New N-way Hybrid Power Combiner to Improve the Graceful Degradation Performance

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ABSTRACT

In this paper, a new N-way hybrid power combiner for improving the graceful degradation performance has been proposed. The proposed combiner has been configured with two dummy transmission lines per each section, where each dummy transmission line has a different characteristic impedance, of the standard combiner. Under this proposed configuration, a detailed theoretical analysis has been performed to show the general function of a power combiner.

When any M amplifiers among N identical amplifiers are suffering the failure mode in a power combining circuit or system, the graceful degradation performance has been improved due to the separation of a transmission line and an internal resistor in every failed section from the proposed combiner by simultaneously operating two shorting devices.

Simulation results for all the items which can be measured from the proposed combiner with an eight-way configuration have been presented.

I. INTRODUCTION

Microwave power combining [1] is of particular importance in radar and satellite earth station transmitter applications when power amplifiers are combined by various techniques to obtain the high output power at microwave frequencies where a large amount of power might not be available from a single amplifier. Especially, the demand for higher solid-state power amplifiers and the output power limitation of individual solid-state devices have increased the need for multi-port combiners with high combining efficiency. But, the use of popular N-way power combiners, such as the standard Wilkinson's combiner [2] or its modified schemes [3-13], to obtain N times of the output power of individual amplifier results in "the graceful degradation" [14,15] in the failure modes of one or more amplifiers in a power combining circuit or system. The graceful degradation refers to the fact that the output power is reduced but not completely lost. Generally, its final output power results in about 2-dB drop when one fifth of the amplifiers fail completely in the standard power combiner proposed previously, or 6-dB drop when half of the amplifiers fail. While this represents some sort of graceful degradation performance, the output power is still significantly smaller than the sum of the output powers of the remaining amplifiers, i.e. with about 1-dB and 3-dB drop, respectively, under the same conditions.

To improve the graceful degradation performance, A. A. M. Saleh had suggested previously his idea in [15], but it had been to use a resistor-free combiner whose port isolation and match could not be made. In addition, if such a scheme with a resistor-free is used to obtain this performance, though the scheme is simple, isolation between ports and port matching will be very poor because internal resistors play a role making them possible[2]. Poor port matching would bring, especially, the strong "load-pull effect" that could reduce the available power from each working amplifier, and so large power insertion or transmission loss would be brought in a power combining circuit or system whose purpose is to add, with high efficiency, the output power of each working amplifier in order to obtain high power. In fact, the resistor-free scheme must be equipped with an external isolator at each input port of the combiner so as to obtain the effect improving the graceful degradation performance from the view point of overall combining circuit or system, and to give the results or the performances described in [15].

Therefore, the purpose of this paper is to present a new N-way hybrid power combiner of the new scheme to solve the isolation and matching problem at input ports without external isolators and to improve the graceful degradation performance. Its basic scheme must not only provide a proper function as a power combiner when all the amplifiers are being operated without any failed amplifier, but also separate each failed amplifier and internal resistor from the combiner by appropriately placed two shorting devices per one section in order to improve the output power degraded gracefully when any amplifier fails.

Such a new combiner is successfully made as inserting two *dummy transmission lines*(DTLs) into each section of the scheme proposed by E. J. Wilkinson.

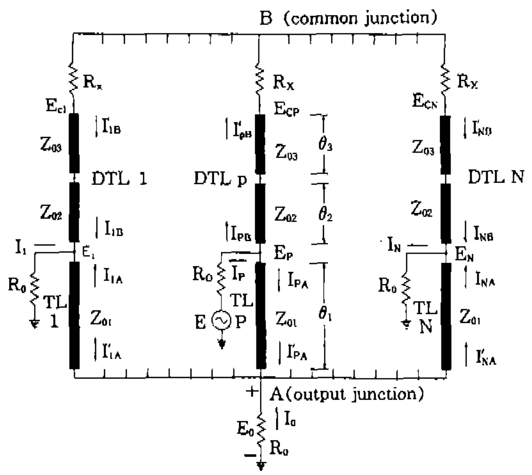


Fig. 1. A new N-way power combiner to improve the graceful degradation performance.

II. THEORETICAL ANALYSIS OF THE PROPOSED SCHEME

To develop a detailed theoretical analysis, consider a new N-way power combiner with two DTLs, per one section, which have two different characteristic impedances (Z_{02}, Z_{03}) and electrical lengths (θ_2, θ_3), respectively, as shown in Fig. 1.

If a generator $E(w)$ with internal resistance R_o is applied to input port p(where, p=1, 2, ..., N), then we can obtain each other dependent current and voltage expressions illustrated in Fig. 1 because of symmetry of the given scheme. When the *transmission line*(TL) equations are applied to each section under the assumption that all TLs are lossless, the general relations written with frequency-dependent parameters can be made as follows.

TL of section p :

$$\begin{bmatrix} E_p(w) \\ I_{pA}(w) \end{bmatrix} = \begin{bmatrix} A_{TL}(w)\, B_{TL}(w) \\ C_{TL}(w)\, D_{TL}(w) \end{bmatrix} \begin{bmatrix} E_o(w) \\ I'_{pA}(w) \end{bmatrix} \tag{1}$$

DTLs of section p :

$$\begin{bmatrix} E_p(w) \\ I_{pB}(w) \end{bmatrix} = \begin{bmatrix} A_{DTL}(w)\, B_{DTL}(w) \\ C_{DTL}(w)\, D_{DTL}(w) \end{bmatrix} \begin{bmatrix} E_{Cp}(w) \\ I'_{pB}(w) \end{bmatrix} \tag{2}$$

TL of section N :

$$\begin{bmatrix} E_o(w) \\ I'_{NA}(w) \end{bmatrix} = \begin{bmatrix} A_{TL}(w)\, B_{TL}(w) \\ C_{TL}(w)\, D_{TL}(w) \end{bmatrix} \begin{bmatrix} E_N(w) \\ I_{NA}(w) \end{bmatrix} \tag{3}$$

DTLs of section N :

$$\begin{bmatrix} E_{CN}(w) \\ I'_{NB}(w) \end{bmatrix} = \begin{bmatrix} A'_{DTL}(w)\, B'_{DTL}(w) \\ C'_{DTL}(w)\, D'_{DTL}(w) \end{bmatrix} \begin{bmatrix} E_N(w) \\ I_{NB}(w) \end{bmatrix} \tag{4}$$

where,

$$A_{TL}(w)=\cos\theta_1(w)$$
$$B_{TL}(w)=jZ_{01}\sin\theta_1(w)$$
$$C_{TL}(w)=jY_{01}\sin\theta_1(w)$$
$$D_{TL}(w)=\cos\theta_1(w)$$
$$A_{DTL}(w)=\cos\theta_2(w)\cos\theta_3(w)-Z_{02}Y_{03}\sin\theta_2(w)\sin\theta_3(w)$$
$$B_{DTL}(w)=j\{Z_{03}\cos\theta_2(w)\sin\theta_3(w)+Z_{02}\sin\theta_2(w)\cos\theta_3(w)\}$$
$$C_{DTL}(w)=j\{Y_{02}\sin\theta_2(w)\cos\theta_3(w)+Y_{03}\cos\theta_2(w)\sin\theta_3(w)\}$$
$$D_{DTL}(w)=\cos\theta_2(w)\cos\theta_3(w)-Y_{02}Z_{03}\sin\theta_2(w)\sin\theta_3(w)$$
$$A'_{DTL}(w)=\cos\theta_3(w)\cos\theta_2(w)-Z_{03}Y_{02}\sin\theta_3(w)\sin\theta_2(w)$$
$$B'_{DTL}(w)=j\{Z_{02}\cos\theta_3(w)\sin\theta_2(w)+Z_{03}\sin\theta_3(w)\cos\theta_2(w)\}$$
$$C'_{DTL}(w)=j\{Y_{03}\sin\theta_3(w)\cos\theta_2(w)+Y_{02}\cos\theta_3(w)\sin\theta_2(w)\}$$
$$D'_{DTL}(w)=\cos\theta_3(w)\cos\theta_2(w)-Y_{03}Z_{02}\sin\theta_3(w)\sin\theta_2(w).$$

And, it is also true that

$$I'_{pA}(w)=\frac{E_o(w)}{R_o}+(N-1)I'_{NA}(w)$$
$$I_{NA}(w)=\frac{E_N(w)}{R_o}-I_{NB}(w)$$
$$\{I_{pA}(w)+I_{pB}(w)\}R_o$$
$$=E(w)-E_p(w)$$
$$\left\{I'_{pB}(w)+\frac{I'_{pB}(w)}{N-1}\right\}R_x$$
$$=E_{Cp}(w)-E_{CN}(w)$$
$$I'_{NB}(w)=\frac{I'_{pB}(w)}{N-1}. \tag{5}$$

Now, we shall describe subjective data group(eight frequency-dependent current parameters : I_{pA}, I'_{pA}, I_{pB}, I'_{pB}, I_{NB}, I'_{NB}, I_{NA}, I'_{NA}) as only objective data group (six frequency-dependent voltage parameters : E, E_p, E_N, E_o, E_{Cp}, E_{CN}). That is, using above thirteen equations, we can obtain the following set of simultaneous equations for unknown voltage parameters.

$$\begin{bmatrix} M_{11}M_{12}M_{13}M_{14}M_{15}M_{16} \\ M_{21}M_{22}M_{23}M_{24}M_{25}M_{26} \\ M_{31}M_{32}M_{33}M_{34}M_{35}M_{36} \\ M_{41}M_{42}M_{43}M_{44}M_{45}M_{46} \\ M_{51}M_{52}M_{53}M_{54}M_{55}M_{56} \end{bmatrix} \begin{bmatrix} E(w) \\ E_p(w) \\ E_{Cp}(w) \\ E_{CN}(w) \\ E_N(w) \\ E_o(w) \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \tag{6}$$

where,

$$M_{11}=\frac{1}{R_oD_{DTL}} \qquad M_{12}=\frac{1}{R_oD_{DTL}}$$
$$M_{13}=\frac{N-1}{NR_x}+\frac{C_{DTL}}{D_{DTL}} \quad M_{14}=-\left(\frac{N-1}{NR_x}\right)$$

$$M_{15} = D_{TL}(N-1)\left(\frac{B_{TL}C_{TL} - A_{TL}D_{TL}}{B_{TL}D_{DTL}}\right)$$

$$M_{16} = \left\{\frac{C_{TL}}{D_{DTL}} + \frac{D_{TL}}{R_o D_{DTL}} + \frac{(N-1)D_{TL}^2}{B_{TL}D_{DTL}}\right\}$$

$$M_{23} = \frac{1}{NR_x D'_{DTL}} \qquad M_{24} = -\left(\frac{1}{NR_x D'_{DTL}}\right)$$

$$M_{25} = -\left(\frac{A_{TL}}{B_{TL}} + \frac{C_{DTL}}{D'_{DTL}} + \frac{1}{R_o}\right)$$

$$M_{26} = \frac{1}{B_{TL}} \qquad M_{32} = -\left(\frac{1}{B_{TL}}\right)$$

$$M_{35} = (N-1)\left(C_{TL} - \frac{A_{TL}D_{TL}}{B_{TL}}\right)$$

$$M_{36} = \frac{A_{TL} + (N-1)D_{TL}}{B_{TL}} + \frac{1}{R_o}$$

$$M_{44} = -1$$

$$M_{45} = A'_{DTL} + \frac{B'_{DTL}}{R_o} + \frac{A_{TL}B'_{DTL}}{B_{TL}}$$

$$M_{46} = -\left(\frac{B'_{DTL}}{B_{TL}}\right) \qquad M_{52} = -1$$

$$M_{53} = A_{DTL} + \frac{(N-1)B_{DTL}}{NR_x}$$

$$M_{54} = -\left\{\frac{(N-1)B_{DTL}}{NR_x}\right\}$$

$$M_{21} = M_{22} = M_{31} = M_{33} = M_{34} = M_{41} = M_{42} = M_{43} = M_{51} = M_{55} = M_{56} = 0.$$

When each TL and DTL is a quarter wavelength long at a center frequency $[\theta_i(w_c) = \frac{\Pi}{2},\ i = 1, 2, 3]$, the following relations can be derived through the eq. (6) for perfect port isolation $[E_N(w_c) = 0]$ and port match $[E(w_c) = 2E_p(w_c)]$ at a center frequency.

$$\frac{1}{NR_x}\left(\frac{Z_{03}}{Z_{02}}\right)^2 - \frac{R_o}{Z_{01}^2} = 0$$

$$\frac{(N-1)R_o}{NR_x}\left(\frac{Z_{03}}{Z_{02}}\right)^2 + \left(\frac{R_o}{Z_{01}}\right)^2 = 1 \qquad (7)$$

Therefore, with eq. (7) two fundamental conditions are obtained

$$\frac{Z_{03}}{Z_{02}} = \sqrt{\frac{R_x}{R_o}}$$

$$Z_{01} = \sqrt{N}R_o. \qquad (8)$$

Thus, if the ratio Z_{03}/Z_{02} becomes a square root of the ratio R_x/R_o and the characteristic impedance Z_{01} of TL is also selected as N square root times of R_o, input ports of the combiner will be completely isolated and matched at a center frequency. That is, above mentioned four circuit parameters ,Z_{02}, Z_{03}, R_x, R_o, are not independent of each other. Therefore, that parameter values can be optimized as $Z_{02} = 45\Omega, Z_{03} = 28.5\Omega, R_x = 20\Omega, R_o = 50\Omega$ through the computer simulation in order that the insertion loss, port isolation, input and output return loss have flatly best performances over about fifty percent bandwidth, which is sufficient to microwave power applications.

The output impedance will be the parallel combination of each impedance observed at the N common output port due to symmetry of the network topology.

$$Z_{out}(w) = \frac{Z_{NR}(w) + jZ_{NI}(w)}{Z_{DR}(w) + jZ_{DI}(w)} \quad (9)$$

where,

$$Z_{NR}(w) = -Z_{01}^2 Z_{02} \tan\theta_1(w) \times \{Z_{02} \tan\theta_2(w) - Z_{03} \cot\theta_3(w)\}$$

$$Z_{NI}(w) = R_o Z_{01} Z_{02} \times \{Z_{02} \tan\theta_2(w) - Z_{03} \cot\theta_3(w)\} - R_o Z_{01}^2 \tan\theta_1(w) \times \{Z_{02} + Z_{03} \tan\theta_2(w) \cot\theta_3(w)\}$$

$$Z_{DR}(w) = NR_o Z_{01} \times \{Z_{02} + Z_{03} \tan\theta_2(w) \cot\theta_3(w)\} - NR_o Z_{02} \tan\theta_1(w) \times \{Z_{02} \tan\theta_2(w) - Z_{03} \cot\theta_3(w)\}$$

$$Z_{DI}(w) = NR_o Z_{01} Z_{02} \times \{Z_{02} \tan\theta_2(w) - Z_{03} \cot\theta_3(w)\}.$$

Therefore, at a center frequency it yields

$$Z_{out}(w_c) = \frac{Z_{01}^2(w_c)}{NR_o} = R_o \quad (10)$$

Now, we know the fact that the output of the proposed combiner is also matched at a center frequency when the conditions for isolation and match between input ports are satisfied simultaneously.

All four performances of the combiner, i.e. insertion loss, isolation between input ports, input return losses and output return loss, may be also described as a frequency variable, not at only a center frequency, respectively, as follows.

- Insertion loss :

$$S_{oi} = \left.\frac{2E_o(w)}{E(w)}\right|_{all\ ports\ matched\ except\ i} \quad (11)$$
$$i = 1, 2, 3, \cdots, N$$

where, $E(w)$: external voltage applied to i-th port, $E_o(w)$: voltage appearing at the combiner output.

- Isolation between input ports :

$$S_{ji} = \left.\frac{2E_j(w)}{E(w)}\right|_{all\ ports\ matched\ except\ i} \quad (12)$$
$$i, j = 1, 2, 3, \cdots, N, \ i \neq j$$

where, $E(w)$: external voltage applied to i-th port, $E_j(w)$: voltage appearing at j-th port.

- Input return losses :

$$S_{ii} = \left.\frac{2E_i(w)}{E(w)}\right|_{all\ ports\ matched\ except\ i} \quad (13)$$
$$i = 1, 2, 3, \cdots, N$$

where, $E(w)$: external voltage applied to i-th port, $E_i(w)$: voltage appearing at i-th port.

- Output return loss :

$$S_{oo} = \left.\frac{2E_o(w)}{E(w)}\right|_{\substack{all\ ports\ matched\ except\\ output\ port\ of\ the\ combiner}} \quad (14)$$

where, $E(w)$: external voltage applied to the combiner output, $E_o(w)$: voltage appearing at the combiner output.

The insertion, isolation, input return losses and output return loss of the combiner described on the above can be easily but tediously obtained after some manipulation from the eqs. (6) and (9), respectively.

Especially, note that the insertion loss decreases abruptly at the point where the normalized frequency (f/f_c) becomes 0.5 and 1.5 due to the DTLs structure of the combiner. Therefore, the bandwidth of the proposed scheme cannot help being limited less than maximum one hundred percent.

Referring to Fig. 1 again, the power, P_i^d, dissipated in the internal resistor R_x of that section when only i-th port of the combiner is excited can be derived to give the following general expression.

$$P_i^d(w) = \left(\frac{N-1}{N}\right)^2 P_i^{av}(w) GF_i(w) \quad (15)$$

where, $P_i^{av}(w)$ is an available power entering on the same i-th port, and $GF_i(w)$ is the general factor or coefficient which describes, at any frequency except a center frequency, imperfect port isolation and input matching, and is given as

$$GF_i(w) = \left(\frac{1+S_{ii}}{1-S_{ii}}\right)\left(\frac{R_o}{R_x}\right) \left|\frac{E_{Ci}(w) - E_{CN}(w)}{E_i(w)}\right|^2,$$

$$i = 1, 2, 3, \cdots, N.$$

The eq. (15) can be expressed as only circuit parameters combining the five rows except the first row of the eq. (6).

While each power, P_j^d, dissipated in the internal resistors of the other sections can be also given by

$$P_j^d(w) = \frac{1}{N^2} P_i^{av}(w) GF_i(w)$$
$$j \neq i \text{ and } i, j = 1, 2, 3, \cdots, N, \quad (16)$$

and the power, P_{out}, flowing to the output port of the combiner is

$$P_{out}(w) = \frac{1}{N} P_i^{av}(w) GF_i(w), \quad (17)$$

finally each power, P_j^{ipi}, appearing at the other ports except the excited i-th port by imperfect port isolation is

$$P_j^{ipi}(w) = \left\{\frac{1 - GF_i(w)}{N-1}\right\} P_i^{av}(w)$$
$$j \neq i \text{ and } i, j = 1, 2, 3, \cdots, N, \quad (18)$$

so that the identity may be verified as follows:

$$P_{out}(w) + P_i^d(w) + (N-1)P_j^d(w)$$
$$+ (N-1)P_j^{ipi}(w) = P_i^{av}(w). \quad (19)$$

If all M ports including the i-th port out of N input ports of the combiner are excited with the conditions of the same phase and amplitude, the power dissipated in the internal resistor of the i-th section can be expressed as

$$P_i^d(w) = \left\{\frac{(N-M)(N+M-2)}{N^2}\right\}$$
$$\times P_i^{av}(w) GF_i(w), \quad (20)$$

and the power dissipated in the internal resistor of the j-th section non-excited can be also expressed as

$$P_j^d(w) = \left(\frac{M}{N}\right)^2 P_i^{av}(w) GF_i(w). \quad (21)$$

All the previous eqs. (15)~(21) can have simple expressions due to $GF_i(w_c) = 1$ at a center frequency under the conditions of perfect port isolation and match.

III. ITS APPLICATION TO IMPROVE THE GRACEFUL DEGRADATION PERFORMANCE

In many applications, microwave high power levels which far exceed the capability of any single device such as solid-state power amplifier are required. Thus, several identical amplifiers must be combined together in order to obtain this power level. To illustrate a general power combining system, let us consider N identical amplifiers whose output powers are combined by means of an N-way power divider and an N-way power combiner as shown in Fig. 2.

With the standard configuration such as Wilkinson's power combiner or its modified one, it is obvious that the total output power will be obtained N times the output power of a single amplifier under the assumption that all the amplifiers are operated, but that output power will

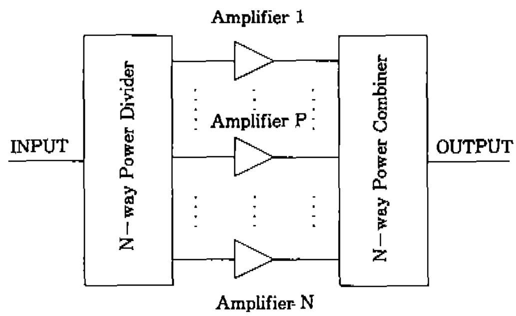


Fig. 2. A general configuration for combining N identical amplifiers.

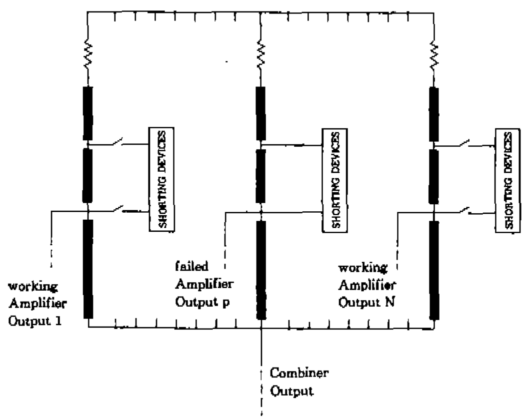


Fig. 3. A new N-way power combiner scheme equipped with two shorting devices.

be gracefully decreased if some amplifiers suffer modes of failure. Hence, the power combiner of the new scheme proposed in this paper will be used instead of the standard combiner in order to improve the graceful degradation performance. For this purpose, each section of the combiner as shown in Fig. 3 is equipped with two external shorting devices which are simultaneously activated when any amplifier connected to them fails. Accordingly, the TL and internal resistor of the failed section can be perfectly separated from the combiner at a center frequency by means of the activation of these two shorting devices. The failed amplifier may be identified, for instance, by noting large changes in its DC bias current. The shorting device could be a mechanical short driven by an electromagnet, or a shunt pin diode that can be biased in its forward direction [15].

With the above provision and under the assumption that the available power from each of the amplifiers is constant or each amplifier is linear, if M out of N amplifiers fail it can be shown that the insertion loss, in dB scale, at a center frequency is

$$|S_{o,i}|^2 = 10\log\left\{\frac{4N}{(2N-M)^2}\right\} \qquad [dB]$$

where

$$N \geq 2, M \leq (N-1), N, M : Integer, \qquad (22)$$

and so the effect improving the graceful degradation performance can be obtained because the eq. (22) is dependent on the number of failure M.

While the insertion loss of the standard combiner at the same conditions is

$$|S_{o,i}|^2 = 10\log\left(\frac{1}{N}\right)[dB], \qquad (23)$$

and so the effect improving the graceful degradation performance can not be obtained because the eq. (23) is independent of the number of failure M.

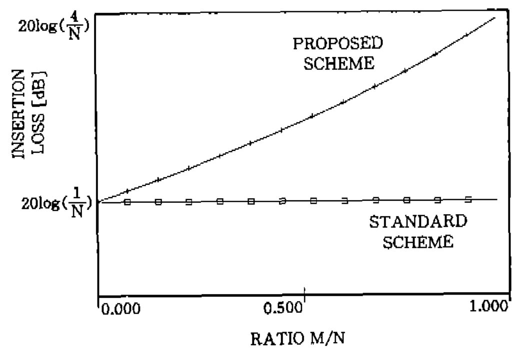


Fig. 4. The insertion loss versus the relative number of failed amplifiers (at $f/f_c = 1$).

When M out of N amplifiers fail it can be also known that each output power of the two combiners at a center frequency, which is normalized by the maximum output power, is given by, respectively,

$$\frac{P_{out}(w_c)}{P_{out,\,max}(w_c)} = 10\log\left\{1 - \frac{M}{(2N-M)}\right\}^2, \qquad (24)$$

$$\frac{P_{out}(w_c)}{P_{out,\,max}(w_c)} = 10\log\left(1 - \frac{M}{N}\right)^2. \qquad (25)$$

In order to compare each other the effect improving the graceful degradation of the output power for each combiner when some amplifiers fail, the quantities of eqs. (22), (23) and (24), (25) are plotted versus the ratio M/N in Fig. 4 and Fig. 5, respectively.

As sketched in Fig. 4 and 5, it is easily shown that the quantity for the output power improvement of the proposed combiner is

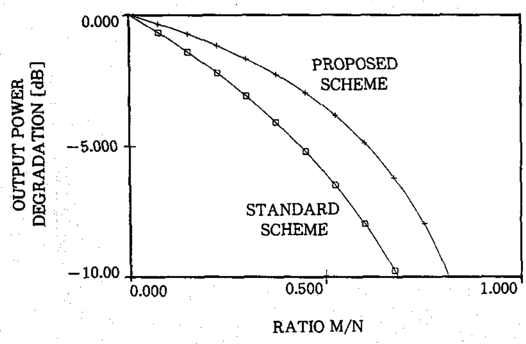


Fig. 5. The degradation of the output power versus the relative number of failed amplifiers (at $f/f_c = 1$).

about 1 dB higher than that of the standard combiner when one fifth of the amplifiers (M/N=0.2) fail completely from the normal states, or about 2.5 dB higher when half of the amplifiers (M/N=0.5) fail. And, with the proposed scheme, the maximum output power improvement is about 6 dB when the value of N is large and the ratio M/N approximates to one. The cause of the above limited improvement can be explained by the output port mismatching, which will be discussed in the next paragraph, resulted from the failure of M amplifiers. That is, the characteristic impedances of the TLs, not DTLs, cannot be varied from the value $\sqrt{N}Z_{01}$ to $\sqrt{N-M}Z_{01}$ due to the fixed structure of the combiner. It yields

$$Z'_{out}(w_c) = \left(\frac{NR_o}{N-M}\right)$$

at a center frequency, and so the output return loss can be easily presented as

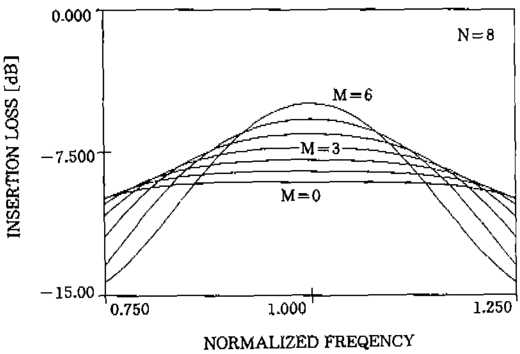
$$|S_{oo}|^2 = 10\log\left(\frac{M}{2N-M}\right)^2 \tag{26}$$

And numerical quantities for additive insertion losses which are resulted from the degradation of the output return loss are presented in Table 1.

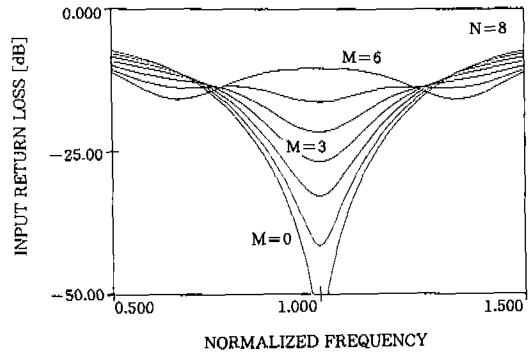
Table 1. The additive insertion loss resulted from the degradation of the output return loss versus the ratio M/N.

Ratio M/N	Output Return Loss [dB]	Additive Insertion Loss [dB]
0.0	Match	0.00
0.1	−25.58	0.01
0.2	−19.09	0.05
0.3	−15.07	0.14
0.4	−12.04	0.28
0.5	−9.54	0.51
0.6	−7.36	0.88
0.7	−5.38	1.49
0.8	−3.52	2.55
0.9	−1.74	4.81

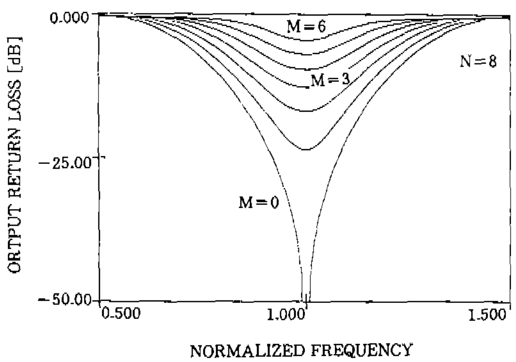
Up to this point, the analysis for the available application of the proposed scheme has been performed under the assumption that each of the working amplifiers is linear. So, we are confronted with the same problem as mentioned in [15]. If each of the working amplifiers is nonlinear, the "load-pull effect" due to



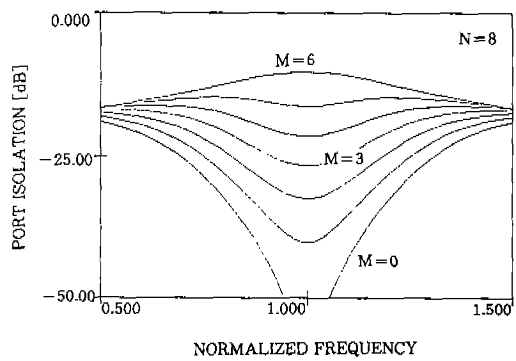
(a) The insertion loss versus normalized frequencies for the failed number M.



(b) The input return loss versus normalized frequencies for the failed number M.



(c) The output return loss versus normalized frequencies for the failed number M.



(d) The port isolation versus normalized frequencies for the failed number M.

Fig. 6. Simulation results for all the items measured from the proposed combiner with an eight-way configuration.

the variation of the power matching point could reduce the available power from the working amplifiers. Its effect could result in an additional degradation in eq. (24), but is considered to be negligible up to the point where half of the amplifiers fail.

To better understand the output responses of the proposed combiner for the variations of the failed number M and normalized frequency, simulation results for all the items which can be measured from it with an eight-way configuration are given in Fig. 6. Referring to Fig. 6 (a), it shows that the insertion loss decreases according to the variations of M over a fifty percent bandwidth and also it can be known that an available bandwidth is about twenty percent in an application improving the graceful degradation performance with the proposed scheme. Similarly, Fig. 6 (b)-(d) show the performance variations of the input and output return loss, and the port isolation, respectively, relating to the variations of M over a hundred percent bandwidth. They show that the simulated performances of Fig. 6 (b) and (d) are less sensitive than those of Fig. 6 (a) and (c) for the variations of M, as a whole. These may be analyzed as the facts that the performances of Fig. 6 (a) and (c) are mainly influenced by physically fixed characteristic impedance of remained TLs although failed M amplifiers or sections are separated from the combiner, and those of Fig. 6 (b) and (d) are mainly influenced by the internal resistors of the combiner.

IV. CONCLUSION

A new N-way hybrid power combiner which is configured with two dummy transmission lines realized in different characteristic impedances in each section and doesn't need external isolators for port isolation and matching, has been presented to improve the graceful degradation performance. A theoretical analysis on the proposed scheme has been made to confirm the proper function of a power combiner. And two fundamental conditions have been also derived from the analysis for perfect port isolation and matching at a center frequency. Under these two fundamental conditions, four circuit parameters, which are closely related to each other, have been optimized within about fifty percent bandwidth through the simulation.

When any M amplifiers among N identical amplifiers are suffering the failure modes in a power combining circuit or system, the graceful degradation performance has been improved by simultaneously operating two shorting devices which separate a transmission line and an internal resistor in every failed section from the combiner. The output power improvement from the graceful degradation of the proposed combiner was about 1 dB higher than that of a standard combiner when one fifth of the amplifiers fail, or about 2.5 dB higher when half of the amplifiers fail completely. The maximum output power improvement which can be obtained with this scheme was 6 dB when the value of N is large and the ratio M/N approximates to one.

As a conclusion, the proposed hybrid power combiner in this paper would be especially useful for a power combining circuit or system whose output power can be detected and monitored to prevent the output power from the graceful degradation when one or more amplifiers fail. And its scheme could be also modified to the multi-stage scheme in order to bring forth much wider bandwidth.

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