Building on Wu and King's landmark paper on continuously loaded antennas, Richard Formato's design procedure for impedance-loaded wideband antennas maximises bandwidth while improving radiation efficiency.

WIDEBAND ANTENNAS

Antennas and resistors are usually like oil and water – they don't mix, at least most of the time. The classic example of an absolutely terrible 'antenna' with an excellent standing-wave ratio is a dummy load. A good dummy load's response is nearly flat well into the uhf range. But because essentially all input power is dissipated as heat from i^2R (Joule heating) losses, for practical purposes its radiation efficiency is zero.

Adding resistance to an antenna invariably reduces efficiency and, as a general rule, adding more resistance makes the antenna worse.

But resistance isn't always bad. As the dummy load shows, resistance can broaden an antenna's response by flattening the variation of input impedance with frequency. Certain types of communication system benefit substantially from wideband antennas, typical examples being spread spectrum, frequency-agile, and ALE, or automatic-link-establishment, systems. In each case, it is desirable to maximise antenna bandwidth while maintaining acceptable power gain and radiation pattern.

One way to accomplish this objective is to add resistance. The question is: how much resistance should be added to strike a reasonable balance between wider frequency response and reduced radiation efficiency?

Adding the correct amount of resistance at the proper location can significantly extend an antenna's frequency range while still providing quite acceptable efficiency and gain. This article describes an improved technique for computing the required loading profile for simple wire antenna elements. A typical monopole antenna is then discussed that provides continuous coverage from about 12MHz to beyond 150MHz with no tuner or matching network.

This is not the first time

The idea of adding resistors to an antenna to improve frequency response has been around for quite some time. In 1953, Willoughby[1] discussed resistively loaded wires in a variety of configurations, including Vees and Rhombics, that provided wideband transmit and receive antennas. The wires were loaded either with discrete resistors or with a gradually tapered resistance profile such that the end nearer the rf source had the lowest resistivity and the end farther from the source had the highest.

Resistance can transform a resonant, standing-wave antenna element into a non-resonant, travelling-wave element, thereby increasing the loaded antenna's bandwidth. The distinction between resonant (standing wave) and non-resonant (travelling wave) antenna elements can be illustrated by considering the centre-fed dipole, or cfd, antenna in **Fig. 1**. In the unloaded antenna, resonance results from the superposition of outward-travelling waves produced by the rf source and reflected waves generated at the impedance discontinuity at the cfd's free ends.

These two oppositely propagating waves combine to produce a standing wave which determines the cfd's resonant frequency. If, however, the outward-travelling wave were not reflected, then no standing wave would exist, and the cfd would not exhibit resonance.

One way to minimise reflections is to add resistance near the ends of the element. The resistors absorb incident energy that has not been radiated away from the antenna, thereby reducing the reflected wave amplitude. This general principle underlies all resistive loading schemes. Of course, there are many ways in which resistance can be added to an antenna, and different approaches can produce dramatically different results.

Altshuler[2] provided the first analysis of the effect of adding a discrete resistance to the cfd. He found that an essentially travelling wave current distribution resulted from inserting a 240Ω resistor in each arm of the dipole a distance λ/4 from the end, where λ is the wavelength. Radiation efficiency was reduced by about 50%, but the input impedance was essentially constant over a 2:1 frequency range.

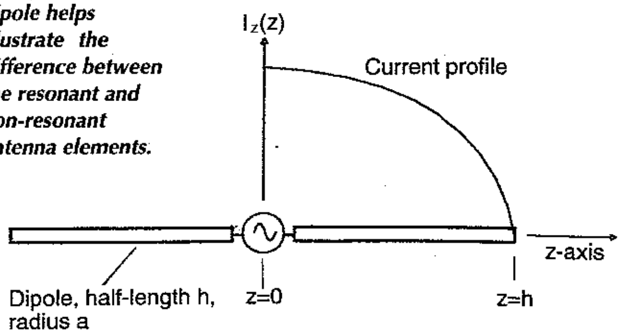
Altshuler's work provided impetus for Wu and King's[3] landmark paper on continuously loaded antennas. Their work forms the basis of recent efforts to improve bandwidth by adding resistance. It is discussed in more detail below.

Some of the results achieved with loaded antennas have been impressive. Kanda[4] built a very small receive-only field probe – a loaded cfd – that exhibited essentially flat frequency response from hf to beyond 1GHz. This sensor was so heavily loaded, however, that its radiation efficiency was far too low for it to be useful as a transmit antenna. Rama Rao and Debroux[5,6] described a 35ft loaded hf monopole with swr≤2 from 5-30MHz and radiation efficiency ranging from about 15%-36%.

This antenna used a fractional loading profile equal to 0.3 times the Wu-King profile and a fixed, lumped-element matching network. Other loading profiles have been proposed that combine resistance and inductance to improve bandwidth and efficiency[7].

This article describes a modification of the original Wu-King profile that increases antenna bandwidth by creating a travelling-wave element

Fig. 1. Centre-fed dipole helps illustrate the difference between the resonant and non-resonant antenna elements.



while at the same time improving radiation efficiency by increasing the antenna's average current. Because the radiated fields are proportional to the antenna's Idl product, a higher average current increases the radiated fields, which in turn improves efficiency. The motivation for this new profile is the realisation that the Wu-King current profile is a special case of a more general travelling-wave current distribution with higher average antenna current.

Wu-King explained

Figure 1 shows a centre-fed dipole antenna consisting of two elements of length h and radius a. Amplitude of the current profile is plotted schematically along one element's length. Maximum current occurs at the rfsource at the feed point, and the magnitude decreases along each arm until it reaches zero at the end. In the Wu-King model, the centre-fed dipole is assumed to have an internal impedance profile along the wire element given by $Z^i(z)=R^i(z)+jX^i(z)$, where Z^i is the (complex) internal impedance per unit length (Ω/m), consisting of lineal resistance R^i and reactance X^i, and where $j=\sqrt{-1}$.

Wu and King develop the differential equation satisfied by the current $I_z(z)$, and then determines by inspection that a travelling-wave current mode exists for one particular impedance profile, Z^i. The Wu-King current distribution is,

$$I_z(z) \approx \underbrace{\left(1-\frac{|z|}{h}\right)}_{\text{linear amplitude decay}} \exp \underbrace{\left(-jk_o|z|\right)}_{\text{travelling wave factor}} \tag{1}$$

which consists of the product of a linearly decreasing ('straight line') amplitude and a travelling wave propagation factor in the complex exponential term. The wave number is $k_o=2\pi/\lambda$. The propagation factor represents a current wave progressing outward along each dipole arm. There is no reflected wave propagating toward the source to form a standing wave pattern, and consequently no resonance effect.

This current distribution exists *only* when the cfd element has a specific '$1/z$' internal impedance profile. The required profile is given by:

$$Z^i(z) = \frac{60(\psi/h)}{1-\frac{|z|}{h}} \tag{2}$$

where $\psi=\psi_R+j\psi_I$ is the complex expansion parameter discussed in Altshuler[2], with real and imaginary parts subscripted R and I, respectively. The ratio of the antenna element's vector potential to current is ψ, and is approximately constant along its length. Because ψ varies with frequency, it is usually evaluated at the fundamental cfd resonance, that is, when $h=\lambda/4$ (see ref. 3). The $1/z$ profile in equation (2) is the basis for the resistive loading used in refs. 4, 5 and 6.

Improved loading profile

An improved loading profile – that is, one that provides better radiation efficiency than the $1/z$ profile – can be obtained by generalising the Wu-King results. The first step is to assume a power law travelling-wave current distribution, of which the Wu-King current distribution is a special case.

The next step is to substitute the assumed current distribution into the current equation developed by Wu and King, which then yields the condition that must be satisfied by the element's internal impedance in order to generate travelling-wave only modes.

This approach is fundamentally different from the one in Wu-King because the loading profile for a particular travelling-wave current mode is now an unknown which is determined by solving the appropriate equations.

The generalised cfd current distribution is assumed to be of the form:

$$I_z(z) = \underbrace{C\left(h-|z|\right)^{\nu}}_{\text{power law amplitude decay}} \exp \underbrace{\left(-jk_o|z|\right)}_{\text{travelling wave factor}} \tag{3}$$

where C is a complex constant determined by the current at the feed point. Note that the amplitude decay is a power law variation with exponent ν. The Wu and King case is recovered when $\nu=1$, but when $\nu\neq1$ the more general case is obtained.

The internal impedance profile that produces travelling-wave only currents of the form in equation (3) is determined as follows. The derivatives dI_z/dz and d^2I_z/dz^2 are computed and substituted into the equation satisfied by $I_z(z)$ (Wu and King's equation[11]). This generates the equation that must be satisfied by the auxiliary function $f(z)$ introduced in Wu-King equation (9). Its solution is,

$$f(z) = 2\nu\left(h-|z|\right)^{\nu-2}\left\{1-j\frac{\nu-1}{2k_o\left(h-|z|\right)}\right\} \tag{4}$$

$f(z)$ determines the impedance profile. Equation (4) generalises Wu and King's equation (12), and recovers their results exactly when $\nu=1$.

Figure 2 shows several current amplitude distributions parametric in the power law exponent ν. It is apparent that values of ν less than 1 can lead to significantly higher average antenna currents. Radiating elements with these current distributions are more efficient than those using the $1/z$ loading profile which results by setting $\nu=1$.

The loading profile resistance and reactance per unit length are computed from $f(z)$ and are given by:

$$R^i(z) = 60\nu\left(h-|z|\right)^{\nu-2}\left\{\psi_R-\frac{(1-\nu)\psi_I}{2k_o\left(h-|z|\right)}\right\} \tag{5a}$$

$$X^i(z) = 60\nu\left(h-|z|\right)^{\nu-2}\left\{\psi_I+\frac{(1-\nu)\psi_R}{2k_o\left(h-|z|\right)}\right\} \tag{5b}$$

The corresponding lineal inductance (henry/metre) or capacitance (farad/metre) is given by $L^i=X^i/\omega$ and $C^i=(\omega X^i)^{-1}$, respectively, for $X^i>0$ and $X^i<0$. The circular frequency is $\omega=2\pi f$ where f is the frequency (Hz) at which ψ is computed.

It is apparent from equation (5) that the improved loading profile in

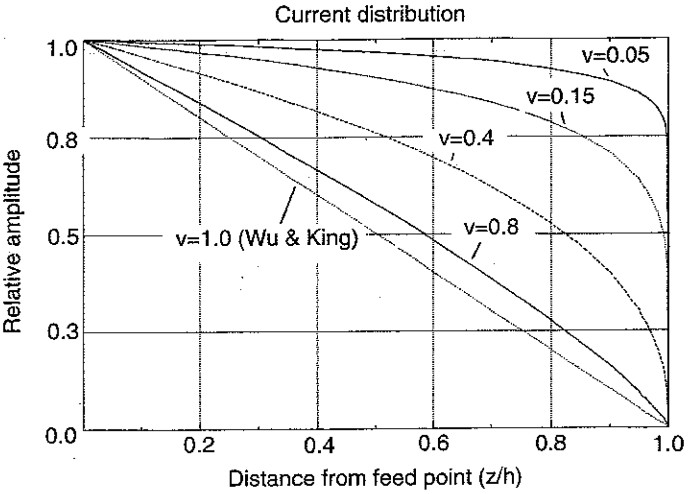


Fig. 2. Values of v less than 1 can lead to significantly higher average antenna currents.

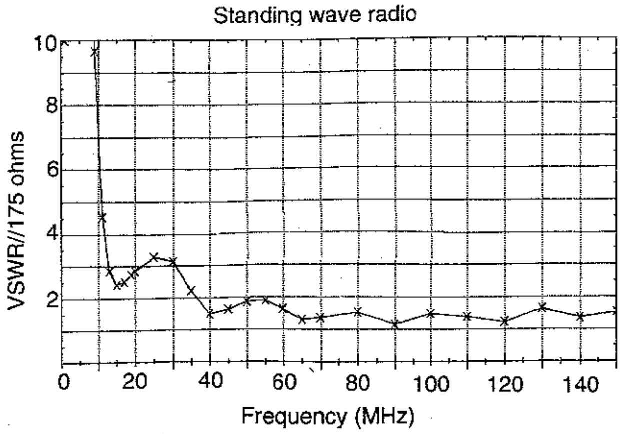


Fig. 3. Compound input swr for a 174Ω feed system, with calculated values marked at points x.

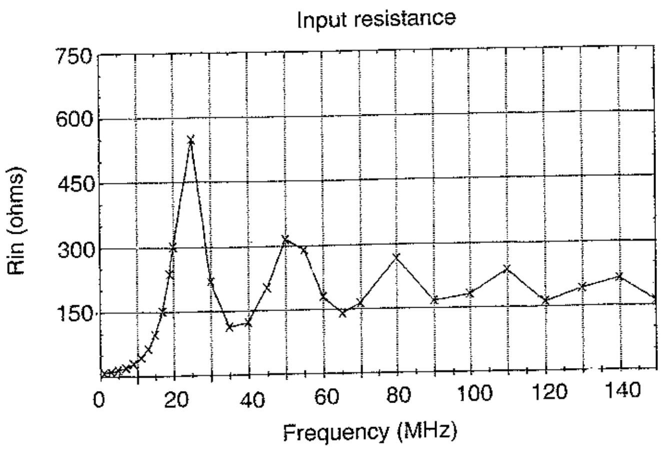


Fig. 4. Monopole feed-point resistance plot.

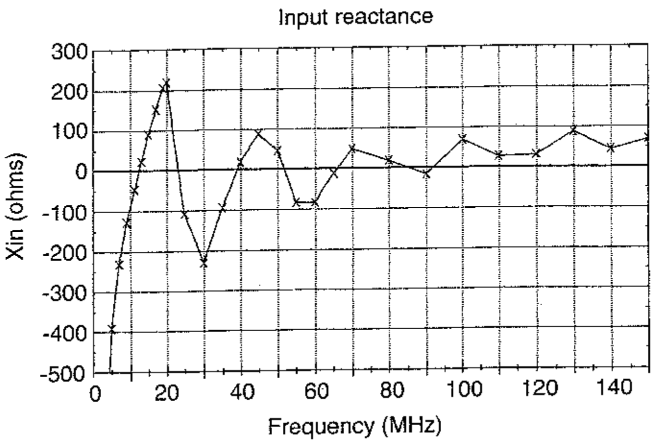


Fig. 5. Reactance plot for the monopole feed-point.

general contains both resistance and reactance. But adding reactance to the antenna, especially capacitive reactance, can complicate construction. As a consequence, many practical designs employ only resistive loading (see refs. 5 and 6, for example), because excellent results are often achieved even without the loading profile's reactive component.

Loaded hf-uhf monopole

To illustrate the degree of broadbanding achievable, a loading profile was computed for a monopole element fed at its base against an infinite, perfectly conducting ground plane. The radiating element height is 5.83m, and its radius 2.54cm. The design frequency for evaluating ψ is 12.86MHz, and the power law exponent v is 0.05. ψ is $8.961-j2.431$.

Using equation (5a), a resistance profile was computed for 14 discrete loading points along the antenna, **Table 1**. The profile increases very gradually from 0.419Ω near the base of the monopole to approximately 787Ω near the top. Reactive loading (in this case, inductive) was not included.

The monopole's performance was computer-modelled from 1 to 150MHz. The computed input SWR for a feed system impedance of 175Ω appears in **Fig. 3**; calculated points are marked x. Because swr was computed for a 175Ω characteristic impedance, matching the usual 50Ω coaxial feed requires a 3.5:1 Unun or another suitable broadband transformer.

The monopole antenna's performance is excellent at all frequencies above 36MHz. The swr is below 2 from there to 150MHz (the upper limit for the computer model), and somewhat worse from approximately 12 to 36MHz, reaching a maximum 3.3 at 25MHz. Below 11MHz, swr increases rapidly due to increasing capacitive reactance and decreasing radiation resistance. This behaviour is characteristic of electrically short antennas, and is evident in the monopole's feed point resistance and reactance plots in **Figs 4** and 5, respectively. The data in these curves were used to compute the swr plot in Fig. 3.

Table 1. Resistance profile for 14 discrete loading points along the antenna.

Height (m)	Resistance (Ω)
0.208	0.419
0.625	0.489
1.041	0.581
1.458	0.699
1.874	0.859
2.290	1.080
2.707	1.401
3.123	1.889
3.539	2.689
3.956	4.129
4.373	7.131
4.789	15.102
5.205	49.473
5.622	786.910

The monopole antenna's impedance bandwidth is remarkably good – especially considering that there is no matching network and only discrete resistive loading is employed. In addition, no attempt was made to further improve the loading profile by, for example, modifying computed resistance values or adding reactance. Adjustments such as these can frequently yield even better performance, but they are not considered further.

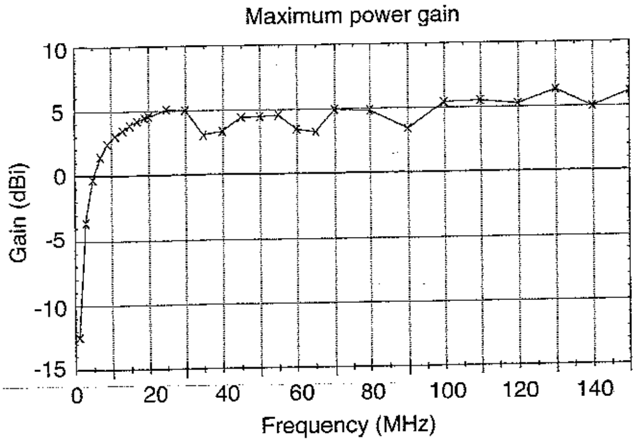


Fig. 6. Maximum gain of the wide-band monopole antenna.

The following observation illustrates how dramatic the effect of loading an antenna can be. For an *unloaded* monopole, the bandwidth for swr≤2.5 (50Ω feed) is typically 15-25% of its $\lambda/4$ frequency, depending on the length-to-diameter ratio. A monopole $\lambda/4$ high at 12.86MHz, such as the one considered here, would show a bandwidth of less than 3.2MHz. Increasing the bandwidth to greater than 115MHz, as the improved loading profile does, is indeed a very substantial improvement.

Of course, as the dummy load example teaches, impedance bandwidth alone does not a good antenna make. Two other key measures of the loaded monopole's performance appear in **Figs 6** and **7**, maximum gain and radiation efficiency, respectively.

Power gain, computed as the product of directive gain and efficiency, is plotted in dBi (decibels relative to an isotropic radiator). For comparison, the maximum power gain of a half-wave cfd in free space is 2.15dBi. The loaded monopole's gain at 10MHz is nearly 3dBi, and from 10 to 150MHz it is mostly in the 4-6dBi range. The monopole with the improved resistance profile thus exhibits power gain figures that are typical of similar antennas with no loading at all.

The point was made at the start of this article that the fundamental issue in choosing a loading profile is the trade-off between bandwidth and radiation efficiency. The merit of a particular profile is determined primarily by these performance measures. An examination of Fig. 3 showed that the monopole's swr curve is more or less flat from 36 to 150MHz, with somewhat higher but still acceptable swr from 12 to 36MHz.

The second measure of merit, radiation efficiency, is plotted in Fig. 7. The efficiency is generally above 60% over the entire range of 10 to 150MHz, with only minor dips below 60%, and some regions where it is near or above 70%. Even the minimum efficiency value of 45% or so near 35MHz is quite acceptable.

The improved resistive loading profile has produced an antenna with exceptionally good swr bandwidth, relatively high power gain, and very acceptable radiation efficiency.

In summary

Adding resistance to an antenna can dramatically improve bandwidth, but doing so reduces radiation efficiency. The trade-off between greater bandwidth and efficiency is not arbitrary. Some loading profiles are much better than others for creating wideband antenna elements.

Previous theoretical calculations of suitable profiles provide a sound basis for loaded element design yielding very good results. But these studies considered only a special case of a travelling-wave current distribution. The improved loading profile described in this article results from extending the previous work to a power law travelling-wave current mode.

Typical computer modelling results show that the improved profile provides better performance than previously used profiles. The technique for calculating the improved element loading promises to yield still better antennas in terms of bandwidth and efficiency, and may be put to good use to accomplish this goal. ■

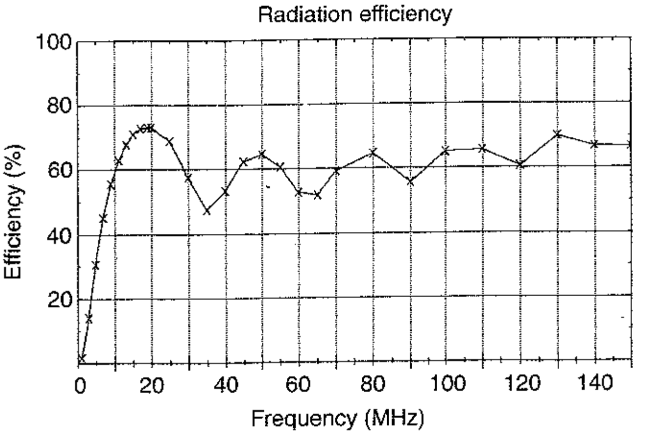


Fig. 7. Radiation efficiency of the loaded wide-band antenna example.

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HP3325A Synthesized Function Generator 1microHz-21MHz 11 Digit ... £1500
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Wavetek Model 1067 Sweep Generator 1-400MHz Power Range +57 to –7dBm ... £400
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Wavetek Model 147 Sweep Generator 0.0005Hz-10MHz 15V P-P ... £250
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OSCILLOSCOPES
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Gould OS3500 60MHz Bandwidth, Dual Channel, Delayed Sweep ... £275
Gould OS4000 10MHz Bandwidth, Dual Channel, Digital Storage ... £150
Crotech 15MHz Bandwidth, Dual Channel ... £125
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HP1740A 100MHz Bandwidth, Dual Channel, Delayed Sweep ... £250
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HP54120A + HP54121A Colour Mainframe, 20GHz Digitizing, 17.5pS Rise Time, TDR System, Histogrammes, HPIB ... £7000
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IWATSU DMS6430 Digital Memory Scope, 8 Bit x 4096 Word Memory Length ... £850
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IWATSU SAS8130 Waveform Analyzer. DC-3500MHz Dual Channel, 10 Bit x 1024 Word Memory Each Channel ... £1500
Philips PM3217 50MHz Bandwidth. Dual Channel, Delayed Sweep ... £325-£400
Philips PM3340 2000MHz Bandwidth. Dual Channel, Digitizing, Auto Set Up, 175PS Rise Time ... £3800
Scopex 4D10A 10MHz Bandwidth, Dual Channel ... £75
Tektronix 453 50MHz Bandwidth. Dual Channel, Delayed Sweep ... £150
Tektronix 465B + DM44 100MHz Bandwidth, Dual Channel, Delayed Sweep ... £400
Tektronix 465 100MHz Bandwidth, Dual Channel, Delayed Sweep ... £350
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Tektronix 2445 150MHz Bandwidth, Four Channel, Delayed Sweep, Cursors, Readout ... £1400
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7A13 Differential Comparator ... £290
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7D11 Digital Delay Unit ... £50
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7603 100MHz Mainframe ... £275
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