depicts the signal flow through the 8 x 8 Butler matrix of Fig. 4.

signal. This simple circuit design is readily manufacturable for connectorized and surface-mount applications.

As mentioned earlier, a Butler matrix provides a specific desired distribution, or set of individual distributions, of amplitude and phase relationships between each antenna aperture relative to a single input signal. The progressive phase distributions at the beamformer output ports are referred to as modes (not to be confused with modes of propagation). Modes can be used to generate omnidirectional as well as directional antenna beams or radiation patterns. For directional beams, a progressive phase distribution is achieved such that each successive antenna beam adds in one direction to form a phase front and cancels in the other directions. The concept is referred to as a beam-cophasal technique.[7]

The concept of modes can be understood through a simple 4 x 4 feed network example consisting of 90° and 180° hybrid couplers (**Fig. 2**). For simplicity's sake, the 4 x 4 feed network shown in this example doesn't include phase shifters, although they are commonly used in Butler matrices. The four-port hybrid junctions are used in this case to provide power division and simple phase-shifting functions. Hybrid junctions are capable of fairly broadband frequency coverage (octave frequency bands) with relative low signal loss. In the beamforming network example, because of the amount of its phase shift, the 90° hybrid junction is often referred to as a quadrature hybrid or 3-dB hybrid coupler.

If one of the two input ports of a 90° hybrid is driven with a signal of arbitrary phase, one of the output signals will have the same phase (be in phase) as the input signal, but at a power level that is one-half (3 dB less) that of the input signal [**Fig. 3(a)**]. The second output signal, usually shown to be diagonally across from the input, will be 90° out of phase with the input signal (in quadrature with it) and one-half of its power level (3 dB less).

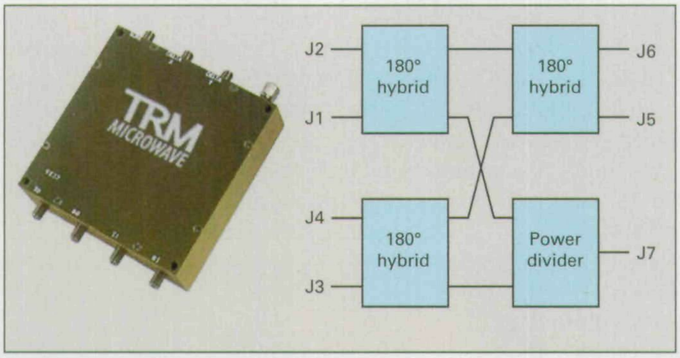
A 180° hybrid coupler is often referred to as a magic tee or "rat race" coupler. The inputs of the rat race coupler [**Fig. 3(b)**] are usually marked as the sum (Σ) and difference (Δ) ports. A signal applied to the difference port produces two signals at the output ports that are 180° out of phase with each other and one-half the power of the input signal. A signal applied to the sum port provides two half-power signals that are in-phase at the output ports.

The concept of modes can be understood by determining the results from the excitation of each of the four inputs of the feed network, one at a time. To do this, the three unused input ports are terminated in 50-Ω matched loads prior to making measurements. The results of each excitation are shown in the table. For each excitation, a progressive phase distribution is produced across the four outputs with a constant value of phase difference between adjacent output ports. To produce a radiation pattern, these output ports are connected to individual radiating elements of an antenna array. These independent progressive phase distributions are referred to as modes.

The 0 mode provides in-phase signals at each of the four outputs, relative to each other. The 0 mode in this example could be used to provide an omnidirectional antenna beam pattern. The directional modes created by excitations to the other ports could provide a directional antenna beam or nulling pattern for a particular array.

This simple 4 x 4 feed network represents a building block, along with fixed phase shifters, for more complex and higher-order antenna arrays. It can be used for create a compact 8 x 8 Butler matrix beamforming network (**Fig. 4**) based on a series of hybrid couplers and additional phase shifters. The 8 x 8 Butler matrix has been produced as a model BM88701 from TRM Microwave. It incorporates a set of 180° hybrids and coaxial lines to achieve fixed phase delays (**Fig. 5**) and operates in two specific frequency bands from 1025 to 1095 MHz. The compact coaxial assembly can handle as much as 8 W average (CW) input power and 400 W peak (pulsed) power, with low input and output VSWR of 1.30:1. The beamforming network, designed with 0 mode capability, offers at least 18 dB isolation between ports with 1 dB or less insertion loss.

Another example of a compact beamforming network is shown in **Fig. 6**. Manufactured as model MPC 4335 from TRM Microwave, it can produce outputs proportional to the phase difference between antennas, for use in monopulse comparator systems. Such a beamformer configuration, with specific receivers, can be used for precision DF applications because of its tightly controlled amplitude and phase characteristics. This unit has been designed for a 50-MHz bandwidth centered at 352 MHz, although other units are available with other center frequencies and bandwidths. This model features low insertion loss of 0.7 dB above the nominal 6.0-dB power split, with 25 dB minimum return loss, worst-case amplitude balance of 0.4 dB, and worst-case phase balance of 3.0°. Typical performance levels for this unit are considerably better.



6. This compact monopulse comparator beamforming network (left) is constructed with three 180° hybrid couplers and a power divider. The simple block diagram (right) shows the interconnection of the microwave passive components. [Photo courtesy of TRM Microwave (www.trmmicrowave.com).]

Beamforming networks are versatile assemblies for both commercial and military applications. They allow for precise control of amplitude and phase when feeding multiple antennas and antenna arrays, and are invaluable in such applications as phased-array radar systems. However, they require unique design and manufacturing capabilities to integrate the various components, such as power dividers, hybrid junctions, fixed phase shifters, cables, and coaxial connectors, with minimal reflections and the optimal impedance matches needed to preserve consistent amplitude and phase performance over wide frequency ranges. In order to meet the many different custom needs (**see sidebar**) for mechanical and electrical requirements, passive beamforming networks demand the application of an intelligent blend of numerous high-frequency circuit technologies, including stripline, microstrip, coaxial, and ferrite technologies. **DE**

KEN GREENWOOD / Director of Engineering, TRM Microwave, 280 South River Road, Bedford, NH 03110; (603) 627-6000, www.trmmicrowave.com.

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