Monopulse Networks for Series Feeding an Array Antenna

ALFRED R. LOPEZ, MEMBER, IEEE

Abstract—**Series networks for feeding an array antenna are attractive because they can be designed compactly. A series "ladder" network is available which is particularly applicable for feeding a monopulse array antenna since it has complete independent control of the sum and difference excitations, minimum dissipative loss, and physical symmetry. This network consists of primary and secondary transmission lines feeding two sets of directional couplers that are interconnected to resemble a ladder. To obtain physical symmetry, the ladder is fed at the center by two hybrid junctions and an additional directional coupler.**

An experimental array fed by a ladder network was fabricated and tested. The design objectives of 25 dB sidelobe suppression for the sum and difference mode patterns were achieved.

I. Introduction

SINCE THE INCEPTION of monopulse antennas, it has been a continuing goal to optimize performance in terms of antenna gain, sidelobe suppression, and tracking accuracy. At the outset, in the design of feeds for reflector antennas, it became clear that physical symmetry, minimum dissipative loss, and independent control of the required sum and difference mode aperture excitations were desirable characteristics.[1] During the development of electronically scanned array antennas, some of the previously developed techniques were applied directly to the design of networks for feeding a monopulse array antenna. Series-feed networks appeared attractive because they could be designed compactly;[2],[3] unfortunately, complete independent control of the excitations did not appear to be simply achievable. Recently,[4] a series network has been described which has complete independent control of the aperture excitations, but lacks physical symmetry and has an inherent dissipative loss. The following paper describes a series-feed network which possesses all three of the desired monopulse characteristics.

II. Series-Feed Networks

A series feed for an array antenna is one in which power to each radiating element is tapped off sequentially from a main feed line. A major feature with respect to a compact design is that, once the basic series-feed configuration has been established, continued growth in the number of array elements will not increase the thickness of the feed network. In this paper, feeds for a linear array will be discussed; the principles may be easily extended to a planar array.

Fig. 1(a) is a sketch of the simplest form of a series-feed network for a monopulse antenna. It is referred to as a "two-module" feed since it is divided into two sections; each consists of a transmission line feeding a set of power dividers. A hybrid junction at the center of the network generates the sum and difference excitations. Directional couplers are utilized as power dividers, with the unused ports terminated; this minimizes the generation of spurious radiation lobes caused by reflections from the radiating elements. This network is ideally lossless (this assumes ideal directional couplers, an ideal hybrid junction, and lossless transmission lines). It also has physical symmetry. However, it lacks any degree of independent control of the sum and difference excitations. That is, if the couplers are set for a good sum excitation, the difference excitation is necessarily identical to the sum in amplitude, as shown in the figure.

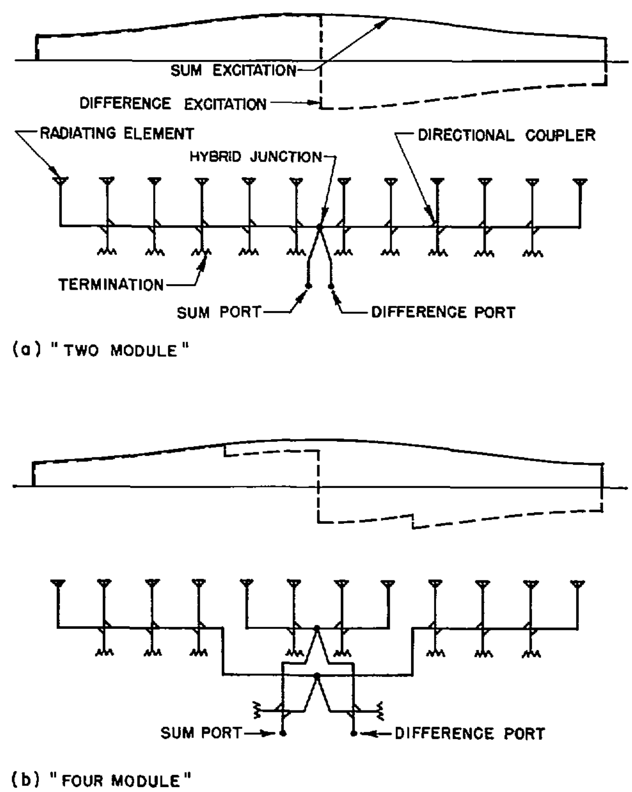

Fig. 1. Monopulse series-feed networks.

Some independent control is achieved by the network shown in Fig. 1(b). This network consists of four modules fed by two hybrid junctions at the center. Controlling the ratio of the inputs to the sum and difference ports of the hybrid junctions permits a limited degree of independence.

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The author is with Wheeler Laboratories, Inc., Smithtown, N. Y.

Extending this process so that the number of modules equals the number of elements yields complete mode independence,[1] but the series feed then becomes actually a complex parallel feed.

Another class of series-feed networks are available which provide complete independent control. These are referred to here as "ladder" networks, and are described and analyzed below.

III. Analysis of Ladder Networks

The basic ladder network consists of primary and secondary transmission lines feeding two sets of directional couplers, as shown in Fig. 2(b). The primary-line and secondary-line directional couplers are interconnected by short sections of transmission lines to resemble a ladder. The primary-line coupler outputs are fed to the radiating elements while the unused ports of the secondary-line couplers are terminated. Two types of ladder networks are described and analyzed below; but first, some general principles are discussed.

A. Proof of Excitation Independence

The following theorem for ladder networks is now proved by induction.

Theorem: If it is assumed that lossless transmission lines and ideal directional couplers are utilized, then ladder networks can be designed that are lossless and provide two independently specified excitations of the elements of an array antenna.

Consider first the simple network shown in Fig. 2(a), consisting of two radiating elements and a single ideal directional coupler. An ideal directional coupler is defined so that the coupler outputs, B_n, are related to the coupler inputs, A_n, by the following matrix relationships:

$$\begin{bmatrix} B_1 \\ B_2 \\ B_3 \\ B_4 \end{bmatrix} = \begin{bmatrix} c & \sqrt{1-c^2} & 0 & 0 \\ \sqrt{1-c^2} & -c & 0 & 0 \\ 0 & 0 & -c & \sqrt{1-c^2} \\ 0 & 0 & \sqrt{1-c^2} & c \end{bmatrix} \cdot \begin{bmatrix} A_1 \\ A_2 \\ A_3 \\ A_4 \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} A_1 \\ A_2 \\ A_3 \\ A_4 \end{bmatrix} = \begin{bmatrix} c & \sqrt{1-c^2} & 0 & 0 \\ \sqrt{1-c^2} & -c & 0 & 0 \\ 0 & 0 & -c & \sqrt{1-c^2} \\ 0 & 0 & \sqrt{1-c^2} & c \end{bmatrix} \cdot \begin{bmatrix} B_1 \\ B_2 \\ B_3 \\ B_4 \end{bmatrix}. \tag{2}$$

Let B_1 and B_2 be one desired excitation ($B_3 = B_4 = 0$) of the two-element array for a signal applied to the first input port.

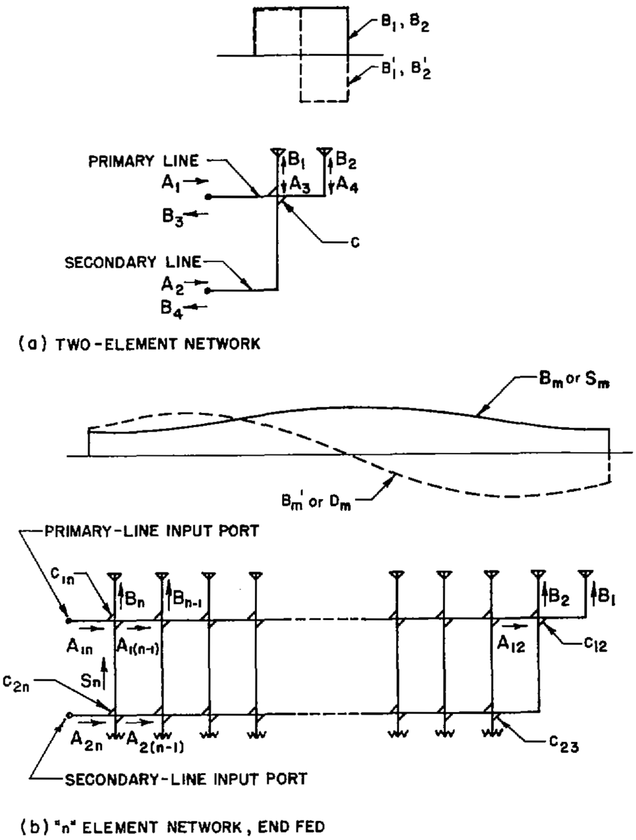

Fig. 2. Basic "ladder" networks.

Then in (1), A_2, A_3, and A_4 are equal to zero and

$$B_1 = cA_1 \tag{3}$$

$$B_2 = \sqrt{1-c^2}\, A_1. \tag{4}$$

With these two equations it is possible to solve for the two unknowns, A_1 and c, to provide the first excitation. Let B_1' and B_2' be a second desired excitation ($B_3' = B_4' = 0$) for *both* A_1' and A_2' applied to the input ports ($A_3' = A_4' = 0$). Equation (2) and c as just determined gives

$$A_1' = cB_1' + \sqrt{1-c^2}\, B_2' \tag{5}$$

$$A_2' = \sqrt{1-c^2}\, B_1' - cB_2'. \tag{6}$$

Thus, A_1' and A_2' are determined and provide the second desired excitation. *Therefore, setting the coupling value c and feeding one input port gives one excitation; providing the proper relative inputs to the coupler gives the other desired excitation.*

It is now possible to prove that if the theorem is true for a two-element array network, it is also true for a three-element array network and, in general, if it is true for an $(n-1)$-element network, it is also true for an n-element network. Fig. 2(b) shows a general n-element array network consisting of primary- and secondary-line directional couplers. Let B_m ($m = 1, 2, \cdots, n$) be one desired excitation of the elements produced by A_{1n}, the input to the primary line.

As now assumed, B_{m-1} is excited by $A_{1(n-1)}$, the primary-line input to the $(n-1)$ primary-line coupler. Equations (3) and (4) are used, as before, to determine c_{1n} and A_{1n} to produce B_n, the desired excitation of the nth element, and $A_{1(n-1)}$. Consequently, B_m, the complete desired excitation is obtained.

Let B_m' be a second desired excitation produced by A_{1n}' and A_{2n}', the inputs to the primary and secondary lines, respectively. As now assumed, B_{m-1}' is excited by $A_{1(n-1)}'$ and $A_{(2n-1)}'$. Equations (5) and (6) are used to determine A_{1n}' and S_n, since c_{1n}, B_n' and $A_{1(n-1)}'$ are known, and (3) and (4) are used to determine A_{2n}' and c_{2n}, since S_n and $A_{2(n-1)}'$ are known. Thus A_{1i}' and A_{2i}' will excite the complete desired excitation B_m'. Since ideal couplers are used, no power goes into the terminations when the array is perfectly matched; therefore, there is no loss in the network. This completes the proof of the theorem.

B. Orthogonality Condition

If a multi-port network is passive, reciprocal, and lossless, the output and input voltages are related by an orthogonality condition.[2],[5],[6] This condition is utilized in the following analysis of ladder networks, and is derived and expressed in a form which is more directly applicable to this type of network.

Let A_1 and A_2 be the inputs to the primary and secondary lines, and B_{1m} and B_{2m} be their respective excitations of the elements. Since the input ports and terminated ports are decoupled (transfer coefficient$=0$) and the excitations are real (phase at each element port$=0°$ or $180°$), then conservation of energy gives

$$A_1^2 = \sum_{m=1}^{n} B_{1m}^2 \tag{7}$$

$$A_2^2 = \sum_{m=1}^{n} B_{2m}^2. \tag{8}$$

If A_1 and A_2 are simultaneous inputs, then

$$A_1^2 + A_2^2 = \sum_{m=1}^{n} (B_{1m} + B_{2m})^2. \tag{9}$$

Combining these three equations results in

$$\sum_{m=1}^{n} B_{1m} B_{2m} = 0 \tag{10}$$

which is the orthogonality condition. Thus, *two excitation input ports are decoupled if and only if the corresponding excitations they produce are orthogonal.*

C. "End-Fed" Ladder Network

Fig. 2(b) shows the general "end-fed" ladder network for series feeding a monopulse array antenna. Also shown in the figure are the envelopes for typical sum and difference mode excitations. These excitations, S_m and D_m, are specified independently of each other. The network can be designed so that an input S to the primary line excites S_m. As indicated in the preceding discussion, the network can be designed to provide a second independent excitation; in this case, D_m. Since S_m and D_m are inherently orthogonal, the ports that generate the excitations must be decoupled. Thus, the D_m excitation is provided by feeding an input D to the secondary line only.

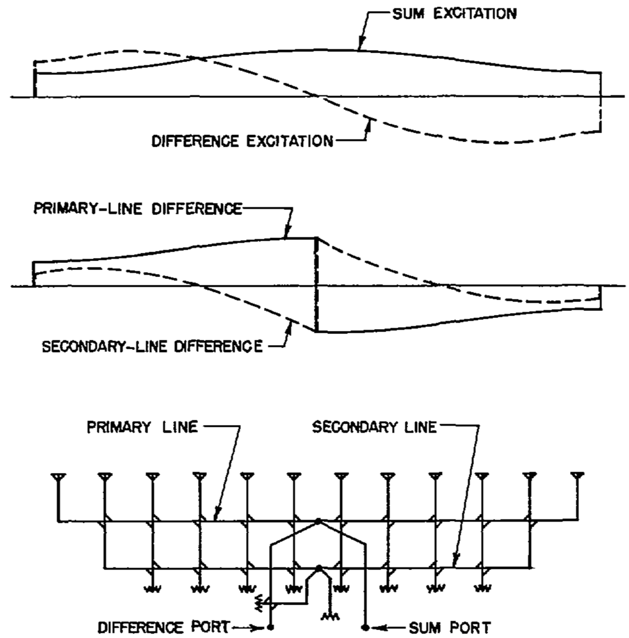

Fig. 3. "Center-fed" ladder network.

This network, even though it is ideally lossless and has independent control of the sum and difference modes, lacks the physical symmetry which is desirable for monopulse operation. The next network to be described does not have this shortcoming.

D. "Center-Fed" Ladder Network

Fig. 3 shows a "center-fed" ladder network for series feeding a monopulse array antenna. This network consists of two end-fed ladder networks fed at the center by two hybrid junctions and an additional directional coupler. Also shown in the figure are typical sum and difference excitations. The sum mode excitation is again provided by setting the primary-line couplers and feeding an input to the primary line. It is noted that the sum and difference excitations are *not* orthogonal in the region between the centerline and the edge of the network. Thus, to excite the difference mode, it is necessary to simultaneously feed the primary and secondary input ports. Since the input ports are inherently decoupled, feeding only the secondary line would produce an orthogonal excitation. The required combination of signals to the input ports is achieved by means of the additional directional coupler feeding the required inputs to the difference ports of the primary and secondary hybrid junctions. Fig. 3 shows the difference excitations produced by inputs to the difference ports of the primary- and secondary-line hybrid junctions. It is noted that these component excitations are orthogonal and that their combination results in the desired difference pattern.

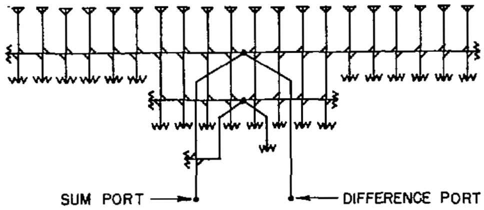

Fig. 4. Experimental array and modified "center-fed" ladder network.

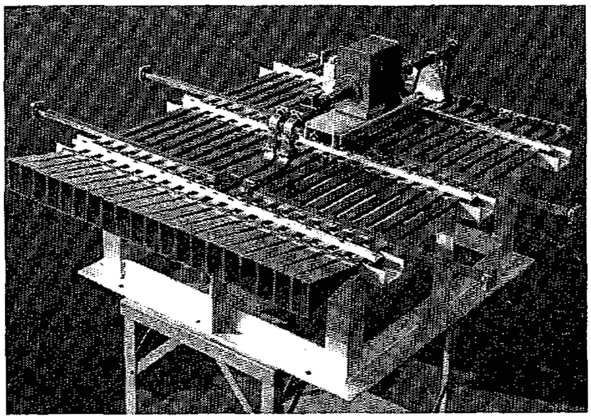

Fig. 5. Photograph of experimental array and modified "center-fed" ladder network.

The "center-fed" ladder network thus has all three desirable monopulse characteristics: 1) it provides complete independent control of the excitations, 2) it is ideally lossless, and 3) it has physical symmetry.

IV. Experimental Array

To verify some of the characteristics of a "center-fed" ladder network, and to gain some insight into its operation, an experimental 20-element array was built and tested. The design objective was 25 dB sidelobe suppression for both the sum and difference modes.

Fig. 4 is a sketch of the network. It is noted that less than half of the available secondary-line directional couplers were actually utilized. For 25 dB sidelobe suppression, the outer portions of the sum and difference excitations are nearly identical; consequently, the objective can be achieved without the outer section of the secondary line. Note also that the difference mode, instead of the sum mode, is excited by the primary line. This is an alternative arrangement that favors the difference pattern over the sum pattern. It is also noted that the primary and secondary lines are terminated by a lossy termination instead of being terminated by the last element. In the short time available for the development of the array, it was impractical to develop the near 3 dB directional couplers required for the ideally lossless design.

Fig. 5 is a photograph of the experimental array. The network utilizes waveguide transmission lines and cross-guide directional couplers spaced one guide-wavelength apart. The radiating elements are waveguide horns. A phase shifter is included to control the relative phase between the primary and secondary lines. Figs. 6 and 7 are the measured sum and

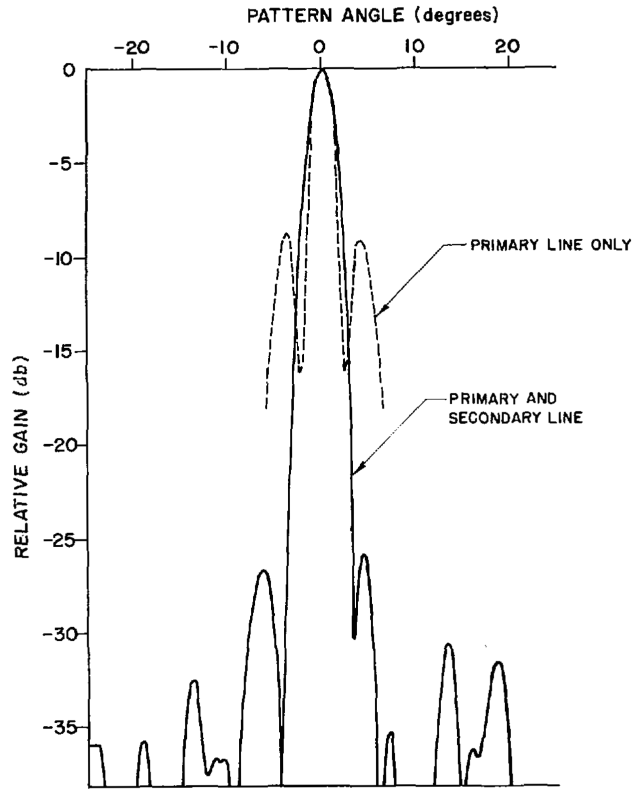

Fig. 6. Sum pattern of experimental array and modified "center-fed" ladder network.

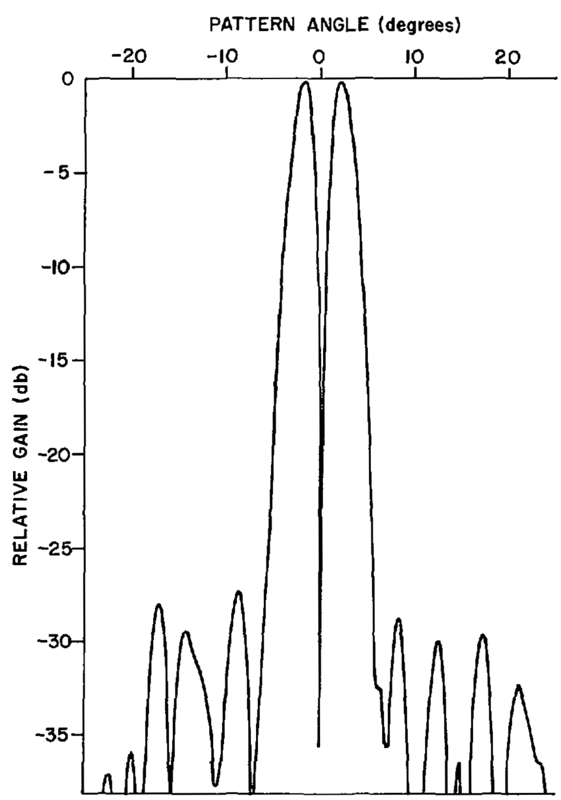

Fig. 7. Difference pattern of experimental array and modified "center-fed" ladder network.

difference patterns. Fig. 6 also shows the central portion of the sum pattern that is obtained when only the primary line is fed in the sum mode. As expected, a significant reduction in the sidelobe level is observed when both the primary and secondary lines are fed together with the proper relative amplitude and phase. The measured difference pattern is seen to have a deep null at the center; this was achieved without any adjustment of the network. In both the sum and difference modes, the 25 dB sidelobe-suppression objective was achieved.

V. Discussion

It has been shown that the "center-fed" ladder network is a direct way of designing a series feed for a monopulse array antenna when it is desirable to have complete independence of the sum and difference mode excitations, ideally no dissipative loss, and physical symmetry. As is characteristic of series networks, it can be extended indefinitely to feed more elements without increasing its thickness.

With respect to operating bandwidth, it is noted that, at any radiating element port, the path length and, consequently, the phase of signal components arriving via various paths are identical for all signal components. Thus, for any frequency in the operating bandwidth, the amplitude excitation of the elements is dependent only on the bandwidth characteristics of the directional couplers and hybrid junctions. In practice, the network components introduce some path inequalities; these, however, can easily be adjusted to be within tolerable limits.

With respect to instantaneous bandwidth, it is noted that, at any radiating element port, the path length and, consequently, the time delay of signal components arriving via various paths are identical for all signal components. Thus, the instantaneous bandwidth characteristics are the same as would be expected for a simple single-line series feed. It is also noted that, for broadside scan, the differential time delay for a "center-fed" ladder network is half that of an "end-fed" ladder network.

The principles of a ladder network can be extended to more than two main transmission lines. If a third line is utilized, three independently specified excitations can be obtained; the first by setting the primary-line couplers and providing an input to the primary line; the second, by setting the secondary-line couplers and feeding the proper relative inputs to the primary and secondary lines; and the third by setting the trinary-line couplers and feeding the proper relative inputs to the primary, secondary, and trinary lines. For an n element array, the procedure can be extended to provide n independently specified excitations.

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