ABSTRACT: The assessment of an alternative six-port circuit in terms of frequency behavior when used to measure complex voltage ratio is presented. A numerical comparison to commonly used and well-known six-port circuits is carried out. The presented results can help us to choose between different six-port configurations depending on the application, and show that the proposed circuit is the most suitable in general. © 2005 Wiley Periodicals, Inc. Microwave Opt Technol Lett 46: 24–27, 2005; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/mop.20890

Key words: six-port circuit; reflectometry; direction finding; microwave circuit

INTRODUCTION

The six-port circuit can be used to calculate the complex voltage ratio between two input signals by measuring the output power at its four output ports. This circuit has been extensively used in different applications [1–5], all of them based on complex voltage-ratio or phase-difference measurements. In a recent paper [6], an alternative six-port circuit configuration, where two branch lines of the typical Engen’s configuration [7] were replaced by two Wilkinson power dividers, was presented by the authors of this paper. This new configuration [6] (referred to as our circuit from now on) was proved to show better frequency response for direction-finding applications. The presented results can help us to choose between different six-port configurations depending on the application, and show that the proposed circuit is the most suitable in general. © 2005 Wiley Periodicals, Inc. Microwave Opt Technol Lett 46: 24–27, 2005; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/mop.20890

Six-port circuits analyzed have been those of Casares et al. [6], Engen [7], and Hansson and Riblet [8]. Our six-port circuit is shown in Figure 1. The two input signals \( a_1 \) and \( a_2 \) at ports 1 and 2, respectively, feed two Wilkinson dividers; one of the four outputs is delayed 90° and all four are driven to two branch lines. There are different configurations for the six-port circuit, other than the two selected for comparison. Nevertheless, the two configurations chosen to be compared with show wideband frequency behavior.

METHODOLOGY USED FOR COMPARISON

The analysis and eventual comparison have been conducted as follows. (i) The analysis is based on the ideal transmission line model at the design frequency \( f_0 \); therefore, the three configurations under study show an ideal behavior only at this frequency \( f_0 \) because the phase differences introduced by all the transmission lines are the nominal ones. (ii) The analysis has been done for 65 different values of the reflection coefficient, \( \Gamma \), uniformly scattered inside the unit circle in the complex plane: one is placed at the origin and the other 64 are placed every \( \pi/8 \) radians, with moduli of 0.25, 0.5, 0.75, and 1, respectively. (iii) The analysis covers a frequency range extending from 0.8 \( f_0 \) to 1.2 \( f_0 \) (simulation step was 0.005 \( f_0 \)). (iv) For every couple of values of reflection coefficient and frequency, the Engen circles [7] were obtained for all three circuits [6–8]. Note that 65 values of reflection coefficients and 81 frequency steps lead to 5265 different couples. An example of two different couples is shown in Figure 2.

Figure 1. Recently proposed six-port circuit [6]
Figure 2  Examples of Engen circles for two different $\Gamma_L$ conditions: (a) $\Gamma_L = 0.3 \; e^{i\pi f_0}$, $f = f_0$; (b) $\Gamma_L = 0.4 \; e^{i\pi/2}$, $f = 1.1 \; f_0$.
An algorithm was needed to estimate the reflection coefficient values from the three Engen circles. The radical center [9] and the centroid of the triangle defined by the three intersection points of the Engen circles that are inside the unit circle [10] were used for the configurations in [6] and [7, 8], respectively. The three circles corresponding to our circuit [6], shown in Figure 1, have collinear centers; hence, the radical center does not exist and the centroid was computed instead. This computation was performed for every value of \( \Gamma_L \) in the frequency range \( 0.8 f_0 \leq f \leq 1.2 f_0 \) or where the three Engen circles intersect, depending on the smaller one. The centroid algorithm is a commonly used approach, but it can only be used when the three Engen circles intersect each other. In the six-port circuits in [7, 8], the Engen circles do not intersect in the most part of the frequency range \( 0.8 f_0 \leq f \leq 1.2 f_0 \), and this is the reason why the radical center has been used for them.

The configuration of our six-port circuit stems from that proposed by Hoer and Roe [11]. The configuration in [11] is not used in the comparison presented in this paper because its Engen's circles, which also have collinear centers, do not intersect in most of the frequency band of interest. Therefore, neither the radical center nor the centroid algorithm would be used in a frequency band wide enough for this six-port circuit configuration.

The absolute errors of the modulus and argument of the \( \Gamma_L \) estimation, defined as

\[
e_{\text{abs}}(\text{mod}) = ||\Gamma_{L,\text{real}}|| - ||\Gamma_{L,\text{estimated}}||, \quad (1)
\]

\[
e_{\text{abs}}(\text{arg}) = |\arg(\Gamma_{L,\text{real}}) - \arg(\Gamma_{L,\text{estimated}})|, \quad (2)
\]

have been used to compare the three circuits.

**RESULTS**

The three six-port circuits under comparison [6–8] were analyzed in the aforementioned frequency range, yielding graphics similar to those shown in Figure 3 for each of the different 65 values of the reflection coefficient. It can be very interesting to know which six-port configuration provides the lowest root mean square (RMS) error, modulus, and argument, for every reflection coefficient. In Figure 4, it can be seen that the Hansson and Riblet’s six-port circuit [8] yields the smallest modulus RMS error in the 43% of the

![Figure 3](image)

**Figure 3** Modulus and argument error examples for two different \( \Gamma_L \) conditions: (a) \( \Gamma_L = 0.5 e^{-j\pi/3} \); (b) \( \Gamma_L = 0.25 e^{-j\pi/3} \). — Proposed six-port circuit (Fig. 1) [6]; - - - Engen’s six-port circuit [7]; Hansson and Riblet’s six-port circuit [8]

![Figure 4](image)

**Figure 4** Six-port circuit showing the smallest modulus RMS error at every \( \Gamma_L \) condition. ■ Proposed six-port circuit (Fig. 1) [6]; ○ Engen’s six-port circuit [7]; ▲ Hansson and Riblet’s six-port circuit [8]
65 values of $\Gamma_L$, very closely followed by our circuit [6], that shows the smallest modulus error for 37% of the values, and Engen’s circuit [7] for 20%. On the other hand, Figure 5 reveals the better performance of our circuit to estimate the argument (phase) of the values of $\Gamma_L$, having the smallest argument RMS error for the 67% of the values (Hansson and Riblet, 25%; and Engen, 8%). Therefore, our six-port circuit is the most suitable in general, and particularly in applications based on phase measurements, such as phase demodulators or direction finding systems.

It should be noted that the radical center of the three Engen circles of the six-port circuits in [7, 8] always exist. On the other hand, the centroid of the Engen circles of our circuit does not always exist. Figure 6 shows the frequency range where the centroid of our circuit is defined for each value of $\Gamma_L$. This does not mean that our six-port circuit will not provide a measurement when the three Engen circles do not intersect. Simply stated, the frequency range in which the errors have been evaluated is the one where the intersection of the three Engen circles, and hence the centroid, does exist.

CONCLUSION

An assessment of a recently proposed six-port circuit has been presented. In general, the proposed circuit shows an improvement in the frequency response compared with the six-port circuits most commonly used in the technical literature. This improvement is due to the replacement of branch lines with Wilkinson dividers, which have a better frequency response. A frequency-performance comparison of our six-port circuit and two widely used configurations has been conducted in order to determine the best choice when designing a particular device that incorporates a six-port circuit. As can be observed from the presented results, the choice will depend on the application. However, taking into account both estimations—modulus and argument—our six-port circuit has lower RMS errors for most of the possible values of the reflection coefficient. Our circuit, which is based on a simple idea, shows a very convenient frequency behavior.

REFERENCES