Broadband Decoupling and Matching of a Superdirective Two-Port Antenna Array

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***Abstract*—Decoupling and matching networks may be used to improve the performance of compact antenna arrays where mutual radiator coupling has caused a degradation of the diversity capabilities. A popular network consists of a 180° rat-race directional coupler, which decouples the antenna ports, followed by impedance matching networks at each port. Researchers, however, usually neglect the presence of losses both within the antenna array and the decoupling and matching network. For this reason, we have built various narrowband and broadband matching networks and compare their performances with the help of calibrated far-field measurement data.**

***Index Terms*—Antenna array mutual coupling, antenna diversity, mobile communication.**

I. Introduction

MUTUAL radiator coupling is known to degrade the radiation efficiency and the diversity performance of compact antenna arrays where radiators are closely spaced [1]–[5]. Decoupling and matching networks (DMNs) provide a way to decorrelate the antenna ports by ideally achieving 100% matching efficiency for all possible antenna excitations [5]–[7]. There are two major problems associated with DMNs: first, due to the high power mismatch involved for superdirective excitations, DMNs are usually very narrowband. Second, although a DMN can be manufactured to provide excellent matching and isolation at its input ports, ohmic power losses within the network are significant [5], [8], [9]. In addition, there will be considerable losses within the antenna array itself.

In contrast with previous work on decoupling and matching networks [6], [7], [10]–[14], the present letter takes ohmic losses into account. The DMN performance is evaluated in terms of its efficiency and its diversity gain for the particular example of a symmetric two-port antenna array (Fig. 1). The DMN design shown on the right-hand side in Fig. 1 is based on the 180° rat-race directional coupler and was chosen for several reasons [5], [10], [11]. First, it is straightforward to manufacture. Second, it decouples the radiators without performing any power matching actions. Matching can be implemented independent of decoupling and we therefore propose the use of multistage matching networks to broaden the bandwidth over previous designs. A third advantage is based on past experience, which has shown that excellent decoupling is achieved over a wide frequency range. This property ensures that there will in fact not be any noteworthy residual coupling to worry about during matching network design. A fourth point is that the basic concept can be extended to asymmetric two-port arrays and to arrays with more than two elements [5], [12]–[14]. Of course, there are disadvantages as well, which become evident towards the end of this letter.

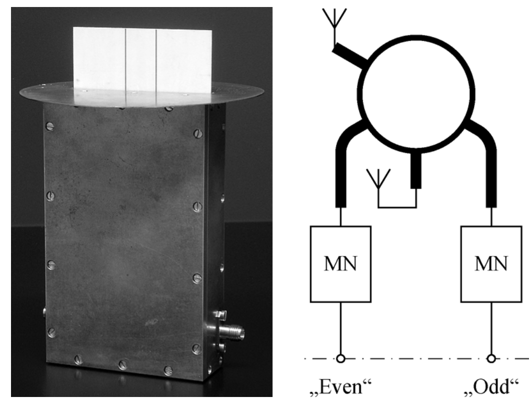

Fig. 1. The left-hand side shows a photograph of the antenna array and the brass housing containing the decoupling and matching networks. The principle of decoupling and matching is sketched on the right-hand side. $\mathrm{MN} = \mathrm{matching\ network}$.

We manufactured five different network versions for the same $\lambda/10$-spaced two-port monopole antenna array shown in Fig. 1. The center frequency is 2.45 GHz. Radiators and networks are printed on 55 mm × 120 mm microwave substrate (Rogers RO3203, $\epsilon_r = 3.02$, $\tan\delta = 0.0016$), and are easily replaced in the brass housing. Our networks under test are shown in Fig. 2 and will be referred to with their corresponding letter: (A) coupled radiators, (B) decoupled radiators without matching, and (C) decoupling with single-stub matching. Network (D) aims at providing better than 10 dB return loss over a broad bandwidth using a multisection matching network. Network (E) was designed to provide a constant improvement of matching over a bandwidth of 100 MHz. We present results for the modal efficiencies [5] and the prospected diversity gain [15] of these networks based on calibrated far-field measurement data. Therefore, our results include all types of power losses: mismatch at the inputs, losses within the network, and losses within the antenna array.

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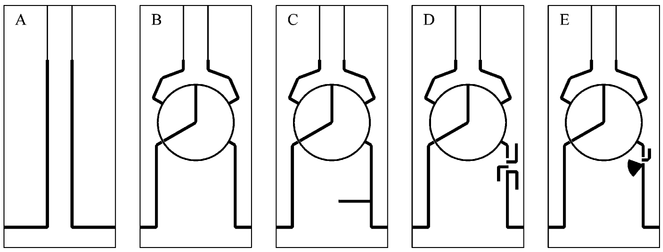

Fig. 2. The various antenna networks investigated here. (A) No network. (B) Decoupling only. (C) Decoupling and single-stub matching. (D) 10-dB broadband matching. (E) 100-MHz broadband matching. The dimensions of the printed circuit board are 55 mm × 120 mm. The different networks are referred to with their corresponding letter in the text.

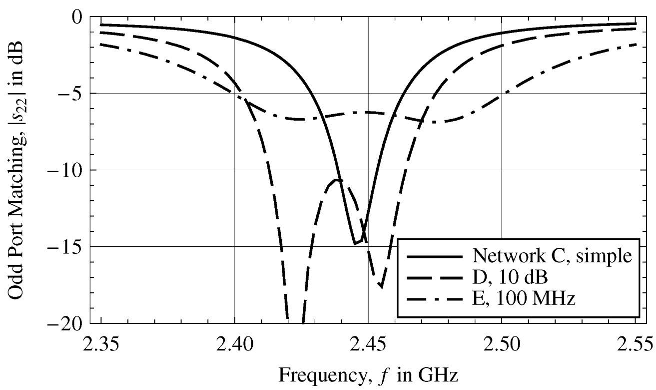

Fig. 3. Reflection coefficient at the odd port for three different matching networks.

II. Matching Network Design

An advantageous property of the 180° rat-race ring based decoupling network is that it works for *any* symmetric two-port antenna array [5]. So the decoupling part of the network can be designed straight away without any measurements. We call the input port, which excites both radiators equal in phase, the "even" port. Similarly, we call the other port, which excites both radiators 180° out of phase, the "odd" port.

Measurements of the scattering parameters of the decoupled antenna array revealed an isolation better than 25 dB between the input ports from 2.4 to 2.5 GHz. At the even port, the return loss was better than 8 dB (matching efficiency 84%) over the same frequency range. The odd port, however, displayed a return loss around 1.3 dB, which corresponds to a matching efficiency of 25%. In an attempt to improve odd port matching we designed three different matching networks.

Matching network "C" (Fig. 2) is the classical narrowband single-stub tuner [16]. The measured input reflection coefficient is shown in Fig. 3 where the 10 dB (matching efficiency 90%) bandwidth is 15 MHz.

Matching network "D" was designed by means of the Simplified Real Frequency Technique (SRFT) to achieve a broader matching bandwidth with 10-dB return loss [17], [18]. The advantages of the technique can be summarized as follows: there is no need for an explicit expression or a circuit realization of the load, measured impedance data can be used. Also there is no need to select any network topology, which is the natural consequence of the matching process. It is almost impossible

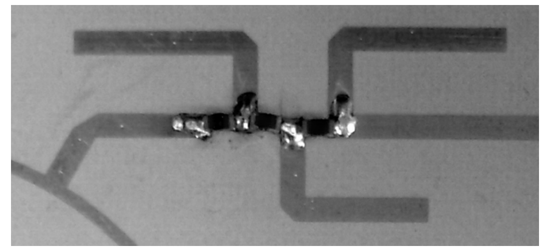

Fig. 4. Close-up of the fabricated odd-port 10-dB broadband matching network "D" shown in Fig. 2.

to estimate the gain-bandwidth limitations of real antenna impedances via analytical theories [19]–[21]. These are applicable only to simple *RC/RLC* types of loads. Using SRFT, however, it is possible to design broadband matching networks converging to the upper flat transducer power gain limit based on measured antenna impedance data. The matching network was designed using lumped components, resulting in a sixth-order low-pass ladder structure. Inductors were replaced by available standard values from muRata's LQW18A high-Q series [22] whose resonant frequencies were all above 4.9 GHz. Since the capacitor values obtained after post-optimization are not available as standard values, they were replaced by shunt open stubs implemented in microstrip. A close-up of the final manufactured matching network is shown in Fig. 4. Measurements show that matching better 10 dB was achieved over a bandwidth of 51 MHz—a more than threefold improvement over the single-stub tuner.

The goal of the third matching network "E" was to provide an improvement in matching over 100-MHz bandwidth from 2.4 to 2.5 GHz. This time, the design was done with the aid of the nonlinear optimization features provided by the ADS simulation software [23]. Blind optimization is successful if only few components are involved. In this case, two series inductors (chip inductors) and two shunt capacitors (shunt open stubs) were used. Scattering parameter measurements revealed matching better 5 dB (matching efficiency 68%) over the desired frequency range.

III. Far-Field Measurements

Although scattering parameter measurements tell how much power is accepted by the antenna array, only far-field measurements can reveal how much power is really radiated.

Calibrated far-field measurements provide us with the complex far-field pattern $\vec{F}(\phi,\theta)$ relative to the ideal (i.e., lossless and perfectly matched) isotropic radiator [24]. The vector $\vec{F}(\phi,\theta)$ contains two orthogonal polarizations and is dependent on azimuth ϕ and elevation θ. The total efficiency η including all types of power losses is then evaluated using

$$\eta = \frac{1}{4\pi} \oint |\vec{F}(\phi,\theta)|^2 \cos\theta \, \mathrm{d}\phi \, \mathrm{d}\theta. \quad (1)$$

We may even compute the radiation matrix $\tilde{H}$[5], [24]. Matrix element $\tilde{H}_{ij}$ is then given by

$$\tilde{H}_{ij} = \frac{1}{4\pi} \oint \vec{F}_i^H(\phi,\theta)\vec{F}_j(\phi,\theta) \cos\theta \, \mathrm{d}\phi \, \mathrm{d}\theta \quad (2)$$

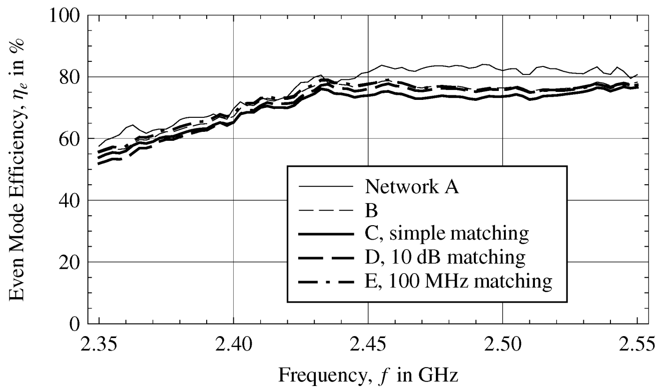

Fig. 5. Even mode efficiency as determined from measured radiation patterns. Thin lines show the unmatched performance. Thick lines compare the matching networks.

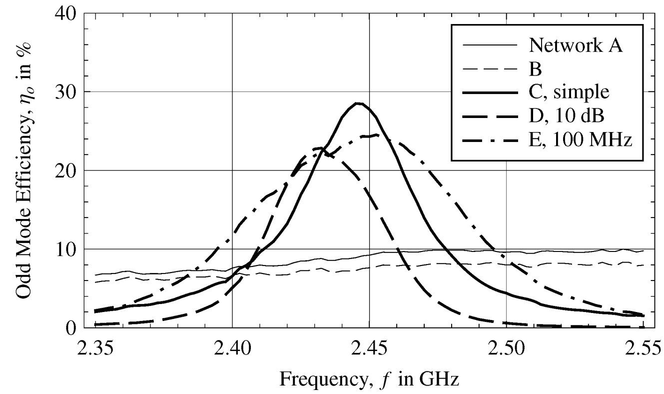

Fig. 6. Odd mode efficiency as determined from measured radiation patterns. Thin lines show the unmatched performance. Thick lines compare the matching networks.

where the superscript ^{H} denotes the Hermitian (conjugate) transpose and $\vec{F}_i$ is the far-field pattern associated with the ith array port. As discussed in [5], the eigenvalues of $\tilde{H}$ can be interpreted as the radiation efficiencies of the degrees of freedom available in an antenna array.

Given the discrete far-field data of each network in Fig. 2, Simpson's rule was used to numerically evaluate above integrals and to obtain an estimate of the radiation matrix $\tilde{H}$.

A. *Modal Efficiencies*

The larger of the two eigenvalues of $\tilde{H}$ is the efficiency η_e of the even mode of the antenna array and is plotted in Fig. 5. As expected, the graphs of the various networks show similar behavior since no matching was performed on the even mode.

The smaller eigenvalue, i.e., the odd mode efficiency η_o, is plotted in Fig. 6. Thin lines show the efficiency of the direct network "A" (Fig. 2, solid line) and the decoupling network without matching "B" (dashed line), respectively. In contrast to the matching efficiency of 25% mentioned in Section II, the actual radiation efficiency including all losses is less than 10%—a dramatic difference. The additional insertion loss caused by the directional coupler is about 0.3 dB. The graphs, however, suggest a much larger loss of about 1 dB. Since the far-field patterns associated with the ports of the direct network and the decoupled network are very different in shape, one explanation for this discrepancy are possible errors that arise during measurement, such as axis alignment errors of the antenna under test, or spurious reflection at the positioning hardware. Another possible source of error is the discretization of the far-field patterns. If undersampling occurs then numeric evaluation of above integrals will yield incorrect results. We have yet to verify whether the 3° sampling resolution used in azimuth and elevation is sufficiently dense for our purposes.

Thick graphs in Fig. 6 represent the efficiency performance of our matching networks. The single-stub matching network "C" is plotted as the solid curve and shows a more than 2.5-fold improvement at the center frequency. The bandwidth over which this simple network provides an improvement over the antenna array without network is almost 80 MHz.

The efficiency of the 10-dB broadband matching network "D," which is plotted as the thick dashed curve in Fig. 6, turned out as a disappointment. Contrary to its broad matching performance, its power efficiency bandwidth is narrower than for the single-stub case. This is presumably due to the large number of reactive elements involved and due to the attempt to achieve relatively good matching. Both facts increase the amount of energy stored within the matching network and in consequence lead to higher losses.

With matching network "E," where the design focus was on the 100 MHz bandwidth rather than on the matching efficiency, we were actually able to increase the bandwidth over the single-stub network. The dash-dot line in Fig. 6 reveals a bandwidth of about 110 MHz where the matching network outperforms the antenna array without network. Its peak efficiency is only little less (about 86%) than the efficiency of the single-stub implementation.

B. *Diversity Performance*

Knowing the eigenvalues of $\tilde{H}$ we may estimate the diversity performance of maximal-ratio combining in a rich multipath environment with uniform angular spread in both azimuth and elevation [3], [4], [15]. Plots of the diversity gain G_ϱ at the 1% probability level are given in Fig. 7. All matching networks yield a peak diversity gain of around 8 dB, which is an improvement of about 2 dB over the antenna array without network. The diversity of an ideal (i.e., lossless, perfectly matched, and uncoupled) two-port antenna array is indicated in the figure with $G_{\varrho,2}$ at 11.7 dB. As expected from the efficiency considerations of the last subsection, network "E" shows the broadest bandwidth.

IV. Conclusion

We presented three different antenna decoupling and matching networks based on a 180° rat-race directional coupler. Calibrated far-field measurements were used to estimate the true performance of these networks in terms of efficiency as well as estimated diversity performance. The results show

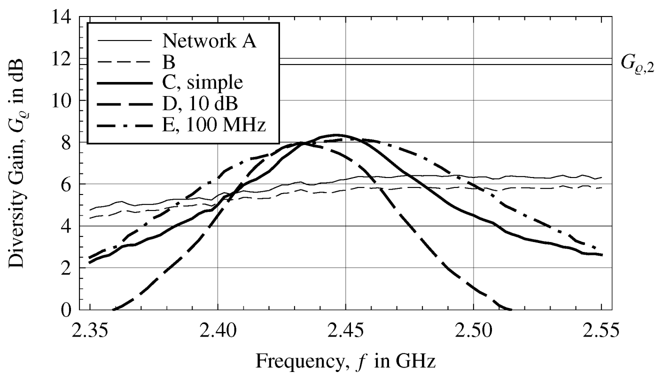

Fig. 7. Diversity gains G_ϱ of the various matching networks at the 1% probability level. $G_{\varrho,2}$ indicates the diversity gain of an ideal two-element array.

that good antenna port matching is by no means a reliable indicator for the efficient operation of the antenna array. Far-field measurements are the only way to practically capture ohmic antenna array and network losses, which dominate the performance at small radiator spacings due to superdirective effects. We demonstrated that broadband matching is possible with few components with little loss of efficiency.

Matching networks implemented at the input ports of the directional coupler improve power transfer not only to the antennas but also to the losses within the directional coupler. This fact is the prominent weakness of the DMNs presented and imposes an inherent limit on the efficiency of the network. The performance may be optimized by keeping connecting transmission lines as short as possible so that the insertion loss between radiators and matching networks is minimized.

Alternative designs in [6], [8], and [9] are not based on directional couplers and may therefore perform better in terms of power losses. Since we are not aware of any detailed comparison between the different network types, a careful and individual analysis of network losses is generally recommended for future compact antenna and DMN designs.

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REFERENCES

[1] J. N. Pierce and S. Stein, "Multiple diversity with nonindependent fading," *Proce. IRE*, vol. 48, no. 1, pp. 89–104, Jan. 1960.

[2] R. G. Vaughan and J. Bach Andersen, "Antenna diversity in mobile communications," *IEEE Trans. Veh. Technol.*, vol. VT36, pp. 149–172, Nov. 1987.

[3] O. Nørklit, P. D. Teal, and R. G. Vaughan, "Measurement and evaluation of multiantenna handsets in indoor mobile communication," *IEEE Trans. Antennas Propag.*, vol. 49, no. 3, pp. 429–437, Mar. 2001.

[4] J. W. Wallace and M. A. Jensen, "Mutual coupling in MIMO wireless systems: A rigorous network theory analysis," *IEEE Trans. Wireless Commun.*, vol. 3, no. 4, pp. 1317–1325, Jul. 2004.

[5] C. Volmer, J. Weber, R. Stephan, K. Blau, and M. A. Hein, "An eigen-analysis of compact antenna arrays and its application to port decoupling," *IEEE Trans. Antennas Propag.*, vol. 56, no. 2, pp. 360–370, Feb. 2008.

[6] H. J. Chaloupka and X. Wang, "Novel approach for diversity and MIMO antennas at small mobile platforms," in *Proc. 15th IEEE Int. Symp. Person., Indoor and Mobile Radio Commun. (PIMRC'04)*, Barcelona, Spain, Sep. 2004, vol. 1, pp. 637–642.

[7] X. Wang, "Kompakte Mehrtorantennen für die Adaptive Keulenformung," Ph.D., Bergische Universität Wuppertal, Wuppertal, Germany, 2004.

[8] J. Weber, C. Volmer, K. Blau, R. Stephan, and M. A. Hein, "Miniaturized antenna arrays using decoupling networks with realistic elements," *IEEE Trans. Microw. Theory Tech.*, vol. 54, no. 6, pp. 2733–2740, Jun. 2006.

[9] J. Weber, C. Volmer, R. Stephan, and M. A. Hein, "Eigenmode decoupling of miniaturised diversity antennas using compact quasi-lumped networks," in *Proc. Loughborough Antennas Prop. Conf. (LAPC 2008)*, Loughborough, U.K., Mar. 2008.

[10] S. Dossche, J. Romeu, and S. Blanch, "Decoupling and decorrelation of two closely spaced monopoles for optimum MIMO capacity," in *Proc. 1st Eur. Conf. Antennas Propag. (EUCAP'06)*, Nice, France, Nov. 2006.

[11] T.-I. Lee and Y. Wang, "Mode-based beamforming with closely spaced antennas," in *Proc. IEEE Int. Symp. Microw. Theory Tech. (MTT-S 2007)*, Jun. 2007, pp. 1723–1726.

[12] V. Riech, "Überlegungen zu entkopplungs- und anpassungsnetzwerken für kleine antennengruppen," *Archiv für Elektronik und Übertragungstechnik*, vol. 30, no. 5, pp. 204–208, May 1976.

[13] W. P. Geren, C. R. Curry, and J. Andersen, "A practical technique for designing multiport coupling networks," *IEEE Trans. Microw. Theory Tech.*, vol. MTT44, no. 3, pp. 364–371, Mar. 1996.

[14] S. Dossche, S. Blanch, and J. Romeu, "Decorrelation of a closely spaced four element antenna array," in *IEEE Antennas Propag. Soc. Int. Symp. Dig.*, 2005, vol. 1B, pp. 803–806.

[15] C. Volmer, J. Weber, R. Stephan, and M. A. Hein, "A descriptive model for analyzing the diversity performance of compact antenna arrays," *IEEE Trans. Antennas Propag.*, accepted for publication.

[16] D. M. Pozar, *Microwave Engineering*, 2nd ed. New York: Wiley, 1998.

[17] B. S. Yarman and H. J. Carlin, "A simplified "real frequency" technique applied to broad-band multistage microwave amplifiers," *IEEE Trans. Microw. Theory Tech.*, vol. MTT82, pp. 2216–2222, Dec. 1982.

[18] M. Şengül, J. Trabert, K. Blau, B. S. Yarman, and M. A. Hein, "Power transfer networks at RF frequencies – New design procedures with implementation roadmap," in *Proc. IEEE Int. Symp. Circuits Syst. (ISCAS'06)*, Island of Kos, Greece, May 2006, pp. 1768–1771.

[19] H. W. Bode, *Network Analysis and Feedback Amplifier Design*. New York: Van Nostrand, 1945.

[20] R. M. Fano, "Theoretical limitations on the broadband matching of arbitrary impedances," *MIT Tech. Rep.*, vol. 41, Jan. 1948.

[21] D. C. Youla, "A new theory of broadband matching," *IEEE Trans. Circuit Theory*, vol. CT11, pp. 30–50, Mar. 1964.

[22] Murata Chip Inductors Murata Manufacturing Co., Ltd., Nagaokakyo-shi, Kyoto, Japan [Online]. Available: http://www.murata.com

[23] Agilent ADS Agilent Technologies, Palo Alto, CA [Online]. Available: http://eesof.tm.agilent.com

[24] A. Stjernman, "Relationship between radiation pattern correlation and scattering matrix of lossless and lossy antennas," *Electron. Lett.*, vol. 41, pp. 678–680, Jun. 2005.