Choosing the Right Power Splitter: Two-resistor or Three-resistor

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ABSTRACT

Power splitters are frequently used in RF and microwave measurements. The two-resistor splitter is widely used and available. The three-resistor splitter is less common and is offered by fewer vendors. Both types have their place, but the two-resistor splitter has been the dominant choice, even when it is not the optimum choice. This paper will explore the differences between them and show how to decide which to use in order to minimize the measurement uncertainty contributed by the power splitter.

Power Splitter vs. Power Divider

The subject of this paper is the broadband (DC to 26 GHz) RF/Microwave power splitter. Some manufacturers (and authors) refer to the two-resistor (2-R) splitter as a power *splitter* and the three-resistor (3-R) splitter as a power *divider*. In either case, the purpose of the device is to divide a source power into two (usually equal) parts. Figure 1 shows a photo of a typical power splitter. Intuitively, for an equal-output power splitter, one expects the power emanating from each output port of the splitter to be *exactly* one-half of the input power level (–3 dB). This is not true, as we shall see below.

Figure 1

Power Splitter Construction

Figure 2 shows the internal schematic of a 2-R splitter. Why are the two resistors needed in the first place? Primarily, they are included to provide isolation between the two output ports, and between those ports and the input port. RF and microwave power splitters must match the typical 50-Ω transmission lines that predominate in high-frequency circuits. If there were no resistors inside the power splitter, and if two 50-Ω loads or transmission lines were connected in parallel across the input transmission line, the resulting load on the source connected to the input of the splitter would be 25-Ω . Energy reflected from either load would be fed directly to the other and to the source.

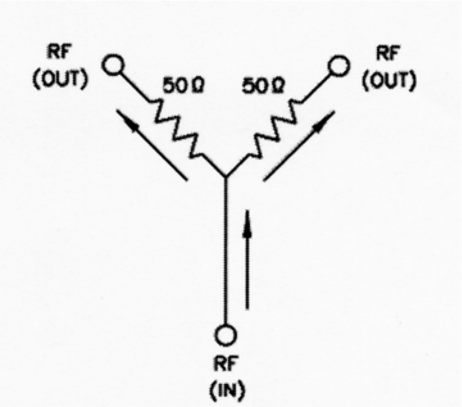


Figure 2

Figure 3 shows the configuration of a terminated 2-R splitter designed for a 50-Ω transmission system. The two internal resistors are each chosen to be 50-Ω. This insures that the impedance looking into the power splitter's input port is 50 Ω. The power delivered to each output termination is one-fourth of the input power level (–6 dB) and each of the four 50-Ω resistors (two internal and two external) dissipates one-fourth of the input power. This is the price we pay for isolation of the two output ports using resistive elements.

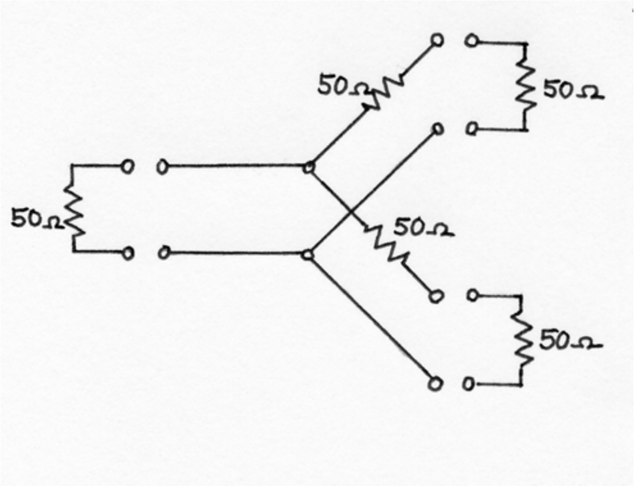


Figure 3

Notice that the stand-alone, matched-terminated 2-R splitter does NOT present an input impedance of 50-Ω at the two output ports. Rather, the input impedance at those ports is 83.33 Ω. (See Appendix.)

Figure 4 shows the configuration of a 3-R splitter (divider). Note the presence of three identical internal $16\frac{2}{3}\Omega$ resistors. This insures that the stand-alone, matched-terminated 3-R splitter *does* present an input impedance of 50-Ω at all three ports. So, which is the true power splitter: 2-R or 3-R? To answer this question, we need to understand the properties of three-port, passive, microwave devices.

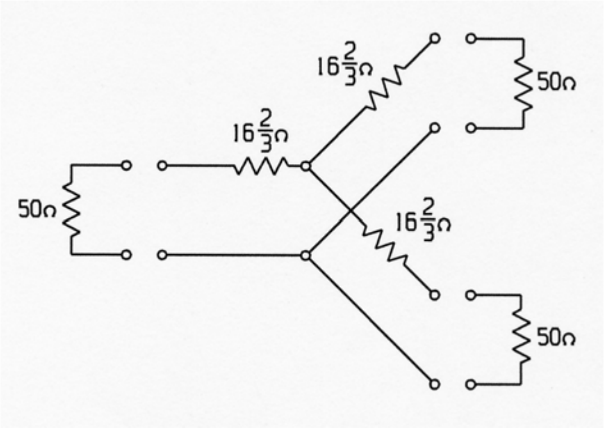


Figure 4

Three-port Passive Devices

A generalized, three-port device is shown in Figure 5.

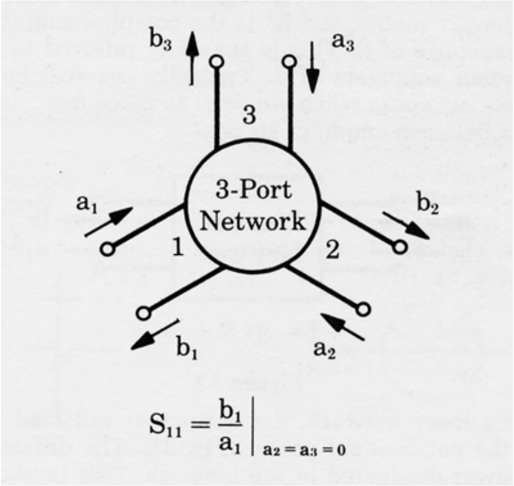


Figure 5

In Figure 5, a_X represents the incident voltage wave and b_X represents the reflected voltage wave at port *X*. The three-port device can be completely characterized by the following set of equations:

$$
\begin{aligned}
b_1 &= s_{11} \cdot a_1 + s_{12} \cdot a_2 + s_{13} \cdot a_3 \\
b_2 &= s_{21} \cdot a_1 + s_{22} \cdot a_2 + s_{23} \cdot a_3 \\
b_3 &= s_{31} \cdot a_1 + s_{32} \cdot a_2 + s_{33} \cdot a_3
\end{aligned}
$$

The s_{ij} are called scattering parameters, or “s-parameters”. They can be evaluated as shown by the equation in Figure 5. The conditions of $a_2 = 0$ and $a_3 = 0$ is insured by terminating ports 2 and 3 with matched impedances (50-Ω).

Ratio measurements and leveling-loops

For many three-port applications, the ratio of the two output voltage waves, b_2 and b_3 is important. This ratio can be expressed in terms of the three-port s-parameters and the terminating impedances as follows [1]:

$$
\frac{b_2}{b_3} = \frac{s_{21} \cdot \left[1 - \Gamma_3 \left(s_{33} - \dfrac{s_{31} \cdot s_{23}}{s_{21}} \right) \right]}{s_{31} \cdot \left[1 - \Gamma_2 \left(s_{22} - \dfrac{s_{21} \cdot s_{32}}{s_{31}} \right) \right]} = \frac{s_{21} \cdot \left(1 - \Gamma_3 \Gamma_{EQ3} \right)}{s_{31} \cdot \left(1 - \Gamma_2 \Gamma_{EQ2} \right)} \qquad \textbf{EQN. 1}
$$

where:

Γ_2 = the reflection coefficient of the termination on port 2;

Γ_3 = the reflection coefficient of the termination on port 3;

$\Gamma_{EQ2} = \left(s_{33} - \dfrac{s_{31} \cdot s_{23}}{s_{21}} \right)$ = the *effective* reflection coefficient of port 2;

$\Gamma_{EQ3} = \left(s_{22} - \dfrac{s_{21} \cdot s_{32}}{s_{31}} \right)$ = the *effective* reflection coefficient of port 3.

For an ideal splitter, $b_2 = b_3$ and $\dfrac{b_2}{b_3} = 1$. In order to evaluate how well the 2-R and 3-R splitters realize this condition, we must evaluate the s_{ij} for each splitter.

s-parameter Computation

Examples in the Appendix show how this is done. The results are given in Table 1.

Table 1

	2-R Splitter	3-R Splitter
s_{11}	0	0
s_{12}	0.5	0.5
s_{13}	0.5	0.5
s_{21}	0.5	0.5
s_{22}	0.25	0
s_{23}	0.25	0.5
s_{31}	0.5	0.5
s_{32}	0.25	0.5
s_{33}	0.25	0

Evaluating $\frac{b_2}{b_3}$ from EQN. 1:

For the 2-R splitter:

$$\frac{b_2}{b_3}=\frac{(0.5)\cdot\left[1-\Gamma_3\cdot\left((0.25)-\frac{(0.5)(0.25)}{(0.5)}\right)\right]}{(0.5)\cdot\left[1-\Gamma_2\cdot\left((0.25)-\frac{(0.5)(0.25)}{(0.5)}\right)\right]}=1$$

For the 3-R splitter:

$$\frac{b_2}{b_3}=\frac{(0.5)\cdot\left[1-\Gamma_3\cdot\left((0.0)-\frac{(0.5)(0.5)}{(0.5)}\right)\right]}{(0.5)\cdot\left[1-\Gamma_2\cdot\left((0.0)-\frac{(0.5)(0.5)}{(0.5)}\right)\right]}=\frac{1+\frac{\Gamma_3}{2}}{1+\frac{\Gamma_2}{2}}$$

For the ideal 2-R splitter, the outputs are exactly equal. For the ideal 3-R splitter, the outputs are equal if and only if the reflection coefficients, Γ_2 and Γ_3 ,of the terminations are identical. This startling result is the reason why the 2-R splitter is preferred for any measurement where the ratio $\frac{b_2}{b_3}$ is involved.

This includes any setup where the splitter is being used in a leveling loop (see Figure 6) or where the splitter's two outputs are being used for a comparison (see Figure 7).

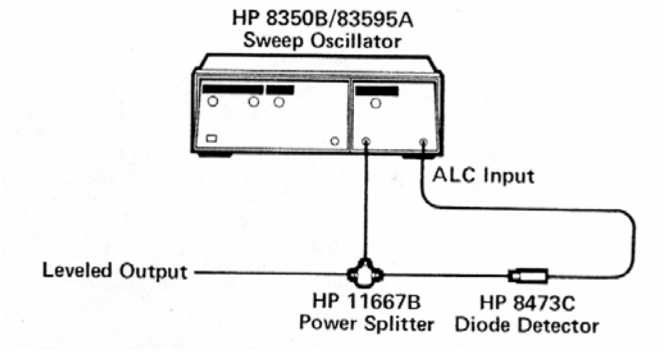


Figure 6

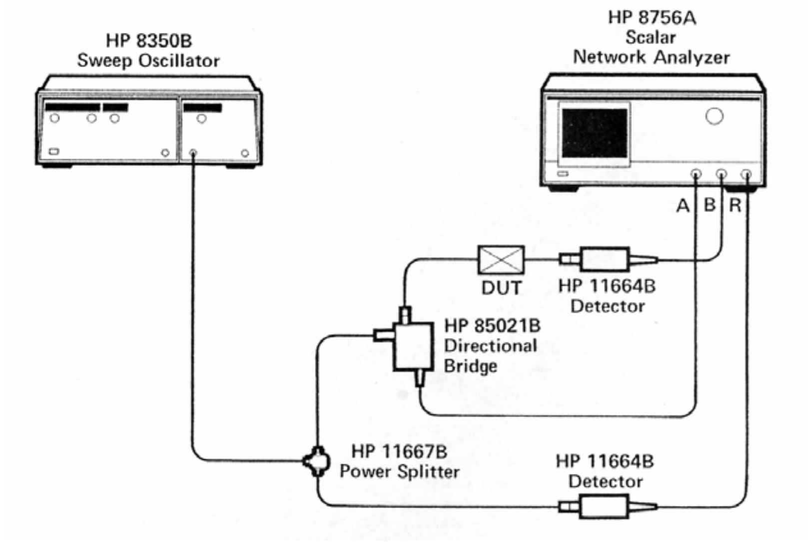


Figure 7

Equivalent Source-Match

The effective output-reflection-coefficient (also known as the equivalent source-match) for a ratio or leveling measurement is very different between the 2-R and 3-R splitters.

For the 2-R splitter: $\Gamma_{EQ-2R} = \left(s_{22} - \frac{s_{21}s_{32}}{s_{31}} \right) = \left(0.25 - \frac{(0.5)(0.25)}{0.5} \right) = 0$

This says that the output ports of the ideal 2-R splitter present a perfect match to the transmission line. Commercially-available 2-R splitters actually exhibit an equivalent source-match of 0.045 to 0.091. The equality $s_{21} = s_{31}$ (see Table 1) means that the input power to the ideal 2-R splitter is indeed split equally between the two output ports. The equality $s_{22} = s_{32}$ means that the portion of the power reflected from the load on port 2 that is reflected by port 2 is equal to the portion transmitted through the splitter to port 3.

This is the reason why a 2-R splitter works so well in a leveling loop. Any power reflected from port 2 also emanates at the exact same level from port 3. This maintains an equal power output from the two ports. If an active leveling loop is attached to port 3, the power transmitted from port 2 to port 3 is multiplied by the infinite negative gain of the leveling loop and appears as a decrease in voltage at the internal junction of the splitter. This action serves to reduce the power out of port 2, counteracting the power that was reflected from port 2.

For the 3-R splitter: $$\Gamma_{EQ-3R} = \left(s_{22} - \frac{s_{21}s_{32}}{s_{31}} \right) = \left(0.0 - \frac{(0.5)(0.5)}{0.5} \right) = -0.5 = 0.5\angle 180^{\circ}$$

This says that, when used in a leveling loop or in a ratio measurement, the ideal 3-R splitter presents a VSWR = 3:1 to the load. This is surprising, since the 3-R splitter has $s_{11} = s_{22} = s_{33} = 0$ when the splitter is terminated in matched (50-Ω) impedances and ratioing is not involved.

Valid Uses for the 3-R Splitter

Since the 3-R splitter is not optimal for ratio or leveling applications, it should only be used for simple power division or power combining, where the two outputs are utilized independently of one another and where an excellent match ($s_{22} = s_{33} = 0$) to each output port is necessary.

For example:

1) Measuring two independent aspects of a broadband signal, such as power and frequency.
2) Distribution of low-power signals to two antennas.
3) Measurements requiring an alternate signal that exactly tracks a reference signal.
4) Power combining.

Valid Uses for the 2-R Splitter

The 2-R splitter must be used in measurements requiring accurate amplitude tracking and low equivalent output VSWR.

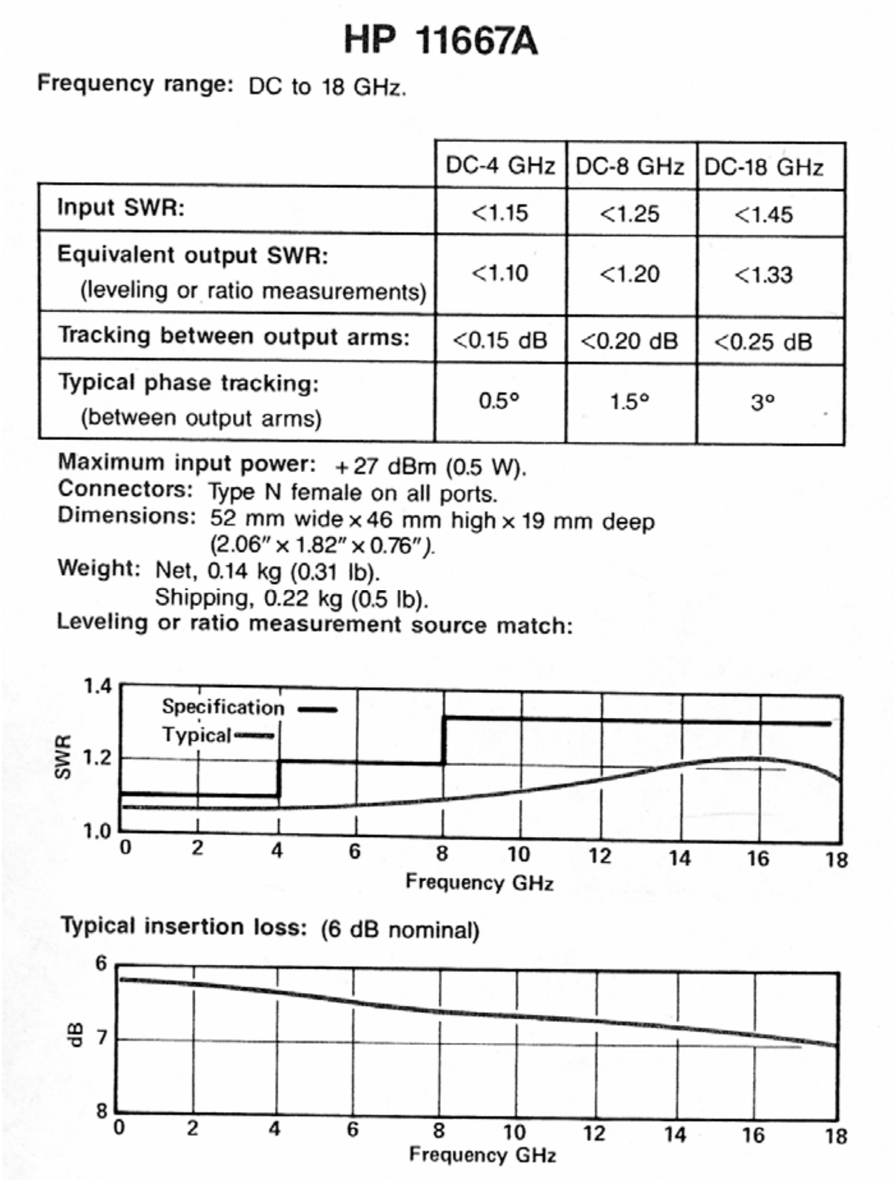
For example:

1) A dual-channel insertion-loss measurement requiring a signal channel and an identical, tracking, reference channel.
2) A precision power source where a power meter is used, either by ratio or leveling, to provide a calibrated output.
3) A leveled power source utilizing a feedback loop connected to one output of the power splitter

Key specifications for the power splitter:

1) Tracking of the two output ports (dB of difference)
2) Insertion loss (nominally 6 dB from input to each output)
3) VSWR
4) Frequency range

Figure 8 shows a typical specification sheet for a 2-R splitter.



HP 11667A

Frequency range: DC to 18 GHz.

	DC-4 GHz	DC-8 GHz	DC-18 GHz
Input SWR:	<1.15	<1.25	<1.45
Equivalent output SWR: (leveling or ratio measurements)	<1.10	<1.20	<1.33
Tracking between output arms:	<0.15 dB	<0.20 dB	<0.25 dB
Typical phase tracking: (between output arms)	0.5°	1.5°	3°

Maximum input power: +27 dBm (0.5 W).
Connectors: Type N female on all ports.
Dimensions: 52 mm wide × 46 mm high × 19 mm deep (2.06″ × 1.82″ × 0.76″).
Weight: Net, 0.14 kg (0.31 lb).
Shipping, 0.22 kg (0.5 lb).
Leveling or ratio measurement source match:

Typical insertion loss: (6 dB nominal)

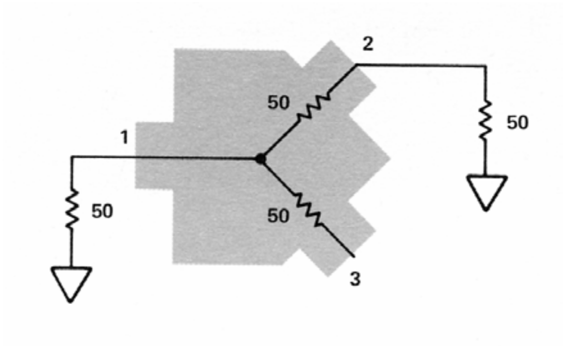
Figure 8

REFERENCES:

[1] Johnson, Russell A., “Understanding Microwave Power Splitters”, *Microwave Journal*, December, 1975.

Appendix

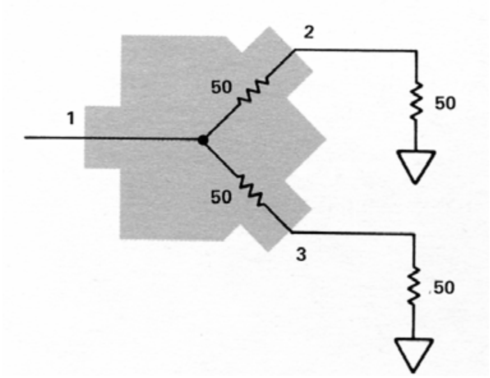
Computation of s-parameters for the 2-R and 3-R splitters:



$$Z_{OUT} = 50\Omega + \frac{(50\Omega)\cdot(100\Omega)}{50\Omega + 100\Omega} = 83.33\Omega$$

$$Z_0 = 50\Omega$$

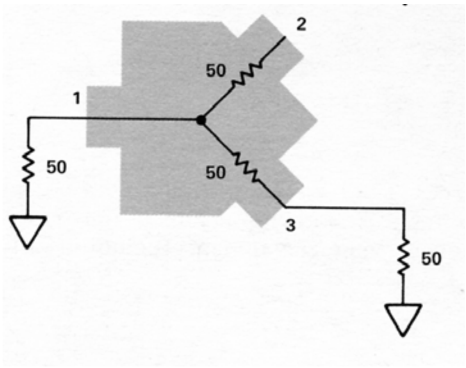
$$s_{33} = \frac{Z_{OUT} - Z_0}{Z_{OUT} + Z_0} = \frac{33.33\Omega}{133.33\Omega} = 0.25 = s_{22}$$



$$Z_{IN} = \frac{(50\Omega + 50\Omega)\cdot(50\Omega + 50\Omega)}{50\Omega + 50\Omega + 50\Omega + 50\Omega} = 50\Omega$$

$$s_{11} = \frac{Z_{IN} - Z_0}{Z_{IN} + Z_0} = \frac{50\Omega - 50\Omega}{100\Omega} = 0.0$$

$$s_{21} = s_{31} = \frac{50\Omega}{100\Omega} = 0.5$$



Since the 2-R splitter does not present a 50-Ω impedance looking into either port 2 or port 3, **b2** (the reflected voltage wave) is not zero.

Therefore: $V_{TOTAL} = a_2 + b_2 = v_{i2} + v_{r2}$

$$V_{TOTAL} = v_{i2} + v_{i2}\cdot s_{22} = v_{i2}(1 + s_{22}) = 1.25 v_{i2}$$

$$v_{r3} = V_{TOTAL}\cdot\frac{33\frac{1}{3}\Omega}{88\frac{1}{3}\Omega}\cdot\frac{1}{2} = \frac{2}{5}\cdot\frac{1}{2}\cdot v_{i2}\cdot(1.25) = 0.25 v_{i2}$$

$$s_{32} = \frac{v_{r3}}{v_{i2}} = \frac{0.25 v_{i2}}{v_{i2}} = 0.25 = s_{23}$$