Characterization of the Branch-line and Rat-Race ideal hybrids through their merit parameters

Rodríguez, Sebastián. Fajardo, Arturo. Paez, Carlos
Department of Electronics
Pontificia Universidad Javeriana (PUJ)
Bogotá, Colombia
{ jrodriguezp, fajardoa, paez.carlos }@javeriana.edu.co

***Abstract*— This paper presents a conventional analysis for narrowband operation using odd-even technique for the ideal structures of the Branch-line and Rat-Race Hybrids. Additionally, it presents the simulated results obtained whit Ansoft Designer® platform, using ideal transmission lines in order to characterize the hybrids through their merit parameters.**

Keywords- Microstrip couplers, Microstrip Circuits, Microstrip bidirectional Couplers.

I. INTRODUCTION

Most of the electronic applications of the modern telecommunications are focused in the capacity of using the wireless environment as a transparent channel of communications. The reason for the use of these technologies is the transparency for the user, portability and ubiquity. In general, every one of these communication systems has receivers and transmitters, that because the high frequencies and complexity of the modulation systems, create a need of development of circuits that allow the simplification of the implementation of all these systems. The circuits used are composed of digital circuits, mixed-signal circuits and circuits for RF (Radio Frequency). The improvement in manufacturing processes, has reduced significantly the size of digital circuits, while the sizes of the mixed-signal circuits and RF circuits have not decreased significantly [1]. Therefore in recent years, radio frequency (RF) circuits with compact size are in urgent demand; the portable devices especially require components with features of compact size and less cost [2]. Consequently, size reduction plays an essential and crucial role for the development of RF components. In planar microwave integrated circuits, the 180º and the 90º hybrids are usually implemented using Rat-race and Branch-line couplers [3]; However, the conventional implementation of these hybrid couplers occupies too much space, in order to reduce the size and volume of the hybrid couplers several techniques have been previously reported [2, 4-13]. As part of the research project "Design, simulation, implementation and evaluation of a hybrid of 180° based on fractal geometry" led by the Telecommunications Research Group (SISCOM) of the Pontificia Universidad Javeriana, it was undertook a systematic study of the merit parameters of Branch-line and Rat-Race ideal hybrids in order to analyze the cost associated with size reduction in other performance parameters. Recently works have appeared comparing different methods of miniaturization [13, 14], however, only compare some parameters of merit.

As a partial result of this study, it is proposed in this paper a set of performance parameters as merit parameters in order to compare the miniaturized hybrids in a straight way. The first part of this document shows the general analysis for narrowband operation using odd-even technique for the ideal structures of the Branch-line and Rat-Race Hybrids topology. The second part shows the set of proposed merit parameters. The third part presents the merit parameters of the ideal Branch-line and Rat-Race Hybrids couplers obtained by simulation whit Ansoft Designer® platform and finally, the last part presents the conclusions found by the researchers.

II. ANALISYS OF THE HYBRIDS

A. Description of the Hybrids

A 90° hybrid or quadrature hybrid is a circuit that takes the input signal, and depending of the output, shifts its phase ±90°. Its traditional implementation is the Branch-Line, which is composes of four transmission lines of length λ/4, as shown in Fig. 1a. The equation (1) describes its scattering matrix. The 180° hybrid is a circuit that takes the input signal of the ports 1 and 4, and depending of the output, add or subtract them. Its traditional form is the Rat-race, shown in the Fig. 1b. The equation (2) describes the scattering matrix of the hybrid.

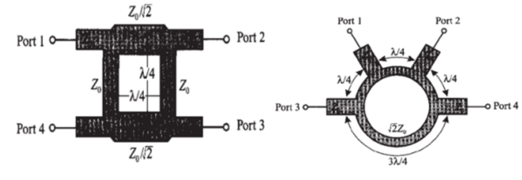

Fig. 1 Branch-line hybrid [3]

$$[S] = \frac{-1}{\sqrt{2}}\begin{bmatrix} 0 & j & 1 & 0 \\ j & 0 & 0 & 1 \\ 1 & 0 & 0 & j \\ 0 & 1 & j & 0 \end{bmatrix} \quad (1)$$

$$[S] = \frac{-j}{\sqrt{2}}\begin{bmatrix} 0 & 1 & 1 & 0 \\ 1 & 0 & 0 & -1 \\ 1 & 0 & 0 & 1 \\ 0 & -1 & 1 & 0 \end{bmatrix} \quad (2)$$

B. Hybrid analysis for narrowband operation using odd-even technique

The analysis of these circuits is made using the analysis of the even and odd modes [3, 15], in which an incident probe voltage is used in different input ports and analyzed the different values of the scattering parameters for this input conditions. For the Branch-line in order to make the analysis, it is supposed the incident voltage in the port 1 as V1=Vs and in the port 4 as V4=0, the circuit is divided in two different circuits, the even mode circuit and the odd mode circuit, in which is supposed the incident voltage in the port 1 as Ve1=Vs/2 and Vo1=Vs/2 and the incident voltage in the port 4 as Ve1=Vs/2 and Vo1=-Vs/2, for the even and odd mode respectably. The Fig. 2, shows the equivalent circuit of the even mode of the half circuit of the quadrature hybrid. To analyze the open ended λ/8 transmission, the impedance of this transmission line is solved in (3), and used to determine its ABCD matrix (4). The ABCD matrix of the series transmission line be found (5). Using (3), (4) and (5) it is calculated in (6) the total ABCD matrix. In a Similar way, the analysis is done for the odd mode circuit illustrated en la Fig. 3. Using (7), (8) and (5) it is calculated in (9) the total ABCD. Once the even and odd mode matrices are obtained, they are used to obtain the reflection and transmission coefficients for the even and odd modes. With these values the voltages in the ports can be found as (14),(15),(16)and(17). Finally solving (14), (15), (16) and (17) it is obtained the first row of the scattering matrix. Thanks to the symmetry of the circuit, the other scattering parameters can be found.

$$Z = \eta_0 \frac{Z_L + j\eta_0 \tan(\beta d)}{\eta_0 + jZ_L \tan(\beta d)} = -j\eta_0 \quad (3)$$

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}_{M_e} = \begin{bmatrix} 1 & 0 \\ j/\eta_0 & 1 \end{bmatrix} \quad (4)$$

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}_L = \begin{bmatrix} 0 & j\eta_0\sqrt{2}^{-1} \\ j\eta_0^{-1}\sqrt{2} & 0 \end{bmatrix} \quad (5)$$

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}_e = \begin{bmatrix} -1/\sqrt{2} & j\eta_0/\sqrt{2} \\ j/(\eta_0\sqrt{2}) & -1/\sqrt{2} \end{bmatrix} \quad (6)$$

$$Z = \eta_0 \frac{Z_L + j\eta_0 \tan(\beta d)}{\eta_0 + jZ_L \tan(\beta d)} = j\eta_0 \quad (7)$$

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}_{M_o} = \begin{bmatrix} 1 & 0 \\ -j/\eta_0 & 1 \end{bmatrix} \quad (8)$$

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}_o = \begin{bmatrix} 1/\sqrt{2} & j\eta_0/\sqrt{2} \\ j/(\eta_0\sqrt{2}) & 1/\sqrt{2} \end{bmatrix} \quad (9)$$

$$\Gamma_e = \frac{A + B/\eta_0 - \eta_0 C - D}{A + B/\eta_0 + \eta_0 C + D} = \frac{-1/\sqrt{2} + j/\sqrt{2} - j/\sqrt{2} + 1/\sqrt{2}}{-1/\sqrt{2} + j/\sqrt{2} + j/\sqrt{2} - 1/\sqrt{2}} = 0 \quad (10)$$

$$\mathrm{T}_e = \frac{2}{A + B/\eta_0 + \eta_0 C + D} = \frac{2}{-1/\sqrt{2} + j/\sqrt{2} + j/\sqrt{2} - 1/\sqrt{2}} = \frac{-1}{\sqrt{2}} - \frac{j}{\sqrt{2}} \quad (11)$$

$$\Gamma_o = \frac{A + B/\eta_0 - \eta_0 C - D}{A + B/\eta_0 + \eta_0 C + D} = \frac{1/\sqrt{2} + j/\sqrt{2} - j/\sqrt{2} - 1/\sqrt{2}}{1/\sqrt{2} + j/\sqrt{2} + j/\sqrt{2} + 1/\sqrt{2}} = 0 \quad (12)$$

$$\mathrm{T}_o = \frac{2}{A + B/\eta_0 + \eta_0 C + D} = \frac{2}{1/\sqrt{2} + j/\sqrt{2} + j/\sqrt{2} + 1/\sqrt{2}} = \frac{1}{\sqrt{2}} - \frac{j}{\sqrt{2}} \quad (13)$$

$$V_1 = \frac{V_s}{2}(\Gamma_e + \Gamma_o) = 0 \quad (14)$$

$$V_2 = \frac{V_s}{2}(\mathrm{T}_e + \mathrm{T}_0) = \frac{V_s}{2}\left(\frac{-1}{\sqrt{2}} - \frac{j}{\sqrt{2}} + \frac{1}{\sqrt{2}} - \frac{j}{\sqrt{2}}\right) = -V_s\frac{j}{\sqrt{2}} \quad (15)$$

$$V_3 = \frac{V_s}{2}(\mathrm{T}_e - \mathrm{T}_o) = \frac{V_s}{2}\left(\frac{-1}{\sqrt{2}} - \frac{j}{\sqrt{2}} - \frac{1}{\sqrt{2}} + \frac{j}{\sqrt{2}}\right) = -V_s\frac{1}{\sqrt{2}} \quad (16)$$

$$V_4 = \frac{V_s}{2}(\Gamma_e - \Gamma_o) = \frac{V_s}{2}(0) = 0 \quad (17)$$

$$V_1 = s_{11}V_s = 0 \rightarrow s_{11} = 0 \quad (18)$$

$$V_2 = s_{21}V_s = -V_s\frac{j}{\sqrt{2}} \rightarrow s_{21} = -\frac{j}{\sqrt{2}} \quad (19)$$

$$V_3 = s_{31}V_s = -V_s\frac{1}{\sqrt{2}} \rightarrow s_{31} = -\frac{1}{\sqrt{2}} \quad (20)$$

$$V_4 = s_{41}V_s = 0 \rightarrow s_{41} = 0 \quad (21)$$

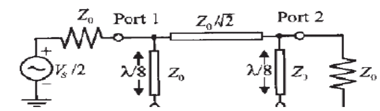

Fig. 2 Even mode of the 90° hybrid [16]

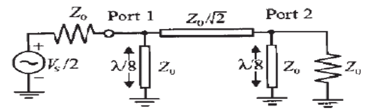

Fig. 3 Odd mode of the 90° hybrid [16]

For the Branch-line in order to make the analysis, Similar to the case of the 90° hybrid, we supposed an incident voltage in the port 1 as $V_1=V_s$ and in the port 3 as $V_2=0$, the circuit is divided in two different circuits, the even mode and odd mode circuit, and it is supposed the incident voltages in the port 1 as $V_{e1}=V_s/2$ and $V_{o1}=V_s/2$ and in the port 2 as $V_{e2}=Vs/2$ and $V_{o2}=-Vs/2$, for the even and odd mode respectably, then the same analysis is done supposing a the incident voltages in the ports 3 and 4. The model used in the even mode is shown in the Fig. 4 and the model used in the even mode is shown in the Fig. 5. The ABCD matrixes for the even mode and odd mode are calculated in (22) and (23). Once the even and odd mode matrices are obtained, they are used to obtain the reflection and transmission coefficients for the even and odd modes. Finally solving (24), (25), (26)and (27) it is obtained the first row of the scattering matrix.

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}_e = \begin{bmatrix} 1 & 0 \\ j/(\eta_0\sqrt{2}) & 1 \end{bmatrix} \begin{bmatrix} 0 & j\eta_0\sqrt{2} \\ j(\eta_0\sqrt{2})^{-1} & 0 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -j/(\eta_0\sqrt{2}) & 1 \end{bmatrix} = \begin{bmatrix} 1 & j\eta_0\sqrt{2} \\ j\sqrt{2}/\eta_0 & -1 \end{bmatrix} \quad (22)$$

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}_o = \begin{bmatrix} 1 & 0 \\ -j/(\eta_0\sqrt{2}) & 1 \end{bmatrix} \begin{bmatrix} 0 & j\eta_0\sqrt{2} \\ j(\eta_0\sqrt{2})^{-1} & 0 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ j/(\eta_0\sqrt{2}) & 1 \end{bmatrix} = \begin{bmatrix} -1 & j\eta_0\sqrt{2} \\ j\sqrt{2}/\eta_0 & 1 \end{bmatrix} \quad (23)$$

$$\Gamma_e = \frac{A + B/\eta_0 - \eta_0 C - D}{A + B/\eta_0 + \eta_0 C + D} = \frac{1 + j\sqrt{2} - j\sqrt{2} + 1}{1 + j\sqrt{2} + j\sqrt{2} - 1} = \frac{-j}{\sqrt{2}} \quad (24)$$

$$\mathrm{T}_e = \frac{2}{A + B/\eta_0 + \eta_0 C + D} = \frac{2}{1 + j\sqrt{2} + j\sqrt{2} - 1} = \frac{-j}{\sqrt{2}} \quad (25)$$

$$\Gamma_o = \frac{A + B/\eta_0 - \eta_0 C - D}{A + B/\eta_0 + \eta_0 C + D} = \frac{-1 + j\sqrt{2} - j\sqrt{2} - 1}{-1 + j\sqrt{2} + j\sqrt{2} + 1} = \frac{j}{\sqrt{2}} \quad (26)$$

$$\mathrm{T}_o = \frac{2}{A + B/\eta_0 + C + D} = \frac{2}{-1 + j\sqrt{2} + j\sqrt{2} + 1} = \frac{-j}{\sqrt{2}} \quad (27)$$

$$V_1 = V_s\left(\frac{1}{2}\frac{-j}{\sqrt{2}} + \frac{1}{2}\frac{j}{\sqrt{2}}\right) = 0 = s_{11}V_s \rightarrow s_{11} = 0 \quad (28)$$

$$V_2 = V_s\left(\frac{1}{2}\frac{-j}{\sqrt{2}} + \frac{1}{2}\frac{-j}{\sqrt{2}}\right) = \frac{-j}{\sqrt{2}}V_s = s_{21}V_s \rightarrow s_{21} = \frac{-j}{\sqrt{2}} \quad (29)$$

$$V_3 = V_s\left(\frac{1}{2}\frac{-j}{\sqrt{2}} - \frac{1}{2}\frac{j}{\sqrt{2}}\right) = \frac{-j}{\sqrt{2}}V_s = s_{31}V_s \rightarrow s_{31} = \frac{-j}{\sqrt{2}} \quad (30)$$

$$V_4 = V_s\left(\frac{1}{2}\frac{-j}{\sqrt{2}} - \frac{1}{2}\frac{-j}{\sqrt{2}}\right) = 0 = s_{41}V_s \rightarrow s_{41} = 0 \quad (31)$$

In the second case, the excitations are in the ports 2 and 4. The model used model used in the even and odd mode is shown in the Fig. 6. The ABCD matrixes for the even mode and odd mode are calculated in (32) and (33). Once the even and odd mode matrices are obtained, they are used to obtain the reflection and transmission coefficients for the even and odd modes. Finally solving and (34), (35), (36) y (37) it is obtained the first row of the scattering matrix. For the symmetry of the hybrid, we can deduce the others parameters.

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}_e = \begin{bmatrix} 1 & 0 \\ -j/(\eta_0\sqrt{2}) & 1 \end{bmatrix} \begin{bmatrix} 0 & j\eta_0\sqrt{2} \\ j(\eta_0\sqrt{2})^{-1} & 0 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ j/(\eta_0\sqrt{2}) & 1 \end{bmatrix} = \begin{bmatrix} -1 & j\eta_0\sqrt{2} \\ j\sqrt{2}/\eta_0 & 1 \end{bmatrix} \quad (32)$$

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}_o = \begin{bmatrix} 1 & 0 \\ j/(\eta_0\sqrt{2}) & 1 \end{bmatrix} \begin{bmatrix} 0 & j\eta_0\sqrt{2} \\ j(\eta_0\sqrt{2})^{-1} & 0 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -j/(\eta_0\sqrt{2}) & 1 \end{bmatrix} = \begin{bmatrix} 1 & j\eta_0\sqrt{2} \\ j\sqrt{2}/\eta_0 & -1 \end{bmatrix} \quad (33)$$

$$\Gamma_e = \frac{A + B/\eta_0 - \eta_0 C - D}{A + B/\eta_0 + \eta_0 C + D} = \frac{-1 + j\sqrt{2} - j\sqrt{2} - 1}{-1 + j\sqrt{2} + j\sqrt{2} + 1} = \frac{j}{\sqrt{2}} \quad (34)$$

$$T_e = \frac{2}{A + B/\eta_0 + \eta_0 C + D} = \frac{2}{-1 + j\sqrt{2} + j\sqrt{2} + 1} = \frac{-j}{\sqrt{2}} \quad (35)$$

$$\Gamma_o = \frac{A + B/\eta_0 - \eta_0 C - D}{A + B/\eta_0 + \eta_0 C + D} = \frac{1 + j\sqrt{2} - j\sqrt{2} + 1}{1 + j\sqrt{2} + j\sqrt{2} - 1} = \frac{-j}{\sqrt{2}} \quad (36)$$

$$T_o = \frac{2}{A + B/\eta_0 + \eta_0 C + D} = \frac{2}{1 + j\sqrt{2} + j\sqrt{2} - 1} = \frac{-j}{\sqrt{2}} \quad (37)$$

$$V_1 = V_s\left(\frac{1}{2}\frac{-j}{\sqrt{2}} - \frac{1}{2}\frac{-j}{\sqrt{2}}\right) = 0 = s_{14}V_s \rightarrow s_{14} = 0 \quad (38)$$

$$V_2 = V_s\left(\frac{1}{2}\frac{j}{\sqrt{2}} - \frac{1}{2}\frac{-j}{\sqrt{2}}\right) = \frac{j}{\sqrt{2}}V_s = s_{24}V_s \rightarrow s_{24} = \frac{j}{\sqrt{2}} \quad (39)$$

$$V_3 = V_s\left(\frac{1}{2}\frac{-j}{\sqrt{2}} + \frac{1}{2}\frac{-j}{\sqrt{2}}\right) = \frac{-j}{\sqrt{2}}V_s = s_{34}V_s \rightarrow s_{34} = \frac{-j}{\sqrt{2}} \quad (40)$$

$$V_4 = V_s\left(\frac{1}{2}\frac{j}{\sqrt{2}} + \frac{1}{2}\frac{-j}{\sqrt{2}}\right) = 0 = s_{44}V_s \rightarrow s_{44} = 0 \quad (41)$$

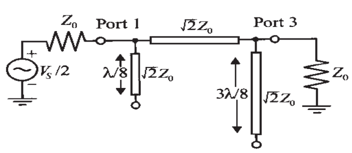

Fig. 4 Even mode for the excitation on the ports 1 and 2

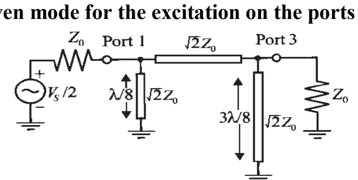

Fig. 5 Odd mode for the excitation on the ports 1 and 2

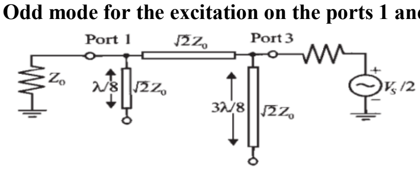

Fig. 6 Even mode for the excitation on the ports 3 and 4.

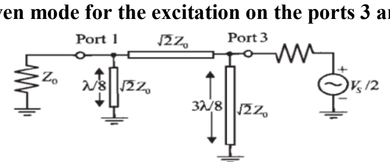

Fig. 7 Odd mode for the excitations on the ports 3 and 4.

III. PROPOSED MERIT PARAMETERS OF THE HYBRIDS

For the Branch-line hybrid has two symmetry axis, as shown in the Fig. 8, this symmetry produces a similar performance in all the ports. For the Rat-race hybrid has one symmetry axis, shown in the Fig. 8, so the behavior of the ports 1 and 2 (sigma) and of the ports 3 and 4 (delta) is the same. Furthermore, After a literature review about hybrids [2, 4-14, 17-25], it can be described by 19 parameters and by 40 parameters respectively as listed in table 1. In order to obtain a set of reference parameters, the conventional hybrids with ideal transmission lines were simulated using the software Ansoft Designer®. All of these parameter must be inferred from the behavior of scattering parameters, the merit parameters for the hybrids are listed in table 1 and the scattering parameters obtained by simulation are presented in the figures 9 and 10 for the ideal branch line coupler and in figures 11 and 12 for the ideal rat-race coupler.

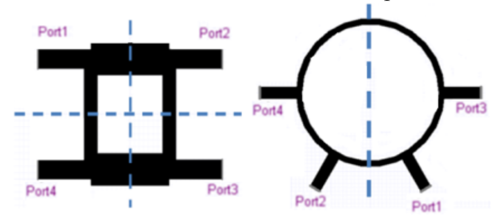

Fig. 8 Symmetry axis of the Branch-line and Rat-race hybrids

TABLE 1. MERIT PARAMETERS OF IDEAL BRANCH-LINE COUPLER (H_{90}) AND OF IDEAL RAT-RACE COUPLER (H_{180}) .

OPERATION AND DESIGN			
Parameter	***Value H_{90}***	***Value H_{180}***	
Design Frequency (F_d)	2.4GHz	2.4GHz	
Operation Frequency (F_o)	2.4GHz	2.4GHz	
Hybrid Bandwidth (HBW)	0.26GHz	0.68GHz	
Hybrid Fractional BW (HFBW)	10.83%	28.33%	
OUTPUT			
Parameter	***Value H_{90}***	***Value H_{180}***	
		Port Δ	***Port Σ***
Magnitude Imbalance (MI)	0dB	0dB	0dB
MI Bandwidth $(MIBW)_{<1.5dB}$	0.84GHz	0.88GHz	0.92GHz
MI Fractional BW (MIFBW)	35%	36,67%	38.33%
Phase Imbalance (PI)	90°	180°	0°
PI Bandwidth $(PIBW)_{<10°}$	1.02GHz	0.76GHz	0.88GHz
PI Fractional BW (PIFBW)	42.5%	31.67%	36.67%
INSERTION LOSS			
Parameter	***Value H_{90}***	***Value H_{180}***	
		Port Δ	***Port Σ***
Insertion Loss (IL_{2in})	-3.01dB	-3.01dB	-3.01dB
IL Bandwidth $(ILBW_{2in})_{<\pm 0.05dB}$	0.42GHz	0.68GHz	1.72
IL Fractional BW ($ILFBW_{2in}$)	17.5%	28.33%	71.67%
Insertion Loss (IL_{3in})	-3.01dB	-3.01dB	-3.01dB
IL Bandwidth $(ILBW_{3in})_{<\pm 0.05dB}$	1.08GHz	2.54GHz	0.74GHz
IL Fractional BW ($ILFBW_{3in}$)	45%	105.83%	30.83%
RETURN LOSS			
Parameter	***Value H_{90}***	***Value H_{180}***	
		Port ΔΔ	***Port ΣΣ***
Return Loss (RL)	-292.18	-317.84dB	-306.77dB
RL Bandwidth $(RLBW)_{>15dB}$	0.44GHz	1.34GHz	0.96GHz
RL Fractional BW (RLFBW)	18.33%	55.83%	40%
ISOLATION			
Parameter	***Value H_{90}***	***Value H_{180}***	
		Port ΣΔ	***Port ΔΣ***
Isolation (I)	-303.34	-319.14dB	-321.30dB
Isolation Bandwidth $(IBW)_{>20dB}$	0.26GHz	0.74GHz	0.68GHz
I Fractional BW (IFBW)	10.83%	30.83%	28.33%

IV. CONCLUSSIONS

In the development of circuits for wireless applications specially in the design of hybrid couplers, there is no a direct way to compare the performance different from the direct analysis of the behavior of the s-parameters, for this reason, in most of the studied literature, the authors do not make an in-depth comparison of their results to other implementations. The framework presented in this paper allows the in-depth comparison of different hybrid implementations, without the need of an exhaustive analysis of the behavior of the s-parameters, undependably of the specific context of the application of the hybrid.

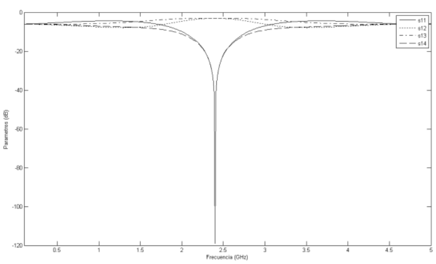

Fig. 9 S parameters for the ideal branch line

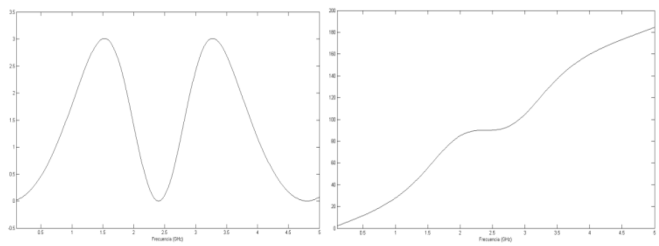

Fig. 10. Phase and Magnitude Imbalance branch line

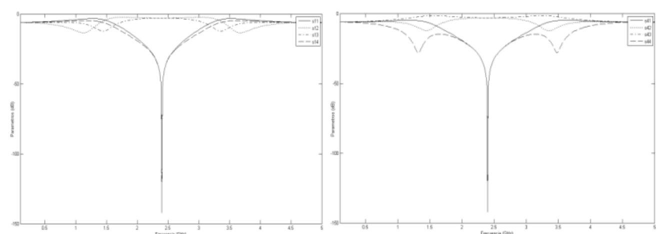

Fig. 11 Sigma and Delta S parameters for the ideal rat-race

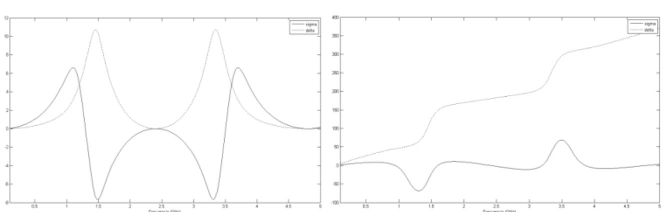

Fig. 12 Phase and Magnitude imbalance for the ideal rat-race

ACKNOWLEDGMENTS

The authors thank the Pontificia Universidad Javeriana, the Department of Electronics and the Electronics Laboratory for their support in the development of this article.

V. REFERENCES

[1] A. Grochowski, D. Bhattacharya, T. R. Viswanathan and K. Laker, "Integrated circuit testing for quality assurance in manufacturing: history, current status, and future trends," *Circuits and Systems II: Analog and Digital Signal Processing, IEEE Transactions on,* vol. 44, pp. 610-633, 1997.

[2] Ching-Wen Tang, Ming-Guang Chen and Janne-Wha Wu, "Realization of ultra-compact planar microstrip branch-line couplers with high-impedance open stubs," in *Microwave Symposium, 2007. IEEE/MTT-S International,* 2007, pp. 995-998.

[3] D. M. Pozar, *Microwave Engineering, 3nd Ed.* 2005.

[4] W. -. Chen and G. -. Wang, "Exact design of novel miniaturised fractal-shaped branch-line couplers using phase-equalising method," *Microwaves, Antennas & Propagation, IET,* vol. 2, pp. 773-780, 2008.

[5] K. -. M. Cheng and Fai-Leung Wong, "A novel approach to the design and implementation of dual-band compact planar 90° branch-line coupler," *Microwave Theory and Techniques, IEEE Transactions on,* vol. 52, pp. 2458-2463, 2004.

[6] Y. Chiou, C. Tsai, J. Wu and J. Kuo, "Miniaturization Design for Planar Hybrid Ring Couplers," *Art of Miniaturizing RF and Microwave Passive Components, 2008. IMWS 2008. IEEE MTT-S International Microwave Workshop Series on,* pp. 19-22, 2008.

[7] K. W. Eccleston and S. H. M. Ong, "Compact planar microstripline branch-line and rat-race couplers," *Microwave Theory and Techniques, IEEE Transactions on,* vol. 51, pp. 2119-2125, 2003.

[8] H. Ghali and T. A. Moselhy, "Miniaturized fractal rat-race, branch-line, and coupled-line hybrids," *Microwave Theory and Techniques, IEEE Transactions on,* vol. 52, pp. 2513-2520, 2004.

[9] Jen-Tsai Kuo, Yi-Chyun Chiou and Juo-Shiuan Wu, "Miniaturized Rat Race Coupler with Microstrip-to-CPW Broadside-Coupled Structure and Stepped-Impedance Sections," *Microwave Symposium, 2007. IEEE/MTT-S International,* pp. 169-172, 2007.

[10] Wen-Ling Chen and Guang-Ming Wang, "Design of Novel Miniaturized Fractal-Shaped Branch-Line Couplers," *Microwave Conference, 2007. APMC 2007. Asia-Pacific,* pp. 1-3, 2007.

[11] Yi-Chyun Chiou, Cheng-Hsiu Tsai, Juo-Shiuan Wu and Jen-Tsai Kuo, "Miniaturization design for planar hybrid ring couplers," in *Art of Miniaturizing RF and Microwave Passive Components, 2008. IMWS 2008. IEEE MTT-S International Microwave Workshop Series on,* 2008, pp. 19-22.

[12] Peng Chen and Zhong-Yun Li, "Miniaturized hybrid ring coupler using fan-shaped apertures on the ground plane," in *Microwave and Millimeter Wave Technology (ICMMT), 2010 International Conference on,* 2010, pp. 1318-1320.

[13] D. Psychogiou and J. Hesselbarth, "Comparing miniaturization techniques for microstrip 180° hybrid ring junctions," in *Microwave Symposium (MMS), 2010 Mediterranean,* 2010, pp. 29-32.

[14] Duxiang Wang, A. Huynh, P. Hakansson, Ming Li and Shaofang Gong, "Study of wideband microstrip 90° 3-dB two-branch coupler with minimum amplitude and phase imbalance," in *Microwave and Millimeter Wave Technology, 2008. ICMMT 2008. International Conference on,* 2008, pp. 116-119.

[15] R. E. Collin, *Foundations for Microwave Engineering.* 1992.

[16] R. Ludwig and G. Bogdanov, *RF Circuit Design: Theory & Applications.* Prentice Hall, 2008.

[17] D. P. Andrews and C. S. Aitchison, "Wide-band lumped-element quadrature 3-dB couplers in microstrip," *Microwave Theory and Techniques, IEEE Transactions on,* vol. 48, pp. 2424-2431, 2000.

[18] M. Caulton, B. Hershenov, S. P. Knight and R. E. DeBrecht, "Status of Lumped Elements in Microwave Integrated Circuits---Present and Future," *Microwave Theory and Techniques, IEEE Transactions on,* vol. 19, pp. 588-599, 1971.

[19] Y. C. Chiang and C. Y. Chen, "Design of lumped element quadrature hybrid," *Electron. Lett.,* vol. 34, pp. 465-467, 1998.

[20] H. Ghali and T. Moselhy, "Design of fractal rat-race coupler," *Microwave Symposium Digest, 2004 IEEE MTT-S International,* vol. 1, pp. 323-326 Vol.1, 2004.

[21] T. Kawai, Y. Kokubo and I. Ohta, "Broadband lumped-element 180-degree hybrids utilizing lattice circuits," *Microwave Symposium Digest, 2001 IEEE MTT-S International,* vol. 1, pp. 47-50 vol.1, 2001.

[22] M. Muraguchi, "Optimum Design of 3-Db Branch-Line Couplers Using Microstrip Lines," *Microwave Theory and Techniques, IEEE Transactions on,* vol. 83, pp. 674-678, 1983.

[23] Shry-Sann Liao, Pou-Tou Sun, Nien-Chung Chin and Jen-Tee Peng, "A novel compact-size branch-line coupler," *Microwave and Wireless Components Letters, IEEE,* vol. 15, pp. 588-590, 2005.

[24] Wei-Shin Tung, Hsu-Hsiang Wu and Yi-Chyun Chiang, "Design of microwave wide-band quadrature hybrid using planar transformer coupling method," *Microwave Theory and Techniques, IEEE Transactions on,* vol. 51, pp. 1852-1856, 2003.

[25] Yi-Chyun Chiang and Chong-Yi Chen, "Design of a wide-band lumped-element 3-dB quadrature coupler," *Microwave Theory and Techniques, IEEE Transactions on,* vol. 49, pp. 476-479, 2001.