Genetically designed Yagi

Richard Formato explains how a natural-selection like design process produces better antennas, and provides evidence in the form of a three-element Yagi example for 50MHz work.

Genetic algorithms, or GAs, are a class of optimisation techniques that mimic natural selection, i.e. 'survival of the fittest'. Such algorithms are applicable to many types of problems, and they are becoming increasingly useful in antenna design[1,2]. This note describes a genetically designed three-element Yagi that provides very good performance and illustrates how effective genetic algorithms can be.

Unlike deterministic optimisation schemes, GAs are based on random selection. A binary-coded genetic algorithm starts by creating a population of 'chromosomes' which are random one and zero bit sequences. Each chromosome contains a complete antenna design – in this example – a complete three-element Yagi antenna.

The chromosome is made up of 'genes' which are strung together one after another. Each gene corresponds to one of the antenna's design parameters.

The Yagi gene relationship appears in **Table 1**. A design is fully specified by eight genes: reflector length and radius *REF*, driven element length and radius *DE*, director length and radius *DIR*, and location along the boom *DE*/*DIR*. Gene length is its length in bits – for example, *REF* length is five bits.

The minimum and maximum values of each design parameter also appear in the table, and all dimensions are in wavelengths, 'waves'. The *DE* length, for example, cannot be longer than 0.6 wave or shorter than 0.4 wave.

Since each design parameter is a decimal number, not a bit sequence, the actual value of the parameter is computed by decoding its binary gene using the following transformation equation,

$$X = X_{\min} + \left(\frac{X_{\max} - X_{\min}}{2^L - 1}\right) \times D$$

where X is the decimal value of the parameter, D is the decimal value of the gene's binary sequence, and L is the gene's length.

To illustrate how this decoding scheme works, consider the 37-bit chromosome that contains the design for the Yagi discussed below:

0010111000011011111001011100010111100

The *DE* length is coded in gene No 3, which starts at bit No 10 and ends with bit No 14. The binary sequence for the *DE* length gene is 00110, and its decimal value is,

$$0(2^0)+0(2^1)+1(2^2)+1(2^3)+0(2^4)=12$$

Since gene No 3 is five bits long, the denom-

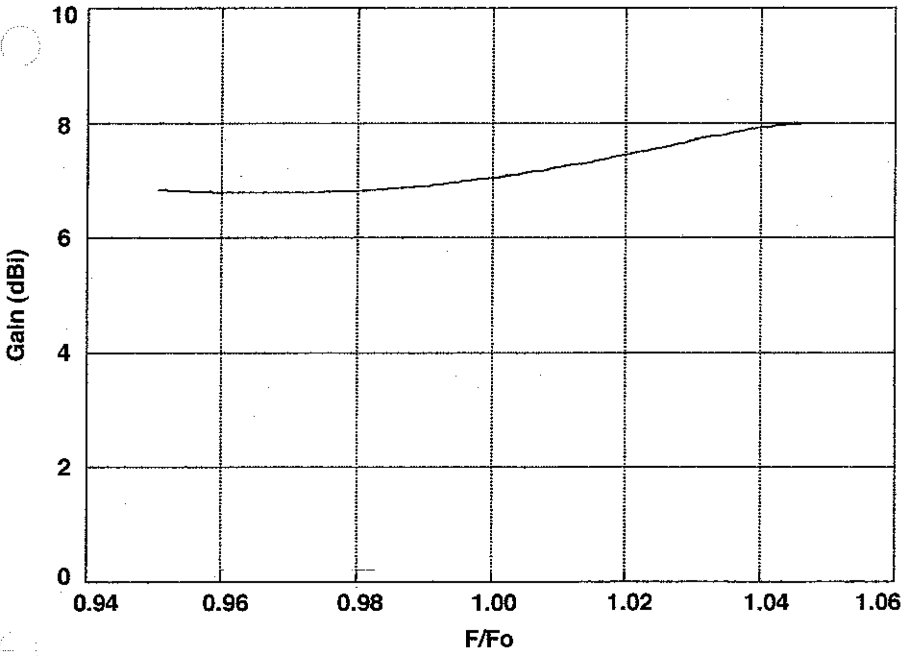

Fig. 1. Main lobe gain for the genetically-designed Yagi example.

Table 1. Gene table for three-element Yagi.

Gene #	Name	Length	Min	Max
1	REF Length	5	0.4	0.6
2	REF Radius	4	0.0005	0.002
3	DE Length	5	0.4	0.6
4	DE Radius	4	0.0005	0.004
5	DE Separation (from ref.)	5	0.05	0.3
6	DIR Length	5	0.4	0.6
7	DIR Radius	4	0.0005	0.002
8	DIR Separation (from DE)	5	0.05	0.3

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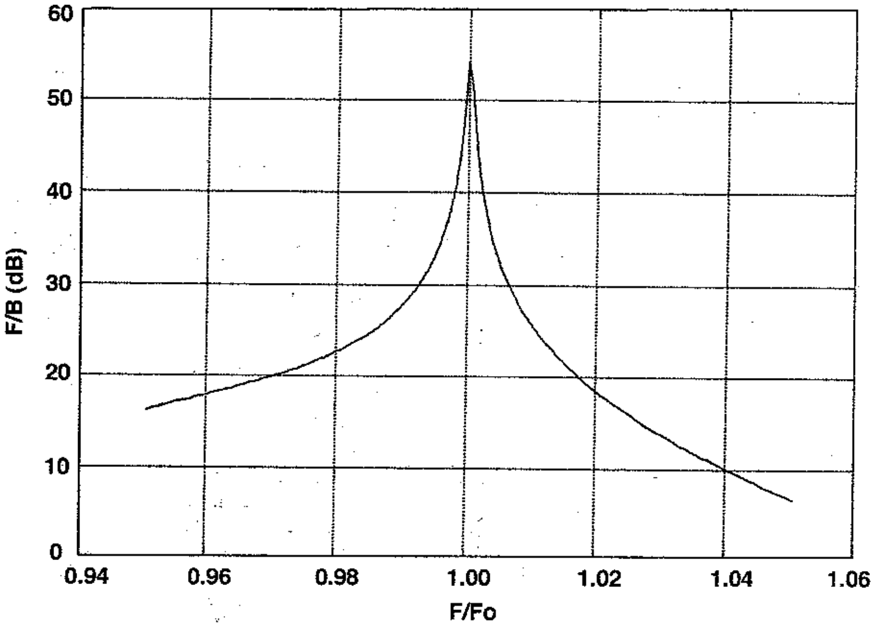

Fig. 2. Front-to-back ratio for the genetically-designed Yagi example.

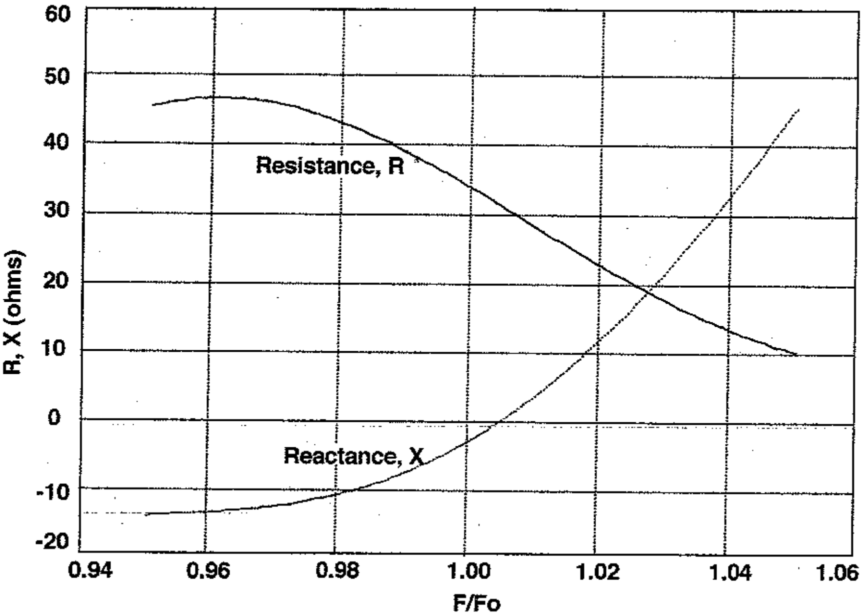

Fig. 3. Genetically-designed Yagi's input impedance.

inator in the transformation equation is $2^5-1=31$. This makes the *DE* length,

$$\frac{0.4+(0.6-0.4)12}{31}=0.477419355$$

wavelengths. Because the computer model used to calculate the Yagi's performance inputs the *half*-length of *DE* instead of its overall length, this value is divided by two and rounded to three places to give 0.239 wave. This decoding scheme is used to evaluate each of the Yagi's design parameters. The *DIR* radius, gene No 7, for example, evaluates to 0.0015 wave, and so on.

The genetic algorithm begins by creating an initial population of random 37-bit chromosomes. It then applies the operators of 'selection', 'crossover', and 'mutation' to filter out 'unfit' designs while retaining the better ones.

Successive applications of these operators create 'generations' of antenna designs, with each subsequent generation hopefully containing better designs than the previous one. But, because of the algorithm's inherently random nature, there is no guaranty of obtaining better designs. They may actually become worse from one generation to another.

Well-designed genetic algorithms, however, usually produce progressively better designs, at least on the average. Every new run holds the intriguing possibility of producing a previously unseen 'best' design.

The selection operator determines which chromosomes are fit enough to survive to the next generation. Some may be automatically discarded – for example, the worst 10% – while others are typically 'killed' at random, as they would be in nature. Others may be automatically retained – the best 5%, for example.

The algorithm designer is free to implement whatever selection process seems best. The crossover operator 'mates' two chromosomes, or 'parents', to produce two new chromosomes, or children', which become members of the next generation. Child chromosomes usually maintain a constant population from one generation to the next, although the population could grow if desired.

Each parent's chromosome is split at a gene boundary, usually randomly selected, and the pieces are swapped (concatenated together) to form two different chromosomes. This is the primary process by which genetic algorithm propagate 'good' genes from one generation to the next.

Finally, the mutation operator randomly flips a bit here and there with some small probability. This simulates the genetic mutation that occurs randomly in Nature.

Deciding which is best

In each generation, all of the designs, or chromosomes, are ranked from best to worst using a figure-of-merit. The figure-of-merit combines various antenna performance measures

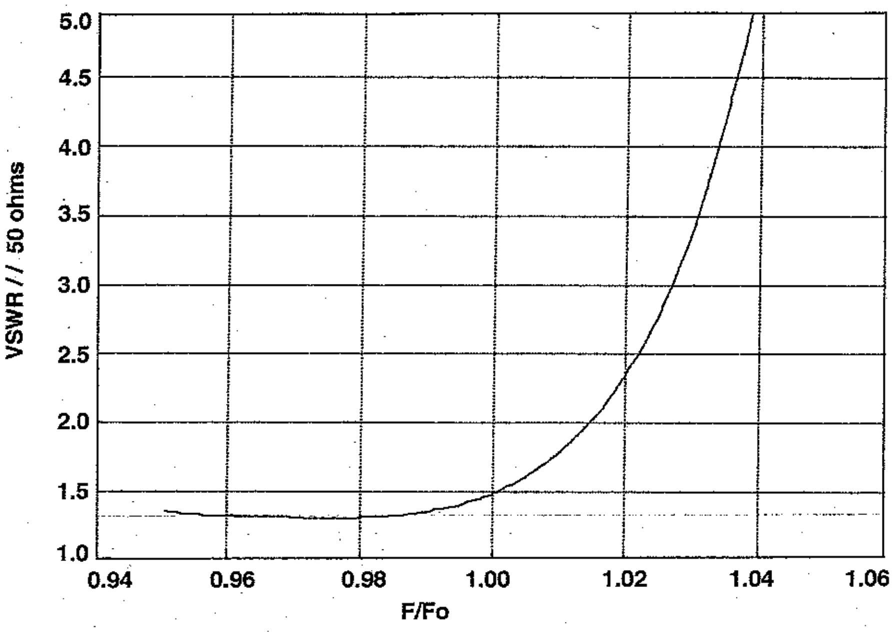

Fig. 4. Standing-wave ratio performance.

computed by a modelling engine, which is another computer program separate from the genetic algorithm.

Individual antenna performance parameters, for example, can be calculated with any suitable antenna modelling program. The figure-of-merit used for the Yagi described below is

$$\frac{5(G)+4(FB)-SWR}{10}$$

This particular figure of merit gives slightly more weight to the main lobe gain *G* than to the front-to-back ratio *FB*, and relatively less weight to the input standing-wave ratio *SWR*.

The algorithm designer is free to define any figure of merit that reflects the relative importance of different performance measures, including even non-electrical parameters such as cost or time to build, or amount of material required, and so on. This feature is a major distinction between genetic algorithm and deterministic optimisations, which frequently cannot optimise arbitrary figures of merit.

Other significant differences are that genetic algorithms produce *groups* of designs with similar figures of merit, instead of the single 'best' design, and they usually require much less computer time than deterministic algorithms.

The genetically optimised three-element Yagi has the following dimensions, in wavelengths at the design frequency F_0:

Reflector length	0.530
Reflector radius	0.0008
Driven element length	0.478
Driven element radius	0.004
DE distance from REF	0.123
Director length	0.446
Director radius	0.0015
DIR distance from DE	0.106

The boom length – the sum of *DE*/*DIR* separations – is only 0.229. This is less than a quarter-wave, which is quite short. At the 6m amateur band frequency of 51MHz, for example, this Yagi is only 53in long. The *REF, DE* and *DIR* lengths are 122.66, 110.62, and 103.22in, respectively, with diameters of 0.37, 1.85, and 0.694in.

Gene *DE* is located 28.47in from *REF*, while *DIR* is located 24.53in from *DE*. It is interesting that the genetic algorithm converged to the maximum allowable value for the *DE* radius, because it is known from analytical considerations that increasing *DE* diam-

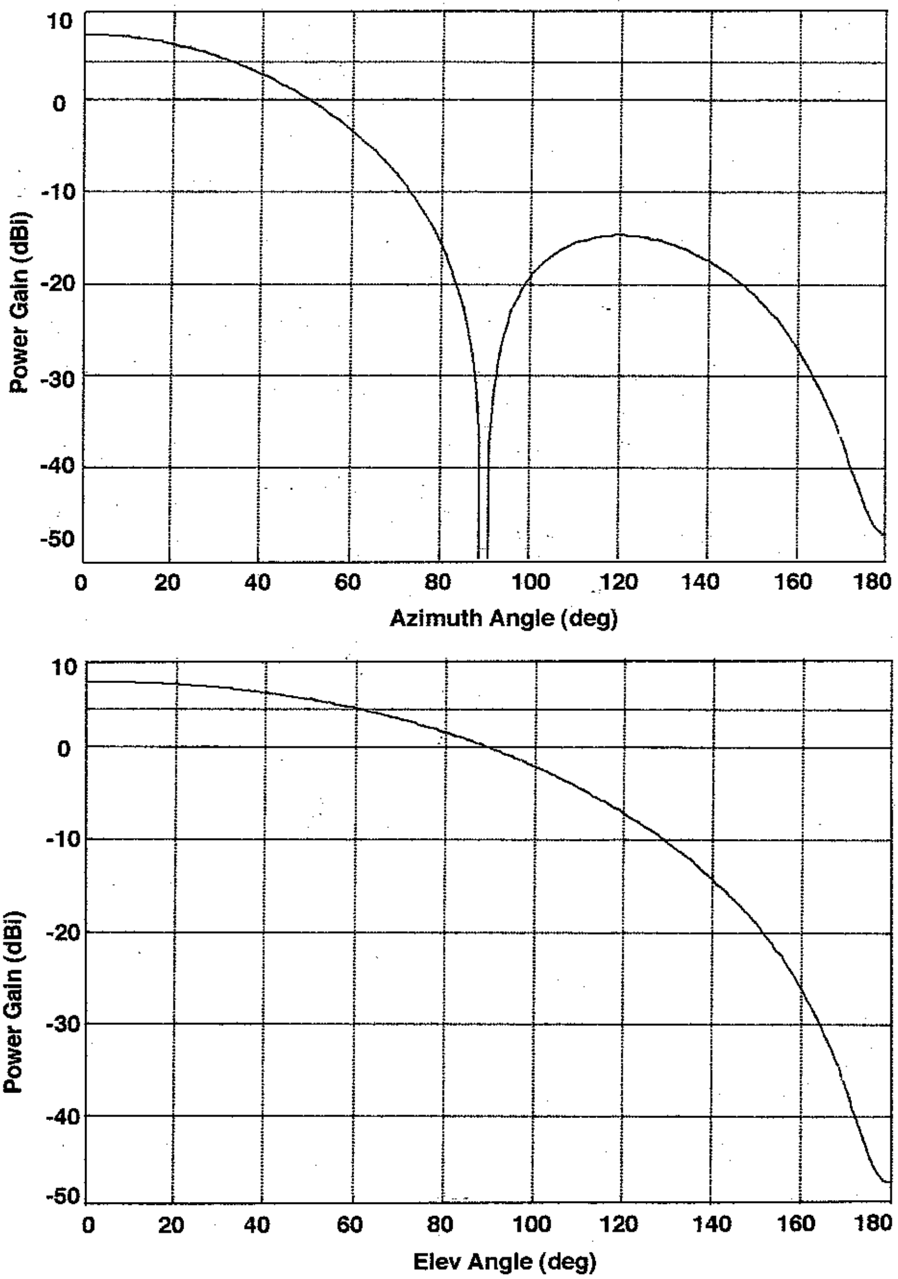

Fig. 5. Azimuth, a), and elevation pattern, b), of the antenna.

eter can improve Yagi performance substantially[3].

Table 2.Performance of the genetically designed Yagi.

Gain	FB	Z_{in}	SWR	HPBW
7dBi	54.2dB	33.9–j3Ω	1.49	66°az, 122° el

Free-space main lobe gain, front-to-back ratio, input impedance (resistance and reactance), and standing-wave ratio relative to 50Ω are plotted in **Figs 1-4**, respectively. These parameters were computed over a 10% band centred at the design frequency F_o.

The azimuth and elevation patterns at F_o appears in **Figs 5a)** and **b)**. Key performance measures are shown in **Table 2.**

The band-centre gain of 7dBi is typical of well-designed three-element Yagis, and the optimised antenna's *FB* of 54dB is exceptionally good. For comparison, this *FB* figure is more than 16dB better than the best *FB*s of typical quarter-wave designs described in W2PV's treatise on Yagi antennas[4] (see especially Fig. 2.9).

The optimised antenna also exhibits good *FB* bandwidth, with values exceeding 20dB from $0.97F_o$ to $1.017F_o$, which equates to 4.7%. The optimised Yagi is nearly resonant at F_o at an input reactance of 3Ω capacitive, which is less than 10% of the input resistance.

From $0.95F_o$ to $1.015F_o$, a difference of 6.5%, the standing wave ratio is less than two. If desired, this antenna can be fed directly with 50Ω coaxial cable, eliminating the insertion loss introduced by a matching network or antenna tuner.

Of course, a balun should be used to maintain feed system balance. But it would be interesting to build this antenna with and without a balun to see how much difference it makes.

For the 51MHz design, the standing-wave ratio is below two, and the *FB* is greater than 20dB, from 49.47 to 51.76MHz – a bandwidth of 4.5%. The lower band edge can be shifted up to 50MHz by increasing the design frequency to F_o=51.55MHz and recalculating the dimensions. Note that the wavelength is computed as $299.7956/F_{MHz}$, which is more accurate than the commonly used formula $300/F_{MHz}$.

The optimised Yagi's E-plane azimuth pattern has a characteristic two-lobe structure with a deep broadside null. The –3dB half-power beamwidth is 66°. The rear lobe is about 22dB down, which is quite low. The H-plane elevation pattern is plotted in Fig. **5b)**. It has a single, broad lobe with half-power beamwidth at 122°.

The genetically optimised, three-element Yagi is a very compact antenna that provides excellent performance. This example illustrates that genetic algorithms can produce very good antennas indeed. Such algorithms are easily implemented on a pc and can provide significant advantages over deterministic techniques.

Communications engineers will probably hear more and more about the genetic design approach. It certainly merits serious consideration by designers who are interested in antennas. ■

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ECC85	3.50	GZ34 GE	7.50	UL84	3.50	6CH6	6.00	30FL1/2	1.50
ECC88 Mull	6.00	GZ37	6.00	UY41	4.00	6CW4	8.00	30P19	2.50
ECC91	2.00	KT61	10.00	UY85	2.25	6D6	5.00	300B(PR)	110.00
ECF80	1.50	KT66	10.00	VR105/30	2.50	6DQ5 GE	17.50	572B	70.00
ECH35	3.50	KT88	15.00	VR150/30	2.50	6DQ6B	12.50	805	50.00
ECH42	3.50	N78	9.00	Z759	25.00	6EA8	3.50	807	5.75
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ECL83	3.00	OD3	2.50	4CX250B STC	55.00	6GK6	4.00	833A	85.00
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EF42	4.50	PCL83	3.00	6AH6	4.00	6JE6C	20.00	5814A	5.00
EF80	1.50	PCL84	2.00	6AK5	1.50	6JS6C GE	20.00	5842	12.00
EF85	1.50	PCL85	2.50	6AL5	1.00	6K6GT	3.00	6080	7.50
EF86	10.00	PCL86	2.50	6AM6	2.00	6K7	4.00	6146B GE	15.00
EF91	2.00	PCL805	2.50	6AN5	5.00	6K8	4.00	6550A GE	20.00
EF92	2.00	PD500	6.00	6AN8A	4.50	6L6G	10.00	6883B GE	16.00
EF183	2.00	PL36	2.50	6AQ5	3.25	6L6GCSYL	12.50	7025 GE	7.00
EF184	2.00	PL81	1.75	6AR5	25.00	6L6GC Siemens	7.50	7027A GE	17.50
EL32	2.50	PL82	1.50	6AS6	3.50	6L6GC GE	12.50	7199	12.00
EL33	10.00	PL83	2.50	6AS7G	9.50	6L7	3.50	7360	25.00
EL34 Siemens	8.00	PL84	2.00	6AT6	2.00	6LQ6	20.00	7581A	15.00
EL36	4.00	PL504	2.50	6AU5GT	5.00	6Q7	4.00	7586	15.00
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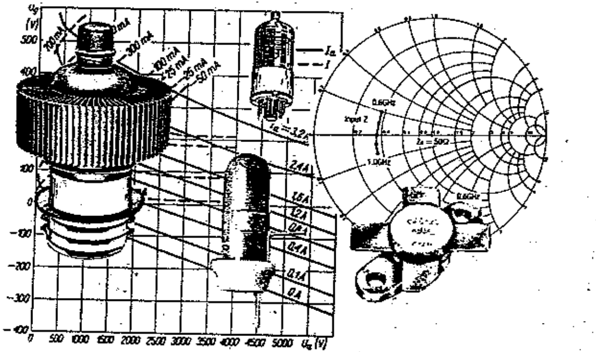

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