From August 2009 *High Frequency Electronics*

Taxonomical and Heuristic Studies on UWB Antenna Design Strategies

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The author borrows from biology to develop a method for evaluating wide bandwidth antenna structures, and create rules for the discovery of potentially usefule new structures

This paper attempts to assist in navigation through the realm of reported designs on ultrawideband (UWB) antennas through systematization of key design principles and ideas using two methodologies proven in other science and engineering fields. The first one is a classification called "taxonomy" used to categorize key structural components of antenna designs. The second one represents inventive principles of problem solving called "heuristics" used to guide design developments towards likely new concepts through manipulation with grouped structural components and minimization of unproductive traditional trial-and-error efforts.

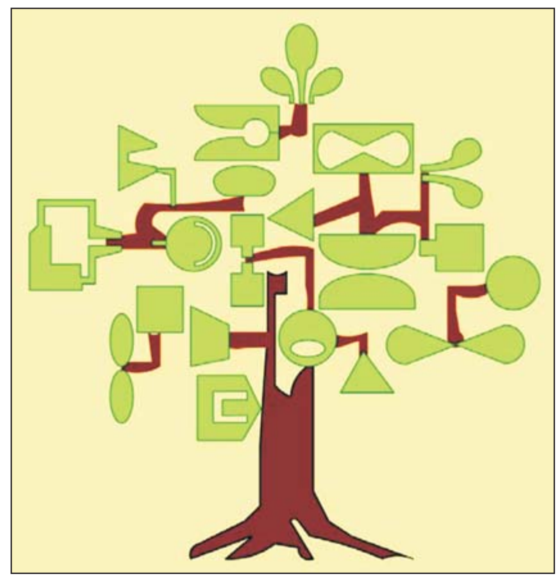

Figure 1 · "Tree" with "leaves" made of arbitrary shaped UWB antennas.

1. Motivation

Electromagnetic technologies of UWB signaling are now spread across a broad spectrum of sensing, imaging, telecommunication and networking applications [1-2]. UWB antenna design still represents a hot topic because of its critical impact on system-level performance, despite impressive advances that have been demonstrated in high-speed digital and microwave electronics, signal processing algorithms and computer hardware. I was involved in several system and component level UWB projects at the beginning of the 2000s. At that time, I also started to collect 4 × 6 in. index cards by noting important, to my opinion, information on UWB antenna designs reported in literature. In a course of several years after starting, the number of relevant publications increased explosively, which stimulated my reorganization of the cards into three sections called "Examples," "Elements" and "Rules." First, I grouped all found antenna shapes due to their similarities and dissimilarities and stored most interesting and representative versions in "Examples." Second, I searched for a taxonomical list of basic structural elements in the antenna designs from "Examples" to group them as "Elements." Third, I extracted a number of heuristic methods systemized in "Rules." Ultimately, manipulating with "Elements" using "Rules" generates antenna designs like those in "Examples" and possibly fresh solutions. Sharing this knowledge might be helpful for many antenna and system designers in a view of a growing wave of reported designs and studies on UWB antennas, which is still growing.

2. Methodological Basis

Taxonomy to Deal with Tremendous Variety in External Appearances

Let's picture a mental experiment in which a botanist standing next to a tree attempts to describe in great detail each individual leaf, while that tree might have many thousands of leaves that are notably varied in shape and size from sample to sample. This insight illustrated in Figure 1 is deeply impractical, but it is what might come to mind when analyzing the trends in publications on UWB antennas. The first historic attempts in systematization of plants and animals probably followed a somewhat similar immature "leaf-by-leaf" pattern. In a course of time, biologists established a comprehensive systematization with several key concepts collectively called "Polymorphism" and "Taxonomy," by which biologists group and categorize species of organisms due to their external/internal similarities and differences [3-4].

Many antenna handbooks and texts deal in different ways with antenna classification [5-8]. Specifically, a set of UWB radiators are categorized in [6] including their historic perspective. Some systematization studies are provided in [7]. Another principle to classify UWB antennas is developed in [8] by referring to several mechanisms to broaden electromagnetic resonances. This study explores this issue from another perception by attempting to answer the questions:

1. What do different UWB antennas have in common despite their apparent distinctions?
2. What are rational rules to guide their design by controlling shape and dimensions?

Methods of Problem Solving in General

Three major mental processes are involved in problem solving or design creation:

1. *Logic* that governs the structure of statements, argument, judgments and reasoning based on explicit rules, viz. algorithms [9].
2. *Heuristics* that represents experience-based "rules of thumb," educated guesses or simply common sense to help in problem solving but without any guarantee of succeeding [10].
3. *Intuition* that is understood as abilities to get knowledge immediately and unconsciously without reasoning through associations to similar models, contexts, problems, etc. [11].

This triad appears in different proportions and depends on complexity and challenges involved in a particular problem. Everything available in a logical form is theoretically convertible to computer programs, but no fully automatic design procedure yet exists. Heuristics shows promise in research, design, invention and art [12]. Some heuristics have been revealed through analysis of many thousands of patents in different engineering fields to extract major inventive principles, independent of application specificity [13]. Such methods might lack a scientific basis, but often demonstrate effectiveness. Obviously, no heuristic rule can serve as a universal problem solver. Still, many mysteries exist surrounding the astonishing abilities of the human mind to generate new ideas and concepts relying on individual skills, talent, background, experience, etc., that is collectively referred to as intuition, the third element of the above triad.

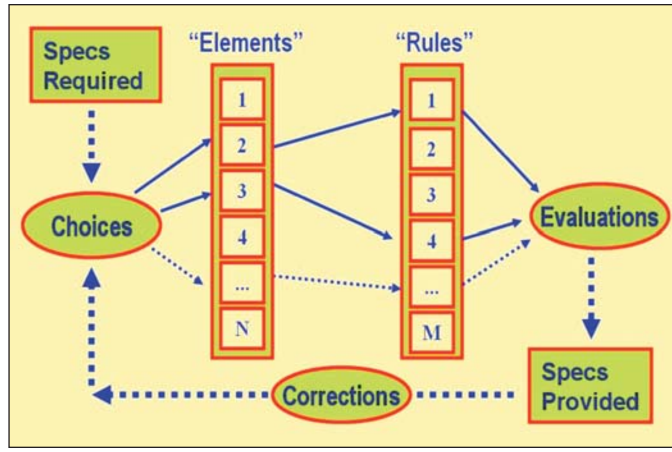

Figure 2 · Inventive design diagram to manipulate with "Elements" and "Rules."

Inventive Problem Solving for Antenna Design

Some heuristic ideas to solve antenna design problems are synthesized in the diagram (Fig. 2) that comprises "Elements" and "Rules" originated from the corresponding sections of the card collection. In this diagram, a designer selects initially a suitable combination, viz. Choices of "Elements" and "Rules" guided mainly by intuition. Nevertheless, referring back to uncontrollable intuition, the diagram in Figure 2 might guide the design process in a robust fashion compared to traditional trial-and-error. Performance metric of any derived solution should be evaluated and compared to that needed. A discrepancy between required and derived features invokes iterative design adjustments to resolve tradeoffs due to simultaneous emergence of wanted and unwanted effects.

Preview on Major Physical Aspects Involved

Major physical ideas are summarized in Figure 3 for a transmit radiator [5]. In essence, the radiator and ground surface current is major physical characteristics required

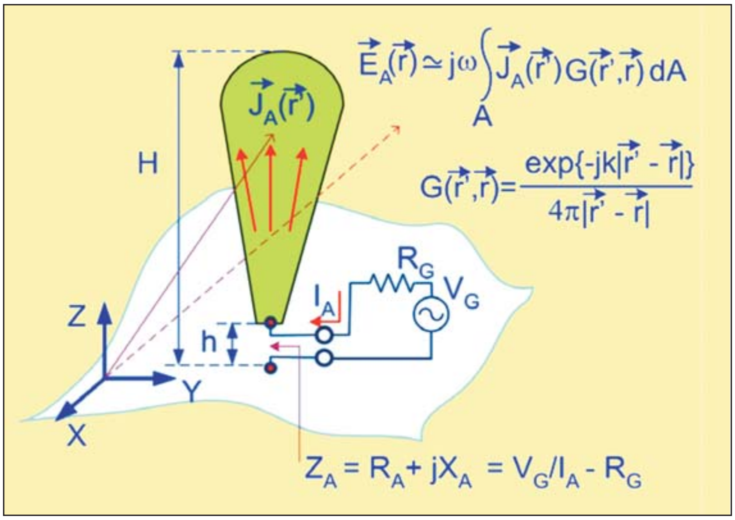

Figure 3 · The surface current distribution defines major terminal and radiation electrical characteristics.

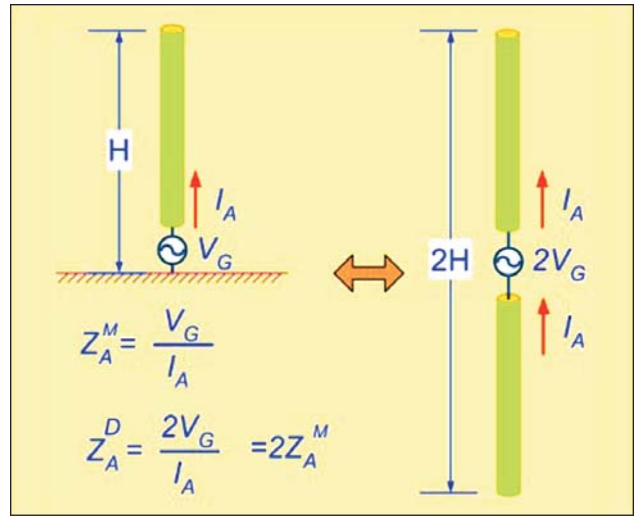

Figure 4 · The image EM principle relates monopole (M) above the infinite PEC ground and dipole (D).

to predict all terminal and radiation antenna features. Once the current is solved, the input impedance and radiated fields can be computed. An important relation exists (Fig. 4) between a monopole over infinite perfect electric conductor (PEC) ground and a free-space operating dipole made of two same radiator arms. This insight exploits the imaging EM principle [5] that relates such two radiators. Similarly, semi-loop and loop radiators are another pair connected through the same principle. For the purpose of further studies, most of the radiators can be categorized as in Table 1.

3. Structural Taxonomy of Design Elements for UWB Antennas

Structural taxonomy is key to understanding antenna design anatomy. This section represents major antenna structural elements extracted from a large body of reported designs accumulated in the "Example" section of the card collection. Some other construction elements like embedded lumped circuits and dielectric materials are not discussed here for the sake of brevity.

Radiator Conductors

A. Topological Properties

Some of the most-used generic 2-D radiator shapes are sketched in Figures 5-7. Their 3-D versions are derivable through a number of 2-D-to-3-D shape transforms in Section 4. Geometrical diversity in Figures 5-7 invokes suitable mathematical concepts as topology [14] for systematization. Assuming open-circuit terminal conditions excludes the generator circuit from topological relations. In terms of topology, all elements in each row in Figures 5-6 are identical because topology relay not on their exact shape but rather on the way they are put together. Specifically, topological dimension summarized in Table 2 depends on the number of isolated distinctive areas of conductors (radiator and ground) and dielectrics (free space, substrates, etc.).

	Electric antennas	**Magnetic antennas**
Characteristic DC terminal mode	Open-circuit	Short-Circuit
Most intense field in close proximity	Electrical	Magnetic
Typical radiation resistance	≥ 50Ω	≤ 50Ω
Representative candidates	Monopole, dipole, horn.	Semi-loop, loop, slot.
Examples	Fig. 5	Fig. 6

Table 1 · Major practical EM radiators with key distinctive features.

Topological dimensions	**1**	**2**	**3**	**4**
Figure	6a, 7a, 7b	5a, 5b, 6b	5c, 7c	7d

Table 2 · Topological dimensions of considered radiator shapes.

Figure 5b exhibits a class of popular broadband radiators refereed to Vivaldi or tapered slot antenna ,which looks like just a modified dipole from a topological perspective. Another class of antennas is sketched in Figure 7c with wide slot areas which can be derived from those in Figure 5a by attaching to slot-coating grounds (Subsection 3.3). Other structures in Figure 7a-b are topologically identical but physically different like magnetic (Fig. 7a) and electric (Fig. 7b) radiators. In general, topology is not sufficient, and metric relations must be involved (3.1.C).

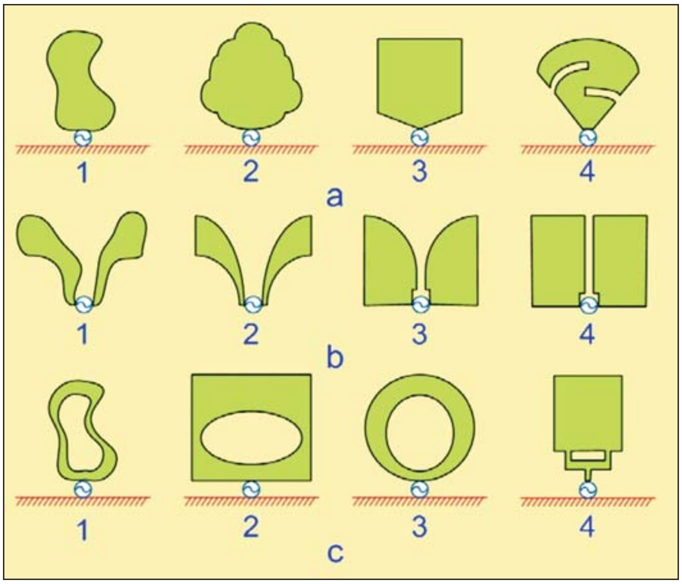

Figure 5 · Generic 2-D electrical radiators with (a) and (c) and without (b) bottom ground having different topological dimensions as one in (a) and (b), and two in (c).

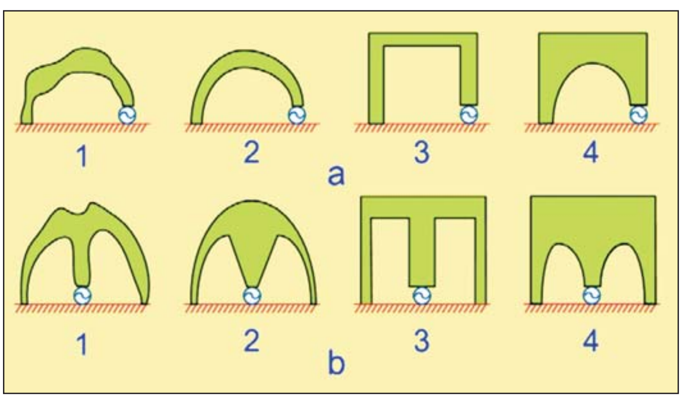

Figure 6 · Generic 2-D magnetic radiators having topological dimensions one (a) and two (b).

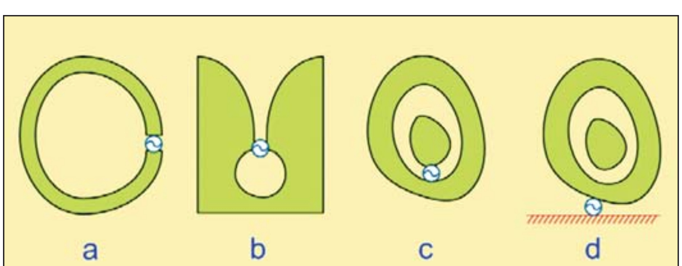

Figure 7 · Different physical and topological radiator properties: same topological dimension for (a) magnetic loop and (b) electric Vivaldi electric antennas; (c) "large slot" magnetic radiator formed with the outer coating ground; (d) electric radiator over ground.

B. Conductor-Dielectric Complementary Properties

Figure 8 provides another useful insight dealing with shape diversity of UWB radiators by exploiting the Babine's principle. This principle exploits the complementary nature of magnetic and electric fields for dipole and equivalent slots or, interchangeably, antenna conductor and air dielectric areas [5].

C. Metric Setting Rules

Metric relations sets all antenna dimensions to meet size constraints traded often against bandwidth. There are many theoretical studies to explore this issue. Instead, two rules-of-thumb are suggested for initial geometry selection [15]. The first rule specifies the physical length of current path that starts to travel from the point where the antenna is driven by the generator, follows along the conductor edge outline towards the end antenna tip where reflection occurs (Fig. 9). As a result, a bounced portion of the surface current will form a standing wave pattern manifested as a resonance observed in the antenna input impedance. For example, for monopole, e.g., limited to the height H (Fig. 9a) and semi-loop limited to the radius R (Fig. 9b), value of P should approach to a quarter of wavelength related to the lowest operational frequency. Some standing wave patterns derived from full-wave EM simulations are shown in Figure 10 for several practical UWB antennas. The second rule deals with techniques to control and broaden such resonances to enhance bandwidth through conductor shape mutations discussed in Section 4.

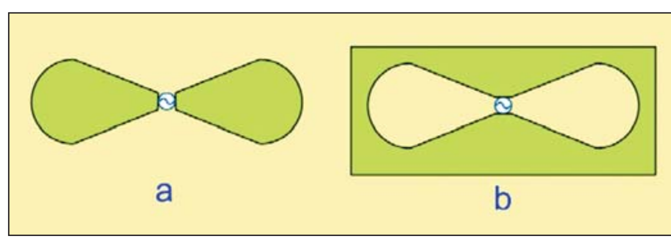

Figure 8 · Conductor-dielectric complementary relations through the Babine's principle for transition from electrical radiator as dipole (a) to magnetic radiator as slot (b) with truncated outer conductor.

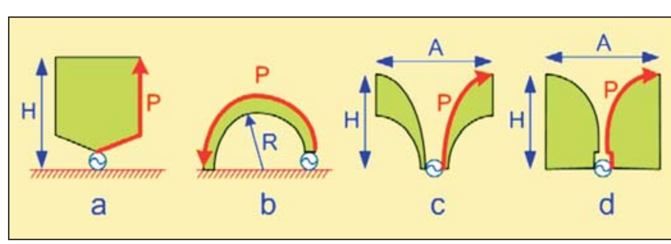

Figure 9 · The rule of thumb to set the antenna physical dimension ensures that the current travel path P approaches to a quarter of wavelength at the lowest operational frequency.

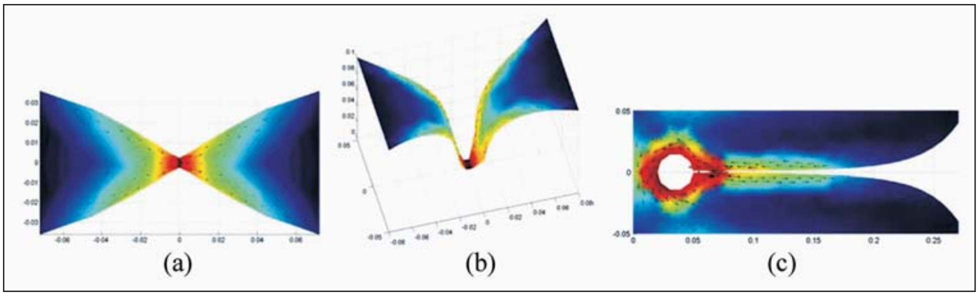

Figure 10 · A standing wave pattern of the surface current distributions for several computed antennas: (a) bow-tie dipole; (b) TEM horn; (3) Vivaldi antenna.

Feed Design Elements

Different feed networks used in most of the reported design are summarized in Figure 11. Two major groups of such feeds are (1) unbalanced (asymmetrical) in Figure 11a,c,d,g and (2) balanced (differential or symmetrical) in Figure 11b,e,f. A combined case with a balun is illustrated in Figure 11g to drive symmetrical radiators as dipoles (V-dipoles) and tapered slot antennas. Some performance improvement is reported using double (Fig. 10b) and triple (trident) strip feed network. Other type of feed network omitted is based on EM coupling between the feed network and radiators [8] and others.

Ground Conductors

Ground conductor shapes extracted from the UWB antenna literature are systemized in Figure 12. Such elements work mainly with monopole (Fig. 5a,c) and semi-loops (Fig. 6) radiators. The extent of ground conductors should be included in an overall antenna real estate budget. These elements of UWB antenna designs are further discussed throughout Section 4 in connection to their involvement in many structural modifications to control gain (Figs. 19, 22-24).

Reflector and Director Elements

Such elements are used in many UWB antennas and important for specific designs and illustrated for several design modifications in Section 4. In particular, reflectors can be formed using: (1) ground conductors shaped through a sequence of shape mutations (Figs. 19 and 24b,c), a part of the radiator structure itself can be converted to a reflective structure using shape modifications (Figs. 18 and 25), using backing structures as corner (Fig. 23a,b) reflector and parabolic semidish reflectors (Fig. 23c) and so on. Other versions could be mentioned as cavity-backed antennas, using metamaterials to build reflectors and others.

4. Heuristics of Design Rules for UWB Antennas

Structural taxonomy from Section 3 provides us with basic design elements but does not say much about their relations in particular designs. Such relations can be represented using a set of heuristic design rules or rules-of-thumb traceable in many of reported designs, e.g., [16]. A list of such major rules is proposed for the use in the design diagram (Fig. 2), as follows:

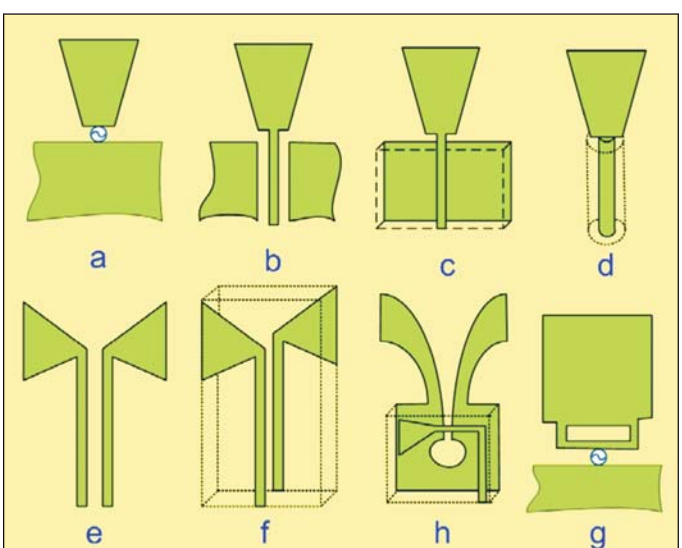

Figure 11 · Feed elements: (a) ideal delta-gap generator; (b) coplanar waveguide (CPW); (c) microstrip; (d) coaxial; (e) collinear two-conductor strip line; (f); two-conductor parallel strip line; (h) microstrip line with balun; (g) double feed strip network.

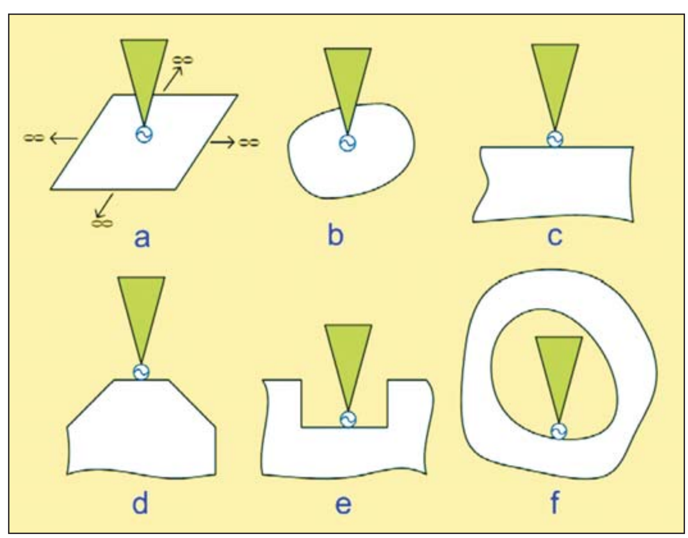

Figure 12 · conductor design illustrated for vertical monopole radiator: (a) ideal infinite ground; (b) arbitrary shaped finite ground; (c) edge ground; (d)-(e) edge tapered grounds; (f) wide-slot coating ground. The ground conductor is pictured in white.

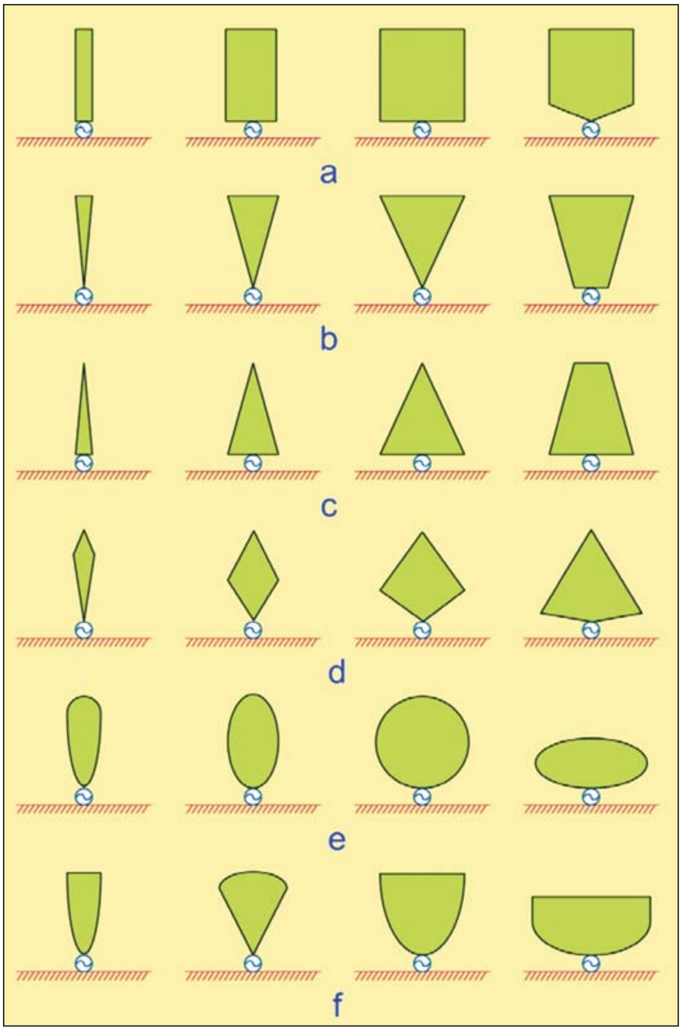

Figure 13 · Examples of 2-D monopole conductor shape variations that preserve topological properties: (a) rectangular monopoles; (b) bowtie structures; (c) inverse bowties or diamonds; (d) rhombic radiators; (e) elliptical shapes; (f) combinations of straight and curved outlines.

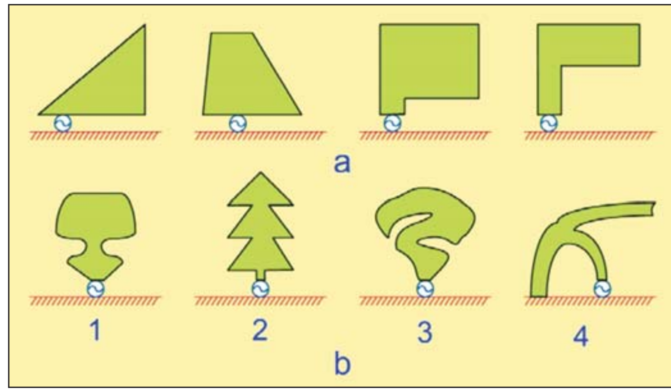

Figure 14 · Asymmetry introduced in radiator geometry: (a) shapes bound by straight line; (b) shapes made of curved boundary profiles.

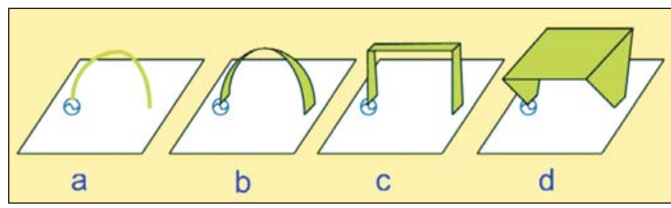

Figure 15 · Consecutive modification of radiator conductor from wire (a) to strip (b) and (c) conductors towards "Large Current" radiator (20) (d).

2-D Conductor Shape Variations

Typical 2-D shape transformations, which are topologically invariant, are shown in Figure 13 among a great number of other possibilities for shape transformations with topological dimensions preserved. Other sort of shape transformations assumes changing topological dimensions, e.g., Figure 5a vs. Figure 5c and so on. Most of them work to broaden the antenna resonances.

Introducing Shape Asymmetry

Such shape modifications are illustrated in Figure 14 through shape mutations like: (1) a symmetrical form is replaced with an asymmetrical one; (2) linear parts or flat surfaces are changed to curved ones; (3) the degree of asymmetry might be increased for already asymmetrical shapes.

Compact Space Filling

Such shape transforms are used to improve space filling and lower Q-factors of involved resonances. Somewhat similar philosophy is used in fractal antennas [5] operating in multi-band modes. For UWB, such features are achievable in different ways illustrated in Figure 14b1-3.

2-D-to-3-D Transform I: Add 3rd Dimension

Using the third dimension compared to just 2-D radiator shapes gives additional degrees of freedom in design to adjust impedance bandwidth and radiation pattern shapes. Such a simple technique is illustrated in Figure 15 for semi-loop antenna (Fig. 15a) transformed finally to large current radiator [20] (Fig. 15d).

2-D-to-3-D Transform II: Extrusion

Planar-to-solid transformations operate through linear and nonlinear extrusions (Fig. 16a) that provide additional flexibility to control bandwidth and possibility to use volume manufacturing processes for metal plates instead of printed conductors and so on. It is applicable to all planar shapes like those in Figures 5-8

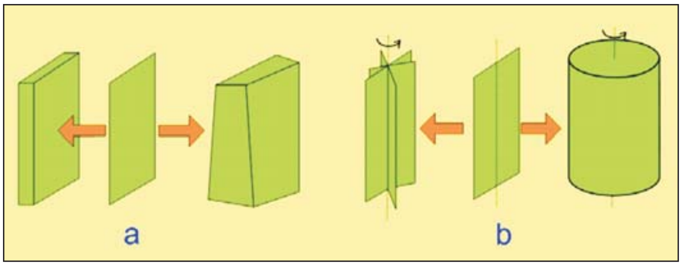

Figure 16 · 2-D to 3-D shape transforms: (a) linear and nonlinear extrusions; (b) discrete and continues body of revolution.

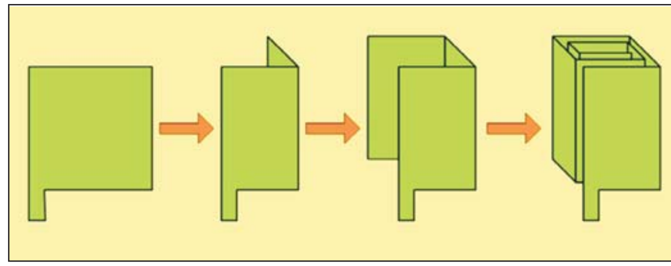

Figure 17 · Step-rolled transform to fill space in a compact way and increase bandwidth for the same overall size and improved omni pattern across the band.

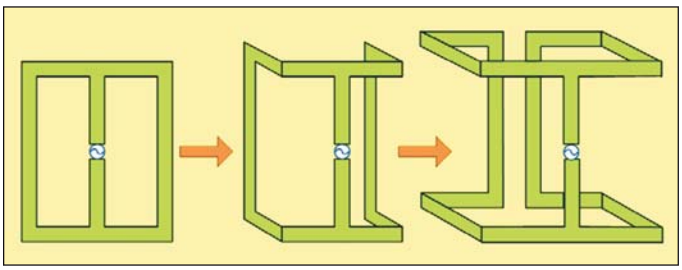

Figure 18 · Converting planar double loop into 3-D structure to improve space filling and control radiation directivity.

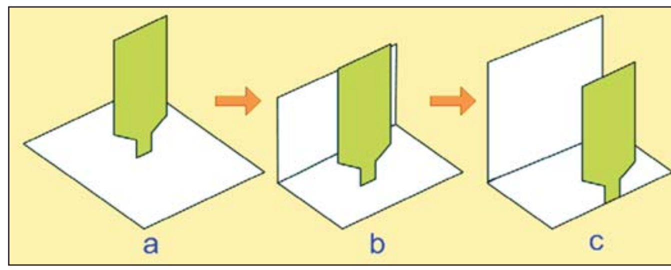

Figure 19 · Transition from omnidirectional planar monopole over finite ground to a reflector-backed monopole (trapezoidal antenna).

and Figures 13-14.

2-D-to-3-D Transform III: Body of Revolution

This transform to 3-D illustrated in Figure 16b includes discrete and continues body-of-revolution shape mutations. It can be applied to all radiators as shown in Figure 13 and similar having mirror symmetry with respect to the axis passing through the antenna feed points. This transform broadens antenna resonance and equalizes azimuth radiation pattern.

2-D-to-3-D Transform III: Rolling and Bending

This rule is illustrated in Figure 17 for step-rolled monopole radiator to increase bandwidth for the same overall antenna real estate and improve omnidirectional radiation features. Similarly smooth rolling can be applied. Another version of the same transform is pictured in Figure 18 for converting planar double loop into a 3-D structure of improved space filling and adjusted radiation pattern. Spiraling in 2-D and 3-D is another form of this transform but is not here illustrated.

Electric-to-Magnetic Radiator and their Combination

It replaces metal areas by air dielectric and vise versa, Figure 8 (3.1.B). At practice, the outer conductor extent is reasonably cut in size. Also, a combination of both electrical and magnetic radiators might be considered as sketched in Figure 14b4 for F-type (PIFA) antenna and others like that in Figure 6b for certain geometrical proportions for their dimensions.

Directivity Transform

Antennas of higher gain are resulted from a number of practical transforms illustrated and commented in Figures 18-25 including:

1. Shape modification to exploit the third dimension like for the radiator in Figure 18.
2. Combined ground-reflector element as in the trapezoidal antenna in Figure 19.
3. Enforcing bi-directivity and getting unidirectional gain as for Vivaldi elements in Figure 20.
4. Shape modification from omni dipole towards V-dipole and TEM-horn, Figure 21.
5. Other shape modifications shown and commented in Figures 22-25.

Ground Transform

Ground type and geometry play a significant role in achieving required electrical performance and antenna packaging. Typical ground conductors are categorized in 3.3 (Fig. 12) and involved in directivity transforms as in Figures 15, 19, 22-24.

Band-Notching Transform

Certain shapes modifications with deep and long cuts

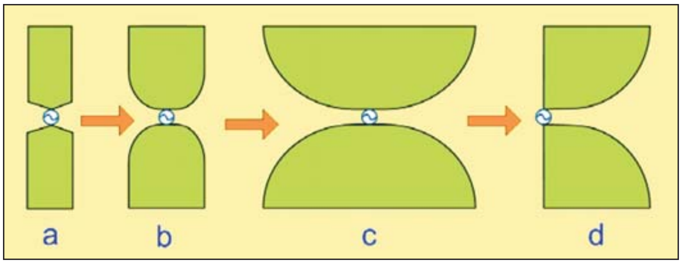

Figure 20 · Shape modification for transition from omni planar dipole (a) to bi-directional antenna (c) through dipole (b) and from bidirectional (c) to unidirectional Vivaldi radiator (d).

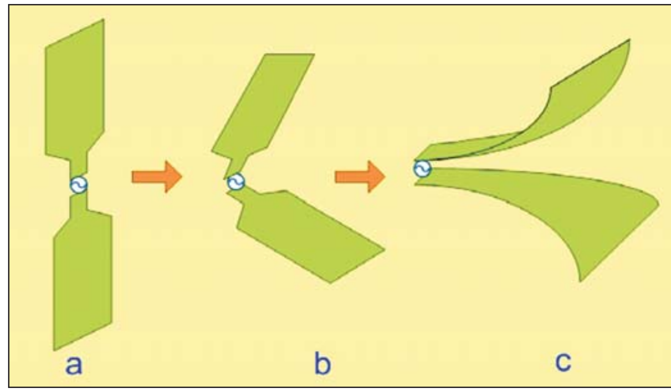

Figure 21 · Shape modification sequence for directivity transformation from omni dipole (a) to antennas of higher unidirectional gain including V-dipole (c) and TEM-horn (c).

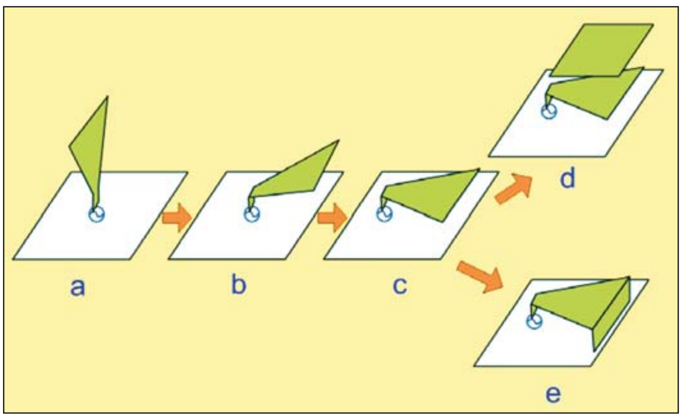

Figure 22 · Directivity transform for omnidirectional bowtie monopole (a) to several unidirectional radiators: (b) TEM-horn cell with higher gain towards the direction of radiator protrusion; (c-e) patch radiators with maximum of radiation normal to the ground in the upper half-space including modifications with added top parasitic patch at the top (d) and shorting to the ground (e).

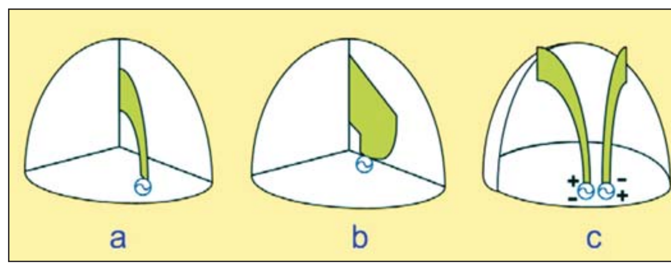

Figure 23 · Reflector backed radiators: (a) quarter of loop with corner reflector; (b) half of Vivaldi-like radiator above the bottom circular sector ground with corner reflector; (c) half of impulse radiating antenna backed by semi-dish reflector.

in the conductor body might lead to high-Q resonances, which should be usually avoided but might be used deliberately to provide band notching features exampled in Figures 5a4 and 13b3. Similar results are achievable by incorporating a suitable slot in a planar conductor as in Figures 5c2 and 7d and similar.

Adding Parasitic Elements

This option is illustrated in Figure 21d for the case of suspended parasitic patch to provide additional degrees of freedom in design for directivity and gain improvement.

5. Summary

This study attempts to systemize UWB antennas through grouping their structural elements and underlying design principles, which are traceable in the periodical, conference, monograph and patent literature. A sketch of proposed design philosophy is presented while many details and partial cases are omitted for the sake of brevity.

The objectives are achieved by employing biology-inspired taxonomy and brain-inspired heuristics. Taxonomy represents a productive basis for structural systematization to deal with the unimaginable polymorphism of radiator shapes and other design elements. The second methodological constituent is represented by heuristics, to assist in the search of design solutions while minimizing the number of unproductive traditional trial-and-error steps. The final stage of any achieved design includes parametric tuning, which seems quite trivial using computational means of modern full-wave EM simulation tools.

The educational aspect of this story looks also quite profound. To the best of my knowledge, universities do not purposefully teach future engineers and researchers the techniques of inventive problem solving. At best, it is assumed that such abilities might be developed somehow, somewhere, by somebody as a result of personal skills and

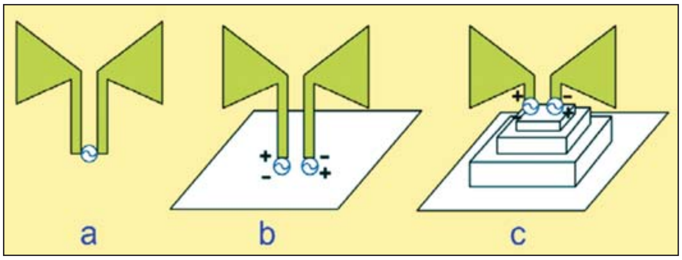

Figure 24 · Bow-tie dipole: (a) in free space; (b) balanced-fed above ground, viz. bottom reflector; (c) balanced-fed above stepped-profiled reflector to enhance bandwidth.

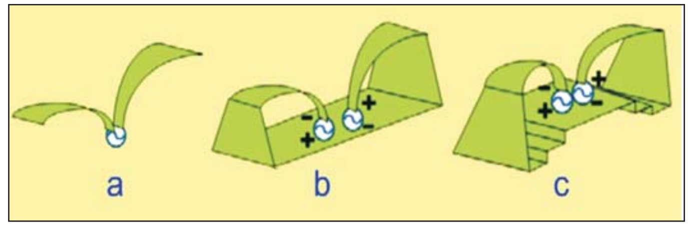

Figure 25 · TEM horn radiator configurations: (a) canonical structure; (b) balanced-fed backed by reflector formed from the same bent conductor; (c) balanced-fed backed radiator with reflector formed from the same bent conductor in a tapered-stepped fashion.

accumulated experience. This may be partially true, but the economic impact of unproductive problem solving methods like empirical trial-and-error might be sufficient justification for such instruction.

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