A Better Antenna-Tuner Balun

Which balun to use? The hybrid balun promises advantages over both voltage and current baluns.

By Andrew Roos, ZS1AN

PO Box 350, Newlands
7725, South Africa
zs1an@qsl.net

Baluns that are situated between an antenna tuning unit and a non-resonant antenna may be subjected to high-impedance, highly reactive or unbalanced loads that can prevent the balun from functioning effectively.

In this article, I apply the analytical model of the transmission-line transformer developed by Roy Lewallen[1] to analyze the performance of the 1:1 current balun and the 4:1 voltage balun in this application. The analysis shows that the current balun operates effectively only for small load impedances, while the voltage balun

[1]Notes appear on page 34.

is effective only if the load impedance is well balanced with respect to ground.

I then introduce a new design: the "hybrid" balun, which overcomes these limitations of the voltage and current baluns. It can operate with much higher load impedances than can current baluns and with unbalanced load impedances that voltage baluns could not drive effectively. The article concludes by describing a simple test I conducted to confirm that the hybrid balun operates as predicted.

Lewallen's Model of a 1:1 Transmission-Line Transformer

Lewallen models the 1:1 transmission-line transformer (TLT) as an ideal 1:1 transformer with a "winding impedance," Z_W, in parallel with one of the windings,[2] as shown in

Fig 1. Although Z_W is shown on only one of the transformer windings, its effects are felt equally on both windings due to the coupling action of the "ideal transformer," which can be expressed by two rules:

1. The currents in the two windings of the "ideal transformer" are equal and opposite.

2. $V_{AC} = V_{BD} = (I_1 - I_2) Z_W$

The model assumes that the length of the transmission line used to construct the TLT is short in terms of wavelength, so transmission line effects can be ignored. Although this assumption holds for the lower part of the HF region, some transmission-line effects do come into play at higher frequencies.

The use of this model does not imply that TLTs operate like conventional transformers. The ideal

1:1 transformer is simply a modeling convenience, and the resulting model applies to any device that exhibits common-mode impedance, irrespective of its operating principle.

The 1:1 Current Balun

Fig 2 shows the schematic of Guanella's 1:1 "current" balun. Z_1 and Z_2 represent the load. The junction between Z_1 and Z_2 is grounded to represent the (typically capacitive) coupling of the antenna system to ground. The load is balanced with respect to ground when $Z_1 = Z_2$.

The principle limitation of this balun is that it can only maintain balance between the currents flowing into the load, I_1 and I_2, for relatively low load impedances. The ability to maintain the correct current balance in the load is of course the reason for using a balun in the first place, so the extent to which a balun maintains this balance is the primary measure of its effectiveness. In the case of the 1:1 current balun, Lewallen shows that

$$I_1 / I_2 = (Z_2 + Z_W) / Z_W \qquad \text{(Eq 1)}$$

Where Z_W is the "winding impedance" (common-mode impedance) of the balun. We can use this to calculate the measure of imbalance proposed by Witt[3] as:

$$\begin{aligned} \text{IMB} &= 2 \ |(I_1 - I_2) / (I_1 + I_2)| \\ &= 2 \ |(I_1 - I_1 (Z_2 + Z_W)/ Z_W) / (I_1 + I_1 (Z_2 \\ &+ Z_W)/ Z_W)| \\ &= 2 \ |Z_2| \ / \ |(Z_2 + 2 Z_W)| \qquad \text{(Eq 2)} \end{aligned}$$

(Note that $|X|$ means the magnitude of complex variable X.) If IMB is small, then $|Z_W| >> Z_2$. So as a good approximation,

$$\text{IMB} = |Z_2| \ / \ |Z_W| \qquad \text{(Eq 3)}$$

Although Witt does not suggest an acceptable maximum figure for IMB, 0.1 seems a reasonable value since this means that the magnitude of the common-mode (unbalanced) current flowing in the antenna is one-tenth the magnitude of the differential-mode (balanced) current. To prevent IMB from exceeding 0.1 we require that $|Z_2| \leq 0.1 \ |Z_W|$. This limits the usefulness of the current balun. Charles Rauch[4] measured the common-mode impedance of several commercially manufactured current baluns using a network analyzer and found that most had a common-mode impedance of less than 1 kΩ at 15 MHz, giving a maximum acceptable value of $|Z_2|$ of less than 100 Ω. For balanced loads, this means that the baluns tested by Rauch would be effective only for load impedances under 200 Ω.

The 4:1 Voltage Balun

We can use the same model to analyze the performance of the Ruthroff's 4:1 voltage balun shown in Fig 3. Once again, Z_1 and Z_2 represent the load. According to Lewallen's model, the voltages across the two windings of the transmission-line transformer (TLT) are equal, and both equal V_S, so

$$I_1 = V_S / Z_1$$

and

$$I_2 = V_S / Z_2$$

We can calculate Witt's measure of imbalance:

$$\begin{aligned} \text{IMB} &= 2 \ |I_1 - I_2| \ / \ |I_1 + I_2| \\ &= 2 \ |Z_2 - Z_1| \ / \ |Z_2 + Z_1| \qquad \text{(Eq 4)} \end{aligned}$$

The degree to which the currents are balanced depends only on the balance of the load impedances with respect to ground. In order to keep IMB ≤ 0.1, the impedances must be
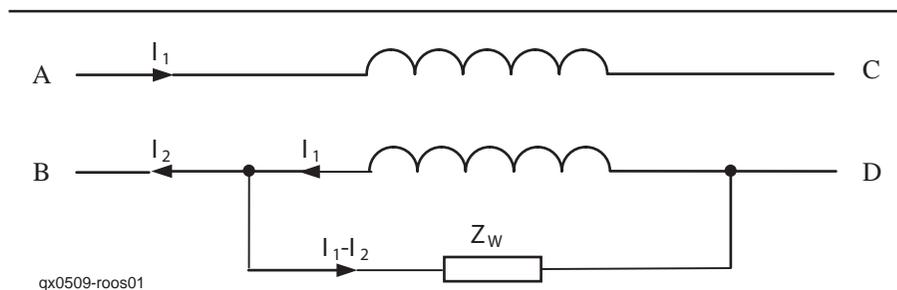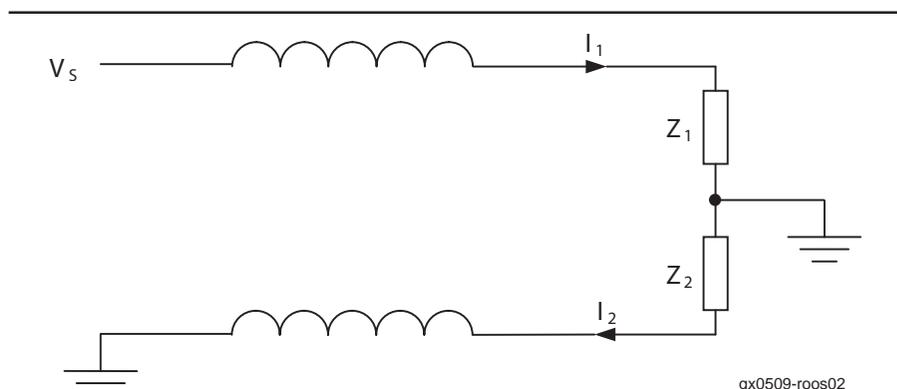

Fig 1—Lewallen's model of the 1:1 TLT.

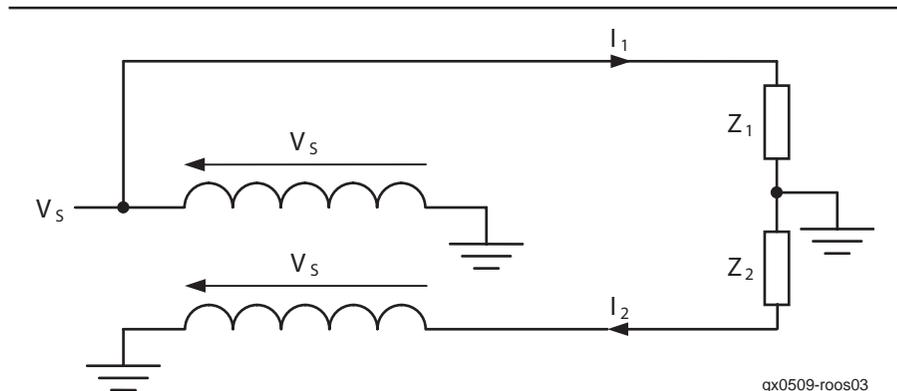Fig 2—A schematic of Guanella's 1:1 current balun.

Fig 3—A schematic of Ruthroff's 4:1 voltage balun.

within about 10% of each other. Imbalance does not impose any constraint on the maximum impedance a voltage balun can drive. This is determined by efficiency considerations and is usually greater than the magnitude of the winding inductance, so the voltage balun can drive balanced loads at least five times larger than can a current balun with the same winding impedance.

Unfortunately, supposedly balanced antennas may present unbalanced loads due to the presence of nearby conductors or asymmetry in the antenna installation imposed by site constraints. Kevin Schmidt[5] describes one such case:

> "One of my antennas is a 'dipole' about 60 feet on a leg running around the outside of my 1-story house. It is fed by about 30 feet of 300 Ω TV twinlead. The legs of the 'dipole' are not straight, and it isn't symmetric about the feed point, since the shack is at a corner of the house."

He measured the differential and common-mode impedances of the antenna at 3.52 MHz using professional instruments and obtained the results shown in Fig 4.[6] If this antenna were driven by a voltage balun, IMB would be 0.22. This shows that the inherent balance of amateur antennas cannot be assumed, so antenna tuner baluns must be able to drive unbalanced loads effectively.

The Hybrid Balun

The preceding sections have shown that the current balun is limited by its inability to maintain current balance when driving all but low-impedance loads, while the voltage balun cannot maintain current balance in unbalanced loads. Since the maintenance of current balance in the load is the principle purpose of a balun, these limitations warrant a search for "a better balun." This section describes and analyses the "hybrid balun," which consists of a voltage balun followed by a common-mode choke. The circuit shown in Fig 5 uses a 4:1 voltage balun, but a 1:1 voltage balun would work equally well and the analysis is identical.

The hybrid balun requires two separate transmission-line transformers. The TLT for the voltage balun is best realized using a bifilar winding on a toroidal ferrite or powdered-iron core. The "hardy" balun designs offered by Dr Sevick[7] would be excellent in this application. I also recommend this approach for the common-mode choke. Although one could use a length of coaxial cable threaded through ferrite beads as suggested by Walt Maxwell[8] for the choke, Rauch's measurements (see Note 4) show that beaded coax chokes have a large resistive component to their common-mode impedance. Equation 13 shows that this will increase the choke's power dissipation and reduce the efficiency of the balun. The voltage balun found on many ATUs can be converted to a hybrid balun by simply adding a common-mode choke after the balun, without need for modification to the ATU or balun.

Although the common-mode choke appears identical to the 1:1 current balun, the term "common-mode choke" is preferred, as it is driven by the balanced voltage at the output of the voltage balun, instead of having one side grounded. This means the voltage across the windings is no longer the full source voltage V_S, but only a portion of V_S that depends on the degree of imbalance of the load. Consequently, the common-mode choke does not suffer from the limitation of the current balun—that $|Z_2|$ must be less than one tenth of $|Z_W|$ in order to maintain balance and can operate effectively and efficiently at much higher impedance levels than could a current balun. In turn, the choke presents a balanced load impedance to the voltage balun preceding it, despite any imbalances in the antenna system, allowing the hybrid balun to drive unbalanced loads more effectively than could the voltage balun alone.

Let V_C be the common-mode voltage across the choke windings as shown in Fig 5. Since V_C also appears across the winding impedance Z_W in Lewallen's model, and the current flowing through the winding impedance is the common-mode current $I_1 - I_2$,

$$V_C = (I_1 - I_2)\,Z_W \qquad \text{(Eq 5)}$$

The voltages at the input side of the choke are V_S and $-V_S$, so

$$I_1 = (V_S - V_C)\,/\,Z_1 \qquad \text{(Eq 6)}$$

and

$$I_2 = (V_S + V_C)\,/\,Z_2 \qquad \text{(Eq 7)}$$

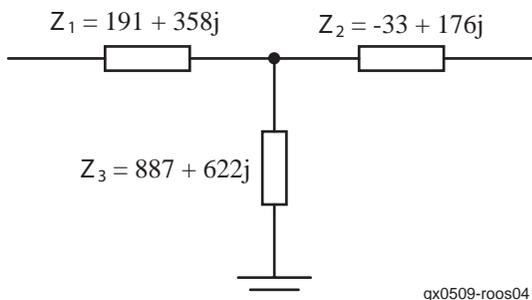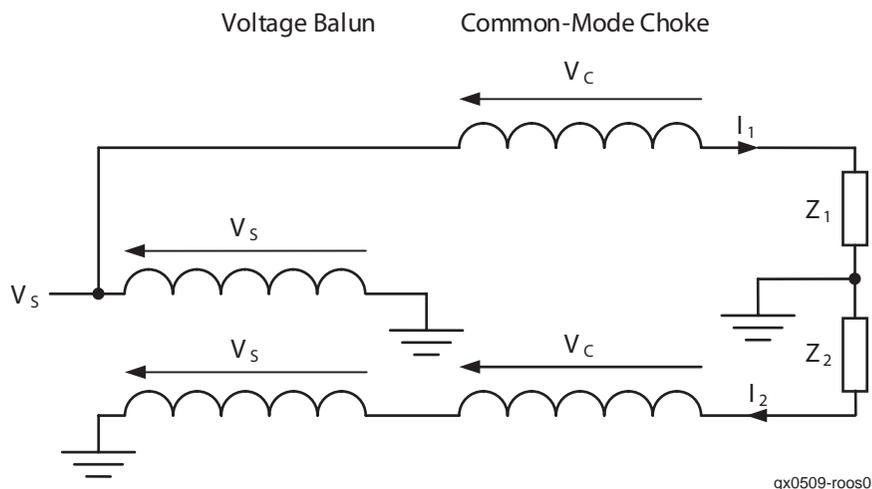Substituting Equations 6 and 7 into Equation 5 and solving for V_C,

Fig 4—The impedances of Schmidt's dipole.

Z₁ = 191 + 358j
Z₂ = -33 + 176j
Z₃ = 887 + 622j

qx0509-roos04

Voltage Balun   Common-Mode Choke

V_C I_1 Z_1 V_S V_S V_C Z_2 I_2 V_S

qx0509-roos05

Fig 5—A schematic of the 4:1 hybrid balun.

$V_C = V_S Z_W (Z_2 - Z_1) / (Z_1 Z_2 + Z_W Z_1 + Z_W Z_2)$

(Eq 8)

We can substitute this value into equations 6 and 7 to obtain

$I_1 = V_S (Z_2 + 2 Z_W) / (Z_1 Z_2 + Z_1 Z_W + Z_2 Z_W)$

(Eq 9)

and

$I_2 = V_S (Z_1 + 2 Z_W) / (Z_1 Z_2 + Z_1 Z_W + Z_2 Z_W)$

(Eq 10)

So Witt's measure of imbalance is

$$IMB = 2 |(I_1 - I_2) / (I_1 + I_2)|$$
$$= 2 |(Z_2 - Z_1) / (Z_1 + Z_2 + 4 Z_W)|$$

(Eq 11)

Comparing this to Eq 4, which gives IMB for the voltage balun, we see that the additional term in the denominator reduces the imbalance by a factor of

$$IMB_V / IMB_H = |1 + 4 Z_W / (Z_1 + Z_2)|$$

(Eq 12)

Where IMB_V and IMB_H are the imbalance measures for the voltage balun and the hybrid balun, respectively, with the same loads.

Efficiency of the Hybrid Balun

Efficiency is as important as balance for antenna tuner baluns. The power loss in a TLT can be derived from Lewallen's model by noting that the power loss in each winding is the dot product of the voltage across the winding, V_W, and the current flowing in the winding, so the total power loss in both windings is:

$$P_{LOSS} = V_W \cdot I_1 + V_W \cdot (-I_2)$$
$$= V_W (I_1 - I_2)$$
$$= V_W (V_W / Z_W)$$
$$= Re (V_{W*}(V_W / Z_W)*)$$
$$= Re(|V_W|^2 / Z_W*)$$
$$= |V_W|^2 Re(Z_W) / |Z_W|^2$$

(Eq 13)

Where "$X*$" means the complex conjugate of "X" and "Re(X)" means the real component of "X." This interesting result shows that the power dissipation in the TLT is proportional to the square of the voltage across the TLT windings. So for the hybrid balun (refer to Fig 5) if the winding impedances of the two TLTs are the same, the relationship between P_C, the power dissipated in the common-mode choke and P_V, the power dissipated in the voltage balun is given by

$$P_C / P_V = |V_C|^2 / |V_S|^2$$

(Eq 14)

Substituting the formula for V_C

given in Eq 8 and canceling $|V_S|^2$ gives

$$P_C / P_V = |Z_W (Z_2 - Z_1) / (Z_1 Z_2 + Z_W Z_1 + Z_W Z_2)|^2$$

(Eq 15)

When $|Z_W|$ is small compared to $|Z_1 Z_2|$, this approaches zero, so the efficiency of the hybrid balun is the same as that of the voltage balun. When $|Z_W|$ is large compared to $|Z_1 Z_2|$, it approaches

$$P_C / P_V = |(Z_2 - Z_1) / (Z_1 + Z_2)|^2$$

(Eq 16)

Substituting the value of IMB for the voltage balun given in Eq 4,

$$P_C / P_V = 1/4 \, IMB^2$$

(Eq 17)

So when $|Z_W|$ is large, the additional power lost in the common-mode choke is proportional to the square of the imbalance that would have existed in the load if it was driven by the voltage balun alone. This suggests the interpretation that the power dissipated by the choke depends on the amount of work the choke has to do in order to maintain the current balance in the load. If the load is perfectly balanced, the choke dissipates no power. In the worst case, when Z_1 or Z_2 is zero (a completely unbalanced load), IMB = 2, and the choke dissipates the same power as the voltage balun. Such an extreme case is unlikely, however, and under normal conditions (with IMB < 1) the choke dissipates less than one quarter of the power dissipated by the voltage balun, so the overall efficiency of the hybrid balun is only slightly less than that of a voltage balun driving a balanced load (which, incidentally, is the same as that of a current balun driving a balanced load, since in both cases the voltage across the TLT windings is one half of the voltage across the load).

Comparison of Balun Performance

The chart in Fig 6 shows the regions in which the different baluns will operate effectively for purely resistive loads. R_1 and R_2, the resistive (real)
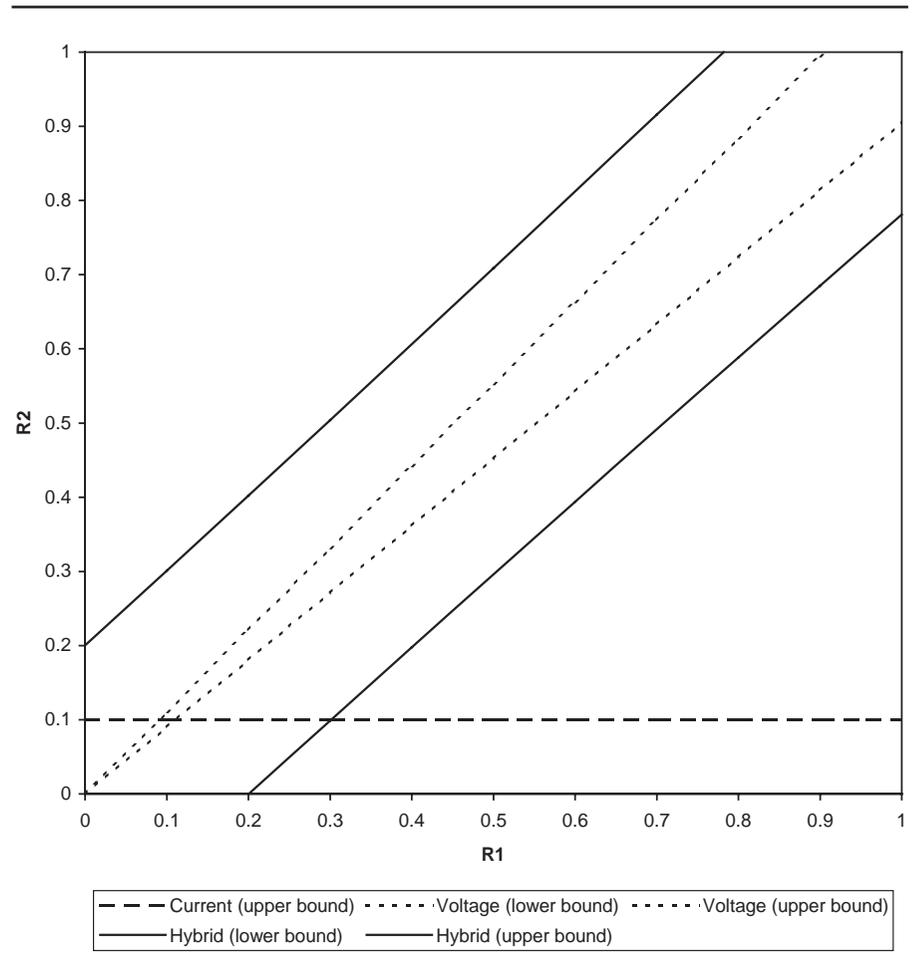

Fig 6—Effective operating regions of the current, voltage and hybrid baluns.

components of Z_1 and Z_2, are shown on the X and Y axes. The plot lines represent the upper and lower bounds of the regions in which each of the baluns will maintain a load imbalance (IMB) not exceeding 0.1. The chart is normalized for $|Z_W| = 1$.

The horizontal line near the bottom of the chart is the upper bound of the current balun's operating region, showing that the current balun is effective when $R_2 < 0.1 |Z_W|$, irrespective of the value of R_1. (Although the current balun is able to drive high-impedance loads that are situated near the X-axis, this not terribly useful since the limiting case as $R_2/R_1 \rightarrow 0$ is an unbalanced load being driven by an unbalanced source, so no balun is required.) The two lines that meet at the origin represent the upper and lower bounds of the region in which the voltage balun can maintain IMB ≤ 0.1. The voltage balun is effective for much larger load impedances than the current balun, but only when the load is well balanced (a perfectly balanced load would be situated on a 45° line passing through the origin). The angled lines that intersect the X and Y axes at the value 0.2 are the lower and upper bounds of the region in which the hybrid balun is effective. The hybrid balun is effective for higher load impedances than the current balun (excluding loads situated near the X axis), and for a greater degree of load asymmetry than the voltage balun.

Although the chart displays only purely resistive loads, similar results are obtained for load impedances that include both resistance and reactance. Any load that has a small resistive component combined with a large reactive component, however, may cause inefficiency and excessive heating in all balun types. If you have a load like this, you need to transform the load impedance, either by using a balanced tuner or by adjusting the length of the transmission line between the balun and the antenna.

Practical Testing

It would require more sophisticated test equipment than I have to directly measure the current balance achieved by the different types of balun. Fortunately, the input impedance of the voltage balun approximately equals the value of Z_1 in parallel with Z_2. This provides a good indication of load-balance quality. That indication is the extent to which the input impedance of the balun approaches the value expected for a perfectly balanced load. For the 4:1 balun, this is one quarter
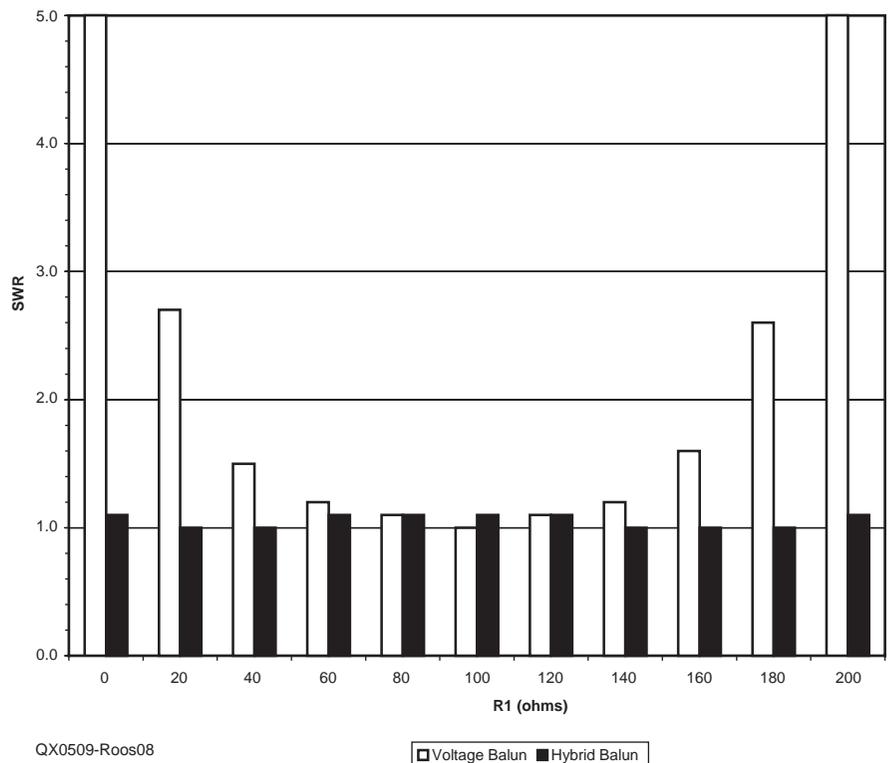

Fig 7—The prototype hybrid balun.

QX0509-Roos08

Voltage Balun Hybrid Balun

Fig 8—SWR measured at the balun input for different ground-tap positions.

of the total load impedance.

To measure this I connected 10, 20 Ω precision resistors in series to make a 200 Ω dummy load. A 12-position switch allows the load to be grounded on either side, at any of the nine junctions between resistors, or to be left floating. I constructed a voltage balun using 10 bifilar turns of #14 AWG Thermoleze enameled copper wire on an Amidon[9] FT-240-61 toroidal core, connected it to the dummy load and measured the SWR at the input of the balun when the load was grounded at each position. I then added a common-mode choke consisting of 10 bifilar turns of #14 AWG wire with a central crossover on an FT-114-61 toroidal core to make a hybrid balun and repeated the SWR measurements. All measurements were performed at 3.50 MHz. Fig 7 shows the prototype, upside-down, with the base removed. The cores used are not an optimum or recommended design, but were simply what I had on hand. With these cores, 10 turns on each core gives a common-mode impedance of 500 Ω or higher from 3.5 MHz to 21 MHz, while 8 turns per core is recommended to cover 7 MHz to 30 MHz.

Fig 8 plots the measured SWR against the value of R_1 (the resistive component of $\mathbf{Z}_1$). The total load impedance $(R_1 + R_2)$ is always 200 Ω. With the voltage balun, the SWR rises rapidly as the earth tap is moved away from the center of the load, indicating that the currents flowing in the load are not balanced. With the hybrid balun, the SWR remains virtually flat, indicating that the load currents are properly balanced, irrespective of whether the load impedance is balanced with respect to ground.

At frequencies above 7 MHz, the SWR measured at the input to the hybrid balun increases, although it remains constant as the balance of the load with respect to ground is changed. This does not indicate a problem with the balun; it occurs simply because the bifilar winding of the common-mode choke acts as a transmission line with a characteristic impedance of approximately 50 Ω, which transforms the load impedance of 200 Ω to a somewhat lower resistive value, with an additional reactive component. This could be avoided by using a transmission line with a characteristic impedance of about 100 Ω to wind the voltage balun, and one with an impedance of about 200 Ω to wind the common-mode choke. Sevick suggests covering the #14 AWG Thermoleze wires with 15-mil-wall Teflon tubing to obtain a characteristic impedance close to 100 Ω. He suggests "tinned #16 AWG wire... covered with Teflon tubing and further separated by two Teflon tubes"[10] for a characteristic impedance of about 190 Ω.

Conclusion

I used Lewallen's model of the transmission-line transformer to analyze the performance of the 1:1 current balun and the 4:1 voltage balun. The analysis showed that the current balun can only maintain the proper current balance in a load when the load impedance is relatively low, while the voltage balun can only maintain balance when the load is itself well balanced with respect to ground. Since current balance is the reason for using a balun in the first place, and the baluns used in antenna tuners may be required to drive loads that do not meet these requirements, neither the current balun nor the voltage balun is perfectly suited to this application.

I introduced a new design, the "hybrid" balun, and showed that it can maintain current balance while driving a wider range of loads than either the current or the voltage balun, including high-impedance and unbalanced loads. The hybrid balun is easy to construct and may be retrofitted to many existing antenna tuners without the need for any internal modifications. Although it is not perfect, I believe that the hybrid design is "a better antenna-tuner balun."

Notes

[1] R. Lewallen, W7EL, 1995, "The 1:1 Current Balun," which is available at **eznec.com/misc/ibalun.txt eznec.com/pub/ibalun.txt**. Lewallen describes it as a model of the 1:1 current balun, but it is relevant to all applications of the 1:1 TLT.

[2] $\mathbf{Z_W}$ is a complex variable with a real component representing resistance and an imaginary component representing reactance. Complex variables are typeset here in bold face.

[3] F. Witt, AI1H, "Evaluation of Antenna Tuners and Baluns—An Update," *QEX*, Sep/Oct 2003, p 13.

[4] C. Rauch, W8JI, "Balun Test," available at **www.w8ji.com/Baluns/balun_test.htm**.

[5,6] K. Schmidt, W9CF, "Putting a Balun and a Tuner Together," available at **fermi.la.asu.edu/w9cf/articles/balun**. Schmidt gives the measurements in terms of the common-mode, differential-mode and unbalanced impedances. I calculated $\mathbf{Z_1}$, $\mathbf{Z_2}$ and $\mathbf{Z_3}$ using the formulae he gives.

[7] J. Sevick, W2FMI, *Understanding, Building and Using Baluns and Ununs, CQ Communications*, 2003, chapter 9.

[8] W. Maxwell, W2DU, "Some Aspects of the Balun Problem," *QST*, Mar 1983, p 38.

[9] Amidon Associates: **www.amidoncorp.com**.

[10] J. Sevick, W2FMI, *Understanding, Building and Using Baluns and Ununs,* CQ Communications (2003), pp 59 and 81.

Andrew Roos has been a radio amateur since 2001. He has a Bachelor of Arts with Honors degree from Rhodes University and is the technical director and principal systems architect of a software development company in Cape Town, South Africa. He is a past chairman of the Cape Town Amateur Radio Center, regularly teaches classes for the Radio Amateurs's examination, and recently initiated a project to introduce Amateur Radio to school children from underprivileged communities. □□