THE ZAGI

Controlled Coupling in Reduced Size "Slow-Wave Structure" Antennas

By Dan Handelsman and David Jefferies

Introduction:

We present a new class of antenna based on a "slow-wave" structure. The antenna discussed here is called a Zagi and an example is shown in **Figure 1**. The antenna elements are formed from regularly bent wires; in this simple case they are just zigzags, but many other regularly bent structures are possible.

Figure 1 - the Zagi

In a "slow-wave structure", the speed of waves along the length of the structure is less than the speed c of electromagnetic waves in free space. Therefore, at a given frequency f the wavelength (lambda) along the axis of the elements is less than the free space wavelength c/f. As is well known, the wave velocity on line with parameters L and C is sqrt(1/LC) meters per second, and for a straight wire this is very nearly equal to c = 3E8 meters per second, the velocity of light in free space.

To make a slow wave structure, it is therefore necessary to increase L or to increase C, or both. Periodically bending the wires does both, and in this case we find it reduces the velocity by a factor roughly equal to the total wire length divided by the total element length. Discussion of other slow wave structures, and of the mathematics behind them, will follow in a later article.

So, these slow wave structures have increased inductance L per unit length, and increased capacitance C per unit length. When two such elements are brought into close proximity, the coupling capacitance and mutual inductance (between the elements) are also increased. There is background reading material about slow wave structures and also about periodically loaded transmission line in the Bibliography at the end of this article.

This class of antenna exhibits the following properties:

Reduced size:

The length of the element at resonance is smaller and the antenna may be made more compact. This benefit comes at the cost of reduced radiation resistance, which falls somewhat as the radiating length is shortened. The radiation resistance may be partially restored by using a folded dipole (zagged version) for the driving element, in the usual manner.

Control of coupling and f/b ratio:

The increased coupling may be adjusted by using the geometric freedom of the design without altering the overall structure of the Zagi. For example, the spatial periodicity and amplitude of the zags may be independently adjusted, as also can their lateral position with respect to the zags in the adjacent elements. Very large front-to-back (f/b) ratios can be attained at a particular spot frequency, even in two-element arrays. The overall size of the array can be reduced significantly when compared to a straight rod yagi.

Historical background of the design:

In this first article on the Zagi, we present a possible structure that is easy to build and to model. The simulations suggest that it will outperform a two-element Yagi in most aspects, at the cost of a minor increase in complexity.

The ideas for the Zagi arose because, first, Handelsman thought that the folding in the structure of Werner Hoedlmayr's "fractal" dipole suggested that such elements would couple more strongly than the rod elements found in a Yagi. This view was supported by Werner, who stated that a parasitic (driver/reflector) pair of "fractal" dipoles required a quarter wavelength of separation (which is large) in order to have a high f/b. David Jefferies pointed out that any kind of bent-wire structure would couple more strongly than do straight rods.

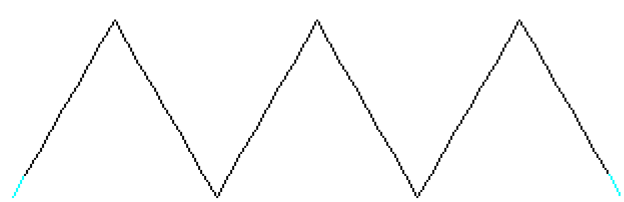

Figure 2 - serrated or saw tooth wire

Second, in his work with the Cube-C and many folded variants, Handelsman had tried a "sawtooth" wire seen in **Figure 2**. The idea was to increase the electrical length while, at the same time, keeping the physical size of the element small. This structure was rejected because the electrical lengthening was only a fraction of the total extra length of wire used. Jefferies said that this was because it resulted in a slow-wave structure with a lower effective wave velocity than in free space. The electrical length was therefore approximately constant irrespective of the wire length.

David Jefferies also suggested that, because of the adjustable parameters in the design, it would be a very good way to test out the effects of having variable coupling in a bent-wire antenna without getting into the complexities of fractal structures.

The name arose because Dan Handelsman's "zig-zagged yagi" proved to be too big a mouthful. L B Cebik suggested the moniker "zigzag yag" for this design, but David Jefferies (who prefers succinctness) suggested "Zagi," encompassing the "Zig," the "Zag," and the "Yagi" ideas.

The need for controlled coupling:

With all parasitic antennas, the standard adjustable parameters in design are the relative sizes of the driver and parasitic elements, the inter-element spacing, and the wire diameter. The resulting properties that we desire to adjust are the resonant frequency, gain, bandwidth and the f/b ratio.

With the Zagi, discussed below, we have additional design parameters which can be varied: the number of serrations, the size of serrations, the base angle of the basic triangles and the relative orientation of the serrations relative to each other on the elements. This gives us added control over the coupling and the consequent properties.

The two most commonly used elements in arrays, the rod dipole and the loop, have fixed inter-element coupling, for a given element spacing. If we wish to optimise the front-to-back ratio, the rod antenna exhibits too little coupling, and the loop too much. Let us look at examples of each.

	driver	reflector	spacing	Rin	gain	f/b	b/w
Yagi	0.452	0.5000	**0.094**	22	6.31	**11.42**	8
Quad		0.2867	**0.164**	145	7.18	**41.9**	62
dimensions in meters-wl, R in ohms, gain in dBi, f/b in dB and bw in MHz at 300 MHz							

Table 1 - quad vs yagi comparison

Compare the 300 MHz two-element Yagi and Quad characteristics shown in **Table 1**. The wire diameter is 5mm.

Note that the two-element Yagi has a very poor f/b ratio, and this is its major disadvantage. The f/b is related to the current magnitude and phase, which can be induced in the parasitic element, a reflector in this case. As a general statement we may say that, to achieve a very high f/b, the induced current should be almost equal in magnitude to that in the driven element. The rod elements in a two-element Yagi do not reach this state. A further advantage of element current-equality is that we believe that the equal current division leads to significantly increased bandwidth (bw) over that of a single element. We refer you to "The Well Behaved Antenna," where we discuss the bw advantage of such coupled antennas: http://www.antennex.com/archive4/Apr00/Apr4/behave.htm, Archive IV, number 06, First published April, 2000].

The Moxon Rectangle Yagi is one solution to the problem of poor coupling among rod elements in a Yagi. Moxon found that he could increase the coupling between dipoles by folding the ends in. See **Figure 3**.

Figure 3 - Moxon rectangle

Loop arrays lead to problems with over-coupling. As we have shown in our antenneX article on the Well Behaved Antenna the wires which are orthogonal to the co-directional radiating wires and which contain the current nodes lead to very strong inter-element coupling. This is fine with a two-element Quad where we can get much higher f/bs and a much greater f/b bw than with a Yagi. However, this leads to the large element spacing with the quad in **Table 1**. Moreover, the increased coupling interferes with the design of multi-element Quad arrays. For more than about 4 elements, the Yagi has more gain for a given boom length and is the preferred antenna for large arrays.

Ideally, we would like an element, which has more coupling than a dipole and less than a loop. Even better, we would like elements where the coupling may be varied to suit conditions and design requirements. Our goal is to do so with antennas that are volumetrically efficient - meaning that we can squeeze out the maximum performance for a given volume of space. The Zagi fits the bill.

The Zagi:

At Jefferies suggestion, Handelsman modeled the Zagi as shown in **Figure 1**. Up until now, there have been few slow wave antennas described in the literature; the classic example is the helix in all its variants. Fractal elements also seem to belong to this class.

Let us first examine, in **Table 2**, the performance of single dipole Zagi elements. Figures 4-6 illustrate three kinds of serrated dipoles that were studied. Each serration or "saw tooth" is a triangle with a base angle of 45, 60 or 70 degrees and an apex angle which is 180 - 2*base angle. We use the base angle in our nomenclature to differentiate the antennas.

Figure 4 - Zagi dipole - 45 degree base angle

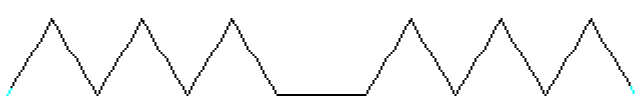

Figure 5 - Zagi dipole - 60 degree base angle

Figure 6 - Zagi dipole - 70 degree base angle

Figures 4-6 are dipoles with base angles of 45, 60 and 70 degrees respectively.

Zagi Dipoles: Center frequency - 300 MHz						
base angle	total wire	Width	Height	Rin	Gain	BW
45	0.5568	0.406	0.030	57.0	2.07	34
60	0.6555	0.353	0.044	45.2	2.01	28
70	0.7734	0.304	0.056	35.6	1.96	23
rod dipole	0.4664			72.3	2.13	40
dimensions in meter-wl. Rin in ohms. gain in dBi and BW in MHz centered						

Table 2 - zagi dipoles

Note that the gain drops slightly and the Rin and bw decrease as we increase the base angle. The total amount of wire increases and the overall element size decreases as we increase the base angle. The latter leads to a progressive fall in radiation resistance.

Studies, which are summarized below, were then made on Zagis where the serrations on each element physically lined up with each other. Such an alignment is seen in **Figure 7** where we show a Zagi, viewed end-on, which has a base angle of 45 degrees and a driver/reflector offset of zero. An additional variable was that the coupling between elements could be varied by physically changing the alignment of the serrations or by rotating the plane of one element with respect to the other.

Figures 7-9 show how the serrations may be offset against each other - between the driver and reflector - so that we can see, in the model results, if the coupling can be varied between elements. Handelsman, to reduce the complexity of his model, arbitrarily used values of zero, 50 and 100% as the offsets of the reflector serrations with respect to those on the driver.

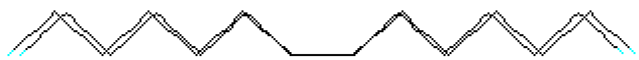

Figure 7 - Zagi - 45 degree base angle - zero element offset

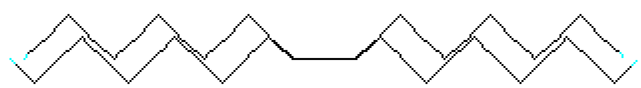

Figure 8 - Zagi - 45 degree base angle - 50% offset

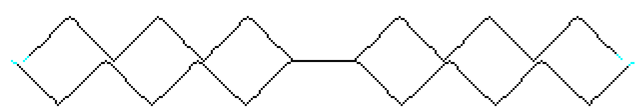

Figure 9 - Zagi - 45 degree base angle - 100% offset

The maximum base angle of 70 degrees, corresponding to an apex angle of 40 degrees, was arrived at because, for 5 mm diameter wires, it was the smallest apex angle which would not cause a NEC modeling error.

Serration size effects:

Zagis - 2 el: Center frequency - 300 MHz Offset - zero,							
Performance Parameters - dimensions in meters							
	driver	reflector					
base angle	total wire	total wire	Spacing m	Rin ohms	Gain dBi	f/b dB	BW MHz
45	0.5383	0.555	0.031	2.9	6.41	40.3	1.5
60	0.6275	0.659	0.071	11.3	6.35	56.9	5.1
70	0.7429	0.779	0.101	17.1	6.33	49.9	8.6

Table 3 - performance parameters of 3 zagis with base angles 45,60 and 70 degrees

Using **Table 3**, we can now compare the performance of Zagis with base angles of 45-70 degrees and zero offset. The "offset zero" means that the peaks of the serrations in the reflector and driven element are not offset from each other and are aligned as much as possible given the length differences between the elements. Note that the gain is little different among the three antennas, and little different from that of a comparison Yagi in **Table 1**. All the f/b ratios are very high and are the product of near-equality in the currents. Each antenna could be tuned to a f/b over 50 dB when the dimensions were modified to another decimal place. The gains were not corrected by using the AGT or Average Gain Test but any correction would be in tenths of a dB and not germane to the discussion about coupling and f/bs.

All of the antennas have very high f/b. Inter-element coupling increases with the base angle. The antenna with a 45-degree base angle has poor coupling and small driver-to-reflector spacing. The latter, in turn, leads to a lower Rin and a narrow bw.

As we increase the base angle to 60 and 70 degrees, the array performance improves. The element spacing increases, because the coupling is increasing, and so does the Rin and the bw. This is all with the added benefit of a decreasing element size. The bw now exceeds that of a full-sized Yagi.

Zagis - 2 el: Center frequency - 300 MHz Offset - zero,					
Overall dimensions in meters					
	driver	reflector	overall	overall	
base angle deg.	total wire	total wire	width	height	spacing
45	0.5383	0.555	0.39	0.030	0.031
60	0.6275	0.659	0.34	0.042	0.071
70	0.7429	0.779	0.29	0.054	0.101

Table 4 - overall dimensions of "zero offset" Zagis - all are in meters

The dimensions in **Table 4** show that the 70 degree antenna fits into a cube which is .29 x .054 x .1 m-wl in size. The width is considerably smaller than a Yagi's and the height and element spacing are smaller than in a quad version. Note the low velocity factors of these antennas when you compare their overall width with the total amount of wire in the element.

Variable coupling:

Let us now examine what happens when we vary the position of the serrations on the reflector with respect to those of the driven element. **Table 5** is a comparison of all of the Zagis - with base angles of 45, 60 and 70 degrees and offsets of 0, 50 and 100%.

Zagis - 2 el 300 MHz - all base angles and offsets							
offset pct.	base angle	spacing	Rin	gain	f/b	dr width	ref width
0	45	0.031	2.9	6.41	40.3	0.5383	0.555
50		0.023	1.8	5.75	42.6	0.5409	0.561
100		0.019	1.7	4.48	36.0	0.5432	0.553
0	60	0.072	11.3	6.35	56.9	0.6275	0.659
50		0.064	9.0	6.31	47.3	0.6300	0.674
100		0.056	7.8	6.04	47.3	0.6310	0.657
0	70	0.101	17.1	6.33	49.9	0.7409	0.779
50		0.093	14.4	6.33	51.0	0.7436	0.808
100		0.084	12.8	6.13	47.8	0.7450	0.778

Table 5 - comparison of zagis with various base angles and element offsets
(dimensions in m, R in ohms, gain in dBi, f/b in dB)

As expected, increasing the lateral offsets, as discussed above, decreases the coupling and necessitates a smaller element spacing, which results in a lower Rin, gain, and bw.

While this may seem a disadvantage in the two element arrays we have studied so far, it may very well be advantageous when constructing larger arrays. In such antennas, we may wish to use directors with lower coupling in order to achieve closer element spacing and shorter boom lengths. This may well go hand in hand with using driven and reflector elements with greater coupling in order to maximize the starting Rin of the antenna. At this time there are many possibilities which need further study.

As mentioned earlier, controlling the coupling by element rotation has been tried and will be the subject of a later article.

Possible variants:

We are by no means limited to "saw tooth" or serrated triangular elements. There is no reason why rectangles or other regularly repeating shapes cannot be used in creating the elements. All should work nicely in slowing down the wave propagated along the wires and may well be superior to the ones discussed herein. Periodically loaded wires have great advantages over pseudo-fractal or randomly bent wires, in that the transmission line parameters do not fluctuate along the elements. We can achieve periodic perturbation with side stubs instead of by bending the wires. This method gives us many adjustable parameters to play with, resulting in a modeler's dream or nightmare depending on which way one looks at it.

In this vein, promising antennas have been modeled by Handelsman using Jefferies' suggestions of ribbon and sheet elements.

Possible construction techniques:

The straightforward Zagi construction suggests bending the element wires to make the zagged elements. It looks as if this might be tricky for antennas made out of copper or aluminum tube. Alternatively, the zagged elements might be cut out of a flat sheet of metal which has appropriate thickness. A long thin rectangular ribbon of metal might be bent perpendicular to its flat faces. A periodically loaded structure might be stamped out of a sheet of metal.

Summary:

We have introduced a new concept in antenna design which takes advantage of slow wave propagation in order to create antennas with increased coupling relative to rod elements and the ability to vary the coupling to meet design needs. This results in performance advantages as far as f/b, size and bandwidth at the cost of a minor increase in complexity.

Due to the ability to vary the coupling between elements by varying their shapes relative to each other, we have the ability to design ideal elements for any given purpose. This is only the beginning and the field is wide open to design innovation by readers of *antenneX*.

Selected bibliography on slow wave structures and on periodically loaded transmission line.

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6) Robert S Elliott, *An Introduction to Guided Waves and Microwave Circuits* (Prentice-Hall, 1993, ISBN 0-13-013616-6), Section 13.3, pages 436-442, "Lossless periodic structures"

BRIEF BIOGRAPHY OF AUTHOR

Dan Handelsman - N2DT

Dan Handelsman, N2DT~ Email

Dan Handelsman, N2DT was first licensed as WA2BCG in 1957at age 13. He became interested in antennas at that time when he had to figure out a way to operate from the 6th floor of his apartment house. This resulted in a mobile whip being stuck out from a window without a counterpoise. At that point he became an "expert" in TVI. He was licensed as N2DT in 1977 and is a DX'er and contester. He is now playing with experimental antennas and low power.

Professionally, he is a Pediatric Endocrinologist and holds M.D. and J.D. degrees and is Clinical Professor of Pediatrics at the New York Medical College. As far as his antenna work he is an "amateur" in the truest sense of the word (Dan's words!).

TO BIOGRAPHY OF AUTHOR

Dr. David J. Jefferies
School of Electronics and Physical Sciences
University of Surrey
Guildford GU2 7XH
Surrey, England
D.Jefferies email
Click Here for the Author's Biography