A White Paper on

Self-Structuring Antenna Technology

By

John Ross, Ph.D., P.E.
John Ross & Associates, LLC
350 West 800 North, Suite 317
Salt Lake City, Utah 84103

And

Edward J. Rothwell, Ph.D.
Department of Electrical and Computer Engineering
Michigan State University
East Lansing, Michigan 48824

Abstract

The Self-Structuring Antenna (SSA) is a new class of adaptive antenna that changes its electrical shape in response to its environment or signal conditions. The shape change is not made by altering the position or shape of the antenna structure, but rather by controlling the electrical connections between the components of a skeletal antenna "template." The template can be composed of wires, patches, slots or a combination of these or any other suitable radiating element. Using an appropriate feedback signal from a receiver, transmitter or other sensor, the structure is rearranged to optimize one or more performance criteria. Modern search methods such as the genetic algorithm (GA) or ant-colony optimization (ACO) are used to quickly locate optimal states from among millions or even billions of possible antenna configurations. This paper presents an overview of the SSA along with results of several theoretical and experimental investigations. Advantages and applications are discussed.

Background

Antennas are most often designed to operate under very specific electrical or environmental conditions. For instance, they may be designed to operate within a specific frequency range or to have a particular radiation pattern, or to operate in the vicinity of particular structures such as vehicle bodies. This is accomplished through the specification of the physical antenna structure. As a result, every antenna is a design compromise with performance characteristics such as gain, bandwidth, VSWR and efficiency being traded off to meet constraints on physical size, weight, cost, manufacturability and time to market. These design compromises result in antennas that only function well in certain environments or over certain frequency bands and provide either directional patterns or omni-directional patterns but generally not both. The fact that the antenna is unable to adjust its physical structure means that it is unable to adapt to changes in its environment or to change its performance for various missions.

While advanced phased-array antennas are capable of adjusting the relative amplitudes and phases of their elements to achieve beam steering, they are still designed for specific environments and typically operate over relatively narrow frequency bands. Beam steering and direction finding are dependent on a-priori knowledge of the phasing and physical layout of the array elements.

Less sophisticated re-configurable antennas have been developed that use electronically controlled switches to connect various radiating elements or loading elements. Here, each state of the antenna is designed to work in the target environment as would be done for a single fixed antenna. Designing such antennas for more than a handful of states can be exceedingly difficult and the end result is an antenna that is functional only under certain environmental conditions. Moving a traditional re-configurable antenna to a different vehicle or changing mission requirements could require a complete redesign of the radiating and loading elements.

An alternative to fixed antennas, phased arrays, and traditional reconfigurable antennas whose every state must be explicitly designed ahead of time is embodied in the Self-Structuring Antenna (SSA). The SSA is an entirely new class of antenna whose physical structure can be altered in response to changes in appropriate stimuli. An overview of this new class of antennas is provided below.

The Self-Structuring Antenna Concept

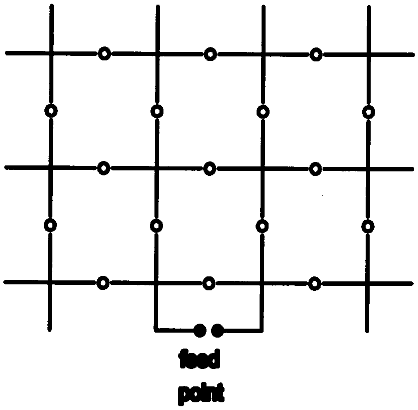

Figure 1. Crossed Wire Template

An antenna that physically moves to alter its structure is impractical to implement. Instead, a basic skeletal structure is electrically manipulated to provide a very large, but finite, number of possible configurations. The skeleton can be highly structured, or quite random in its geometrical configuration. Consider the simple two-dimensional structure shown in Figure 1. Here a rectangular array of metal wire crosses is laid out, with a controllable junction located at the intersection of each cross (denoted by a circle). This junction may either be short-circuited or open-circuited under the control of an embedded microcomputer. When adjacent crosses are shorted together, they form a conducting path. By choosing which junctions are connected, a wide variety of physical shapes are allowed, including loops, dipoles, stubs, etc. Note that the crosses need not be physically connected to effect the performance of the antenna. Thus, parasitic arrays and parasitic tuning stubs are allowed, and possible configurations include classical Yagi-Uda arrays. In a more recent embodiment, complimentary elements (i.e. slots in a conducting ground plane) are used as the radiating elements with the switches placed across the slots at various points to effect changes in the length of the slot, form slot loops, arrays or other configurations. The complementary elements have the advantage of radiating a polarization orthogonal to that of the conducting elements. This has been found to be significant in certain situations where low-profile antennas are required. Embodiments with a combination of both element types are also possible.

A less geometrically uniform skeletal structure is useful for embedding antennas within electronic systems and their containers. For instance, a skeletal structure could be incorporated into the plastic cabinet of a television set or within the plastic casing of a cellular telephone or other mobile transceiver. The skeletal configuration could take on whatever shape is convenient. "Randomly extended" structures may also be used, in which case the skeletal elements are ejected from a capsule and the antenna optimized for the resulting configuration. These types of antennas may find use in emergency beacons. Non-stationary elements can also be used, along with continuous optimization to compensate for the moving skeleton. Possible applications here include antennas towed by aircraft, ships and submarines as well as antennas that could be embedded in clothing and worn by the users of a personal wireless network.

The antenna feed structure may be attached at any convenient point on the skeletal structure, such as at the points of two crosses as shown in Figure 1. Multiple feed points are possible, and can be used to control multi-path ghosting and fading. All portions of the skeletal structure need not be in close proximity; feed points may be located a significant electrical distance from each other.

The needed short-circuiting may be provided through mechanical means (i.e., relays placed at the cross intersections) or electronically through solid-state relays or solid-state switches. The control lines to the junctions may be embedded within the skeletal support structure (e.g., embedded in a plastic structure) or be a simple wire harness. Ordinarily, the interaction of the antenna structure with the control lines would be a serious design consideration, but the nature of the self-structuring antenna allows it to automatically compensate for any interactions. If these interactions prove to be severe, a fiber optic cable, or an embedded fiber optic channel, could be used to carry a control signal to an opto-electronic switch at the short-circuit junction.

Control of the antenna structure is achieved using an embedded microprocessor under the influence of one or more feedback signals. For instance, a receiving antenna may be structured to provide maximal received signal strength by taking the voltage at the output of the receiver RF amplifier and using it as a feedback signal. A fuzzy system may be used when several qualities are desired – e.g., high signal strength, good audio clarity, efficient multi-path suppression, etc. A transmitting antenna pattern may be controlled by providing feedback via a secondary receiving probe placed in the near-zone or far-zone field of the antenna. Optimal transmit VSWR could be obtained by using a feedback signal from an in-line SWR meter. The block diagram of a self-structuring antenna is shown in Figure 2.

The success of a self-structuring antenna is highly dependent on the microcomputer algorithms. A trade-off exists between the "diversity" of the antenna – i.e., the number of possible configurations allowed by its structure – and the complexity of searching for the optimum structural arrangement. An antenna with a higher level of diversity should provide a more optimum performance, but will require a longer time to find the optimum configuration. For example, when the antenna of Fig 1 has three rows of three crosses there are eight junctions, and thus $2^8=256$ structural arrangements are possible. These could be easily searched for the one that produces the desired optimized effect. However, when six rows of six columns of crosses are used, there are 50 junctions and thus 2^{50} or over one *trillion* possible structures. Obviously, even a fast microcomputer cannot sort through this many possibilities in any practical real-time application. However, the benefit of the self-structuring skeleton approach is that the problem is *binary* – each junction is either on or off. Many recently developed algorithms can be used to optimize the structure without exhaustively searching all possibilities. Some of the most promising are Genetic Algorithms (GA), Simulated Annealing (SA), and Ant Colony Optimization (ACO). A simple random search is not effective. Without efficient algorithms, the SSA concept would not be plausible.

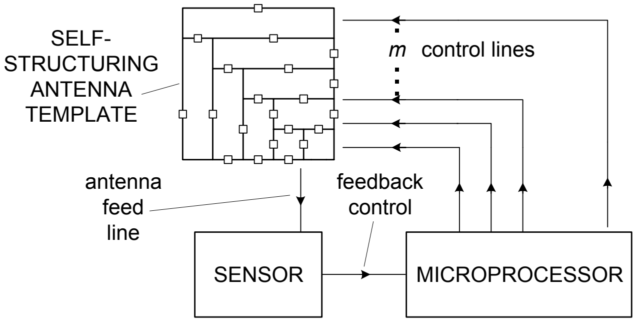

Figure 2. Block diagram of Self-Structuring Antenna System

One way to reduce the size of the optimization problem is to maximize diversity – that is, to pick a skeletal arrangement where duplication of configurations is minimized. It is easy to see that the cross-wire arrangement shown in Figure 1 can have identical configurations for different selections of the shorting points. This is mainly due to the symmetry of the structure. Other selections may produce only slightly different arrangements. Thus, much optimization time is spent considering arrangements that are not very different from each other. To eliminate these as possibilities, a more geometrically “diverse” skeleton is considered. Figure 3 shows non-symmetric structures where each combination selection of shorting parameters gives a different geometrical arrangement. It has been designed to provide wideband operation by allowing both very short current paths (for high frequency operation) and very long current paths (for low frequency operation). Care does need to be taken that the skeleton does not result in a “hard” optimization problem – i.e., a problem in which only a small handful of arrangements work well. Such optimal configurations are notoriously difficult to find without an exhaustive search.

Examples of some of the template configurations that have been investigated to date are shown in Figure 3. The first geometrically diverse template investigated was denoted the standard template (A). The log periodic template (B) has enhanced bandwidth. The edge switched configurations (C and D) are of interest to the automotive industry where antennas are integrated on the window glass and switches must be concealed. Complementary elements (e.g. slots) (E) are low profile alternatives to vertical whip antennas. The prototype (F) has 24 switches and over 8 million possible configurations.

The most appropriate shape of the skeleton and optimum feeding techniques are dependent on the particular application of the antenna. However, the range of frequencies and applications for any single template is vastly larger than any fixed antenna, phased array or re-configurable antenna. The key factor is diversity in the skeletal template and the ability of the algorithms to efficiently locate desirable states. Thus, malleable, plastic-based skeletal sheets would provide a flexible means of applying self-structuring antennas to a wide variety of geometrical conditions. Generalized placement of elements in three dimensions are also possible and may lead to reduced size and weight for certain applications. Such configurations have yet to be investigated.

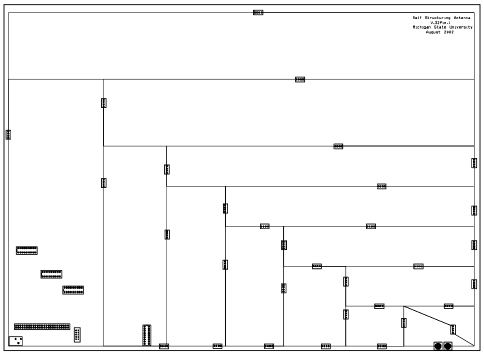

Figure 3-A. Standard template

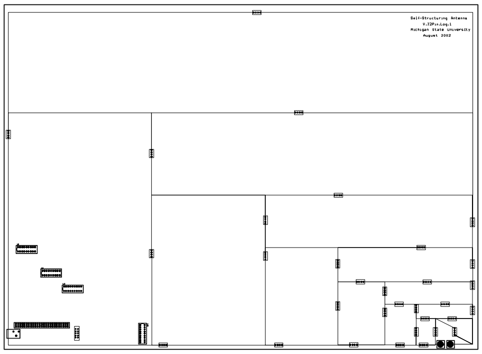

Figure 3-B. Log Periodic template

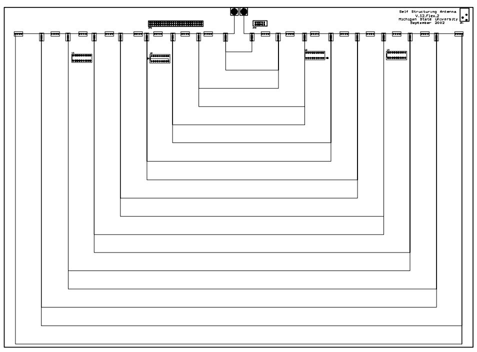

Figure 3-C. Edge Switched I - Meander

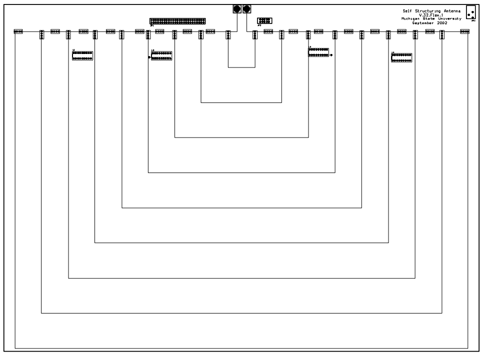

Figure 3-D. Edge Switched II – Loop

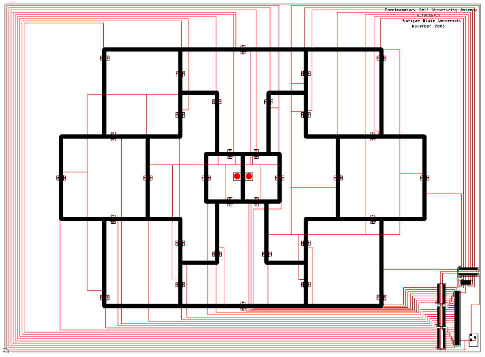

Figure 3-E. Complementary Elements (black) indicate slots in top conductor layer.

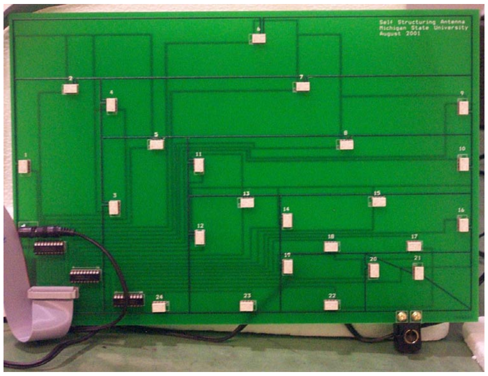

Figure 3-F. Photo of prototype SSA.

Measured SSA Performance

Tuneable VSWR Bandwidth

The SSA is capable of exceptional tuneable bandwidth. Figure 4 shows a plot of the **measured** VSWR versus frequency for various template configurations. All templates were 16 x 22 inches in size and used 32 switches for a total of approximately 4 billion states. Switching was accomplished by electromechanical relays and control was performed using a general-purpose notebook computer equipped with commercially available interface and control boards. The VSWR was minimized at each frequency using a smart algorithm. The minimum value achieved at each frequency is plotted. While VSWR of the Standard template is very good, it begins to increase substantially above 650 MHz. The Log-Periodic and Edge Switched I Meander templates continue to have good performance out to 850 MHz, the upper limit of the experiment. Data for the Edge Switched II – Loop template above 500 MHz is currently unavailable. It should be noted that at 50 MHz, the lowest frequency used in this experiment, all of the antennas are electrically small and achieve good performance by coupling intelligently to larger nearby structures, including control and power lines used to drive the antenna.

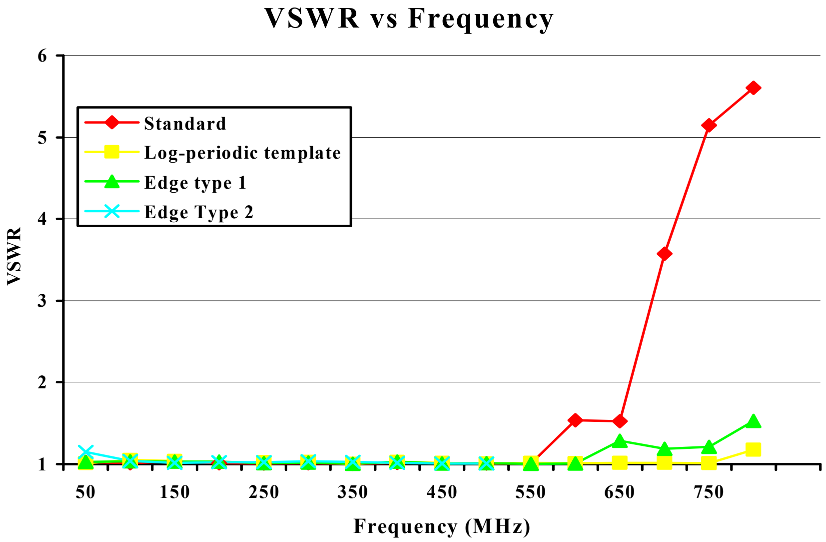

Figure 4. Measured VSWR versus Frequency for various template configurations.

Omni-directional and Directional Patterns

The SSA can exhibit directionality and omni-directionality. To date, research has focused on evaluation of the ability of the antenna to optimize signal for various configurations. Figure 5 shows measured radiation patterns for the standard and edge switched type-1 templates (described above) at 400 MHz. The black curves are the radiation patterns associated with states optimized for reception at 0 degrees aspect (broadside). The red curves show gain achieved if the antenna is allowed to optimize at each angle. The plot clearly shows the ability of the SSA to improve performance at every aspect angle.

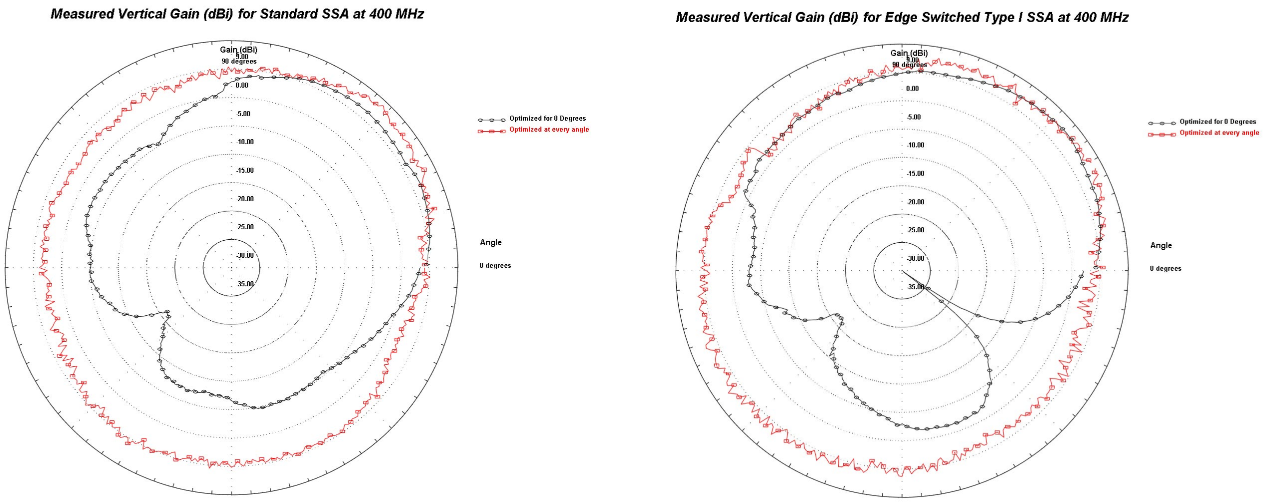

Figure 5. Measured gain patterns for Standard (left) and Edge Type I (right) SSA templates. Scale is 5dB/div with outer most circle corresponding to +5dBI.

Complementary SSA Analysis

The Complementary SSA (CSSA) uses slot radiators to produce vertically polarized radiation from a horizontally oriented template. A computer model of a CSSA template over a vehicle roof is shown in Figure 7. The CSSA can be used as a single antenna alternative to the multiplicity of vertical whip antennas often seen on military and commercial vehicles. For military users, the low profile CSSA can save lives by reducing the visible signature of the vehicle and thus risks of drawing enemy fire. Automakers can benefit from reduced drag and improved aesthetics.

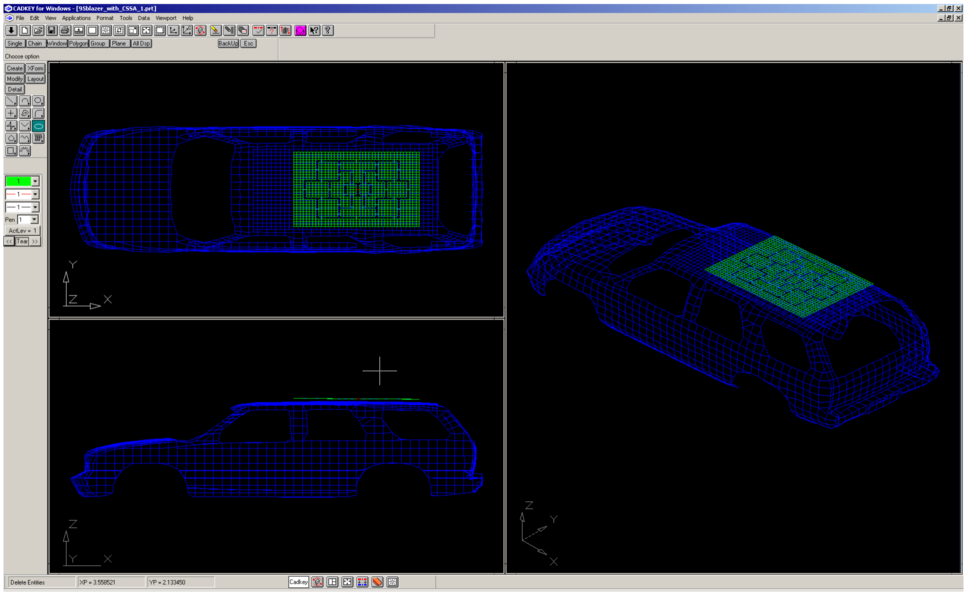

Figure 6. Computer model of CSSA mounted above vehicle roof.

Numerical analysis reveals that the CSSA exhibits a wide tuneable bandwidth similar to that of the wire based SSA. Figure 7 shows VSWR versus frequency when the CSSA is placed in a free space environment. The VSWR is superb from 50 MHz through 1000 MHz. The poor results at 40 MHz are a result of the small electrical size of the template.

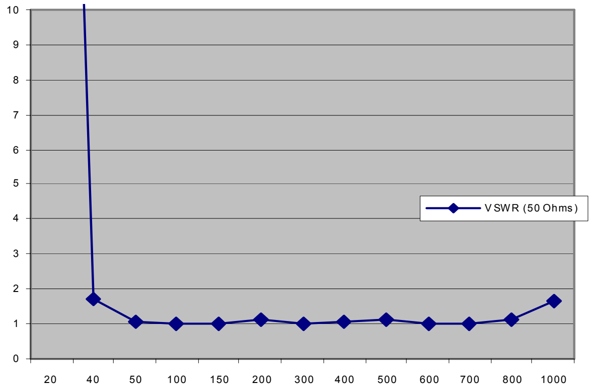

Figure 7. Computed VSWR versus Frequency for CSSA in free space.

Figure 8 shows the performance of the same template when it is placed near a vehicle. Here, the VSWR results improve substantially at the lower frequencies due to coupling to the vehicle structure. While the advantages of coupling to the vehicle have been know for many years, until now, it has required substantial engineering effort to ensure that the coupling was done properly. With the advent of the SSA technology, the coupling is used intelligently without requiring large up front engineering costs. Note that the vehicle simulations were limited to 300 MHz due to the grid size employed in the mesh model. In both cases, the VSWR is excellent across a wide frequency range.

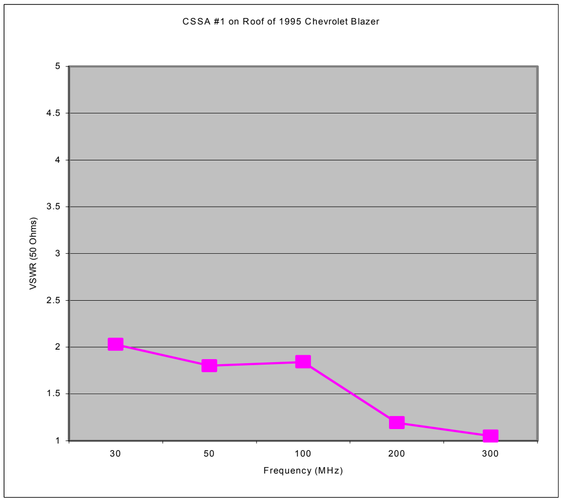

Figure 8. Computed VSWR versus Frequency for CSSA on vehicle.

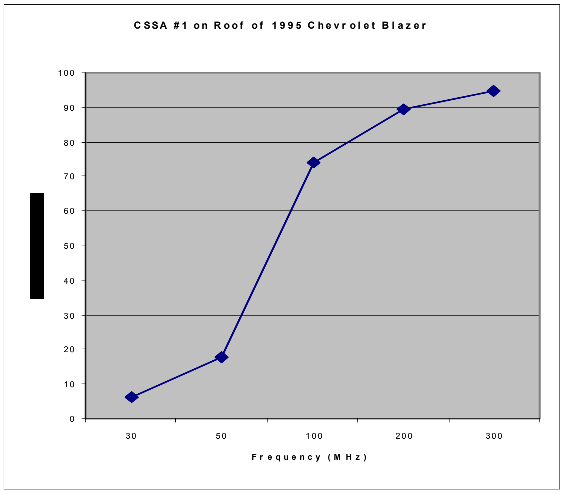

Figure 9. Computed efficiency versus Frequency for CSSA on vehicle.

The computed radiation efficiency of the vehicle mounted CSSA is shown Figure 9. As would be expected, the efficiency suffers at low frequencies, where the antenna is electrically small, but improves nicely by 100 MHz. Computations performed with the CSSA in free space indicate that the efficiency remains high out to 1 GHz, the limit of the free-space simulations. It should be noted that the computational requirements for the CSSA on the vehicle were substantial and the GA was stopped once a usable result was obtained. It is entirely possible, and perhaps likely, that better results could have been obtained by allowing the GA to run longer. Fortunately, in practice, the functional evaluations are simply a matter of measuring signal strength so thousands of measurements are possible in a very short amount of time.

Figure 10 shows the results of a computer simulation of the CSSA on a vehicle at 50 MHz. The algorithm was directed to find a configuration with optimal VSWR. No attempt was made to optimize pattern shape. Because the CSSA is based on slots, the antenna exhibits strong vertical polarization at the horizon as would be required in most vehicular communications systems. Gains for horizontal polarization are also strong, allowing some sensitivity to cross-polarized signals. The total gain pattern is remarkably uniform due to the inherent symmetries of the CSSA template.

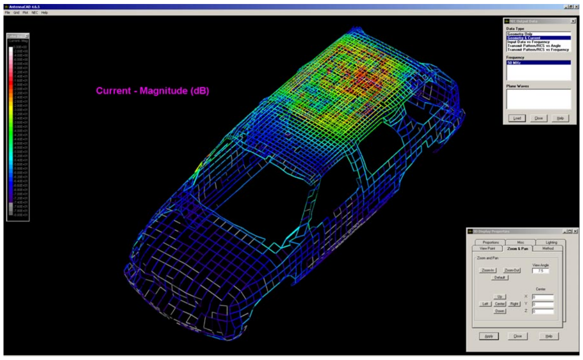

Figure 10-A. Surface currents at 50 MHz.

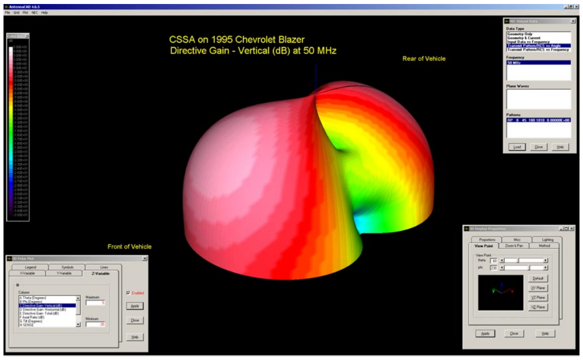

Figure 10-B. Vertical gain at 50 MHz.

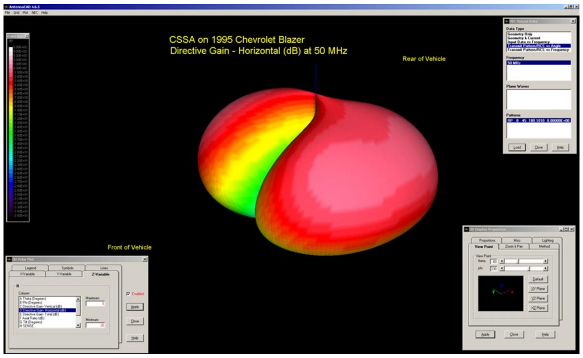

Figure 10-C. Horizontal gain at 50 MHz.

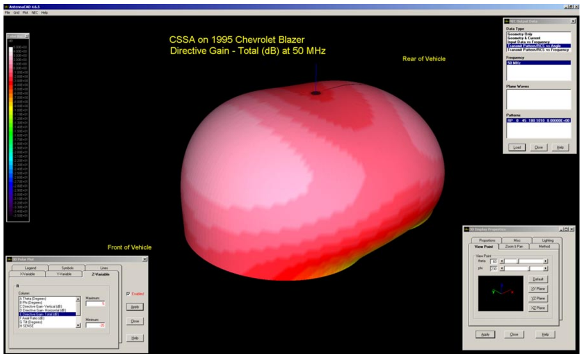

Figure 10-D. Total gain at 50 MHz.

Figure 11 shows similar results for simulations at 100 MHz. While there is more variation in the elevation plane patterns, there is still substantial vertical gain at the horizon. Again, the total gain pattern is remarkably uniform due to the symmetry of the template.

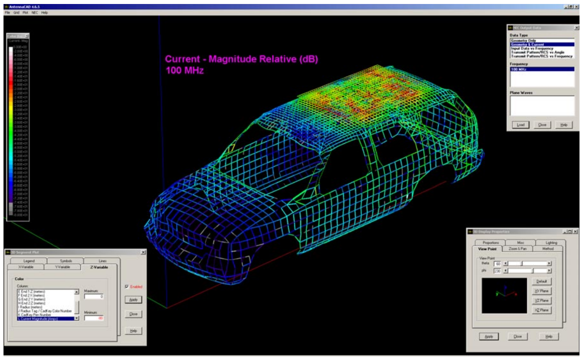

Figure 11-A. Surface currents at 100 MHz.

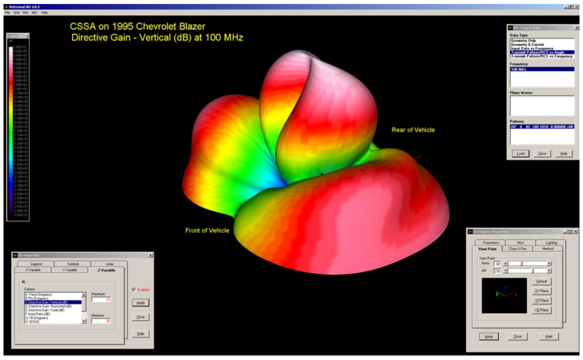

Figure 11-B. Vertical gain at 100 MHz.

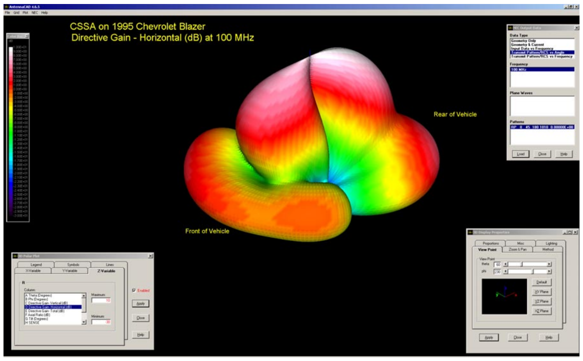

Figure 11-C. Horizontal gain 100 MHz.

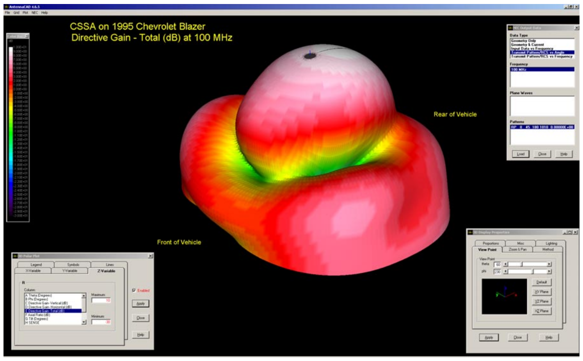

Figure 11-D. Total gain at 100 MHz.

Many other aspects of the SSA have been investigated and are reported in the literature listed in the bibliography.

Potential Applications

There is a wide range of potential applications for the SSA technology. A few of these are listed in this section.

Wideband antennas

The initial prototypes of the SSA have demonstrated how a self-structuring antenna may be used for wideband applications. The optimized SWR was maintained at < 2:1 over a range from 50 MHz through 850 MHz for some of the templates. Although this antenna was optimized at each individual frequency, a self-structuring system could be optimized to provide maximal received signal strength at several frequencies simultaneously.

Small antennas

An appropriately shaped self-structuring antenna can be optimized for performance at frequencies much lower than those associated with the resonant size. An SWR of 1.031 was obtained using a prototype antenna at 40 MHz. At this frequency the antenna is only 0.041 wavelengths wide by 0.027 wavelengths high. Performance such as this is made possible by the fact that the SSA can intelligently couple to other nearby structures to effectively increase its electrical size and enhance its performance. While for fixed antennas, the coupling to a vehicle, mounting platform or even cabling can have a negative effect, the SSA can use these structures to best advantage without additional engineering and design expenses.

Mobile radio antennas

Mobile radio antennas are difficult to design because of the constantly changing environment in which they are used. Different users couple to the antennas differently, users are constantly in motion, and users are often in environments subject to multi-path and fading. Self-structuring antennas can respond quickly to this changing environment.

Randomly-deployed antennas

Often antennas of specific geometry either cannot be physically deployed or are difficult to fit to the environment. A self-structuring antenna can be of great use in these situations. A self-structuring antenna in the form of a net can be temporarily thrown over a vehicle or hung from a tree in any convenient configuration. An unmanned probe can have a self-structuring antenna that is ejected from a canister, deploying randomly about the probe. In each case the antenna can be optimized for performance in its environment.

EMC mitigating antennas

In situations where many antennas exist in a confined space (such as on a ship or tank), interference between antennas is a prime concern. Self-structuring antennas can be used to mitigate the interference by using the cross-coupled signal as an input to determine the structural shape. They can be optimized to eliminate cross talk while maximizing received or transmitted signal strength.

"No-design" uses

By its very nature, the self-structuring antenna requires little design effort. When a specific antenna need arises, a self-structuring antenna may be taken "off the shelf," placed into the system, and allowed to adapt via specific feedback stimuli. This may provide a simple, no-design, "good enough" antenna for many uses.

Multi-path canceling antennas

Because a self-structuring antenna can have several feedpoints, it may be possible to cancel the effects of multi-path by combining the output signals in an appropriate way. The antenna structure would adapt so that a feedback signal describing the effect of multi-path interference would be minimized.

Factory or Field-Programmable Re-Configurable Antenna

In some instances such as direction finding, it is important to know which direction the antenna is pointed and in others, it is important to have a known omni-directional pattern. While pattern information for an SSA is generally not known a-priori, it is possible to program the SSA with a list of states with known patterns either at the factory or in the field by using a control computer linked to an array of sensors positioned about the SSA as shown in Figure 12. Measurements from these sensors could be used to have the SSA configure its radiation pattern to closely match pre-determined standards. By having a list of states with pattern maximums in various directions, one could easily perform beam sweeping for direction finding purposes. The advantage of the SSA is that these states would not require the enormous upfront engineering costs that might be associated with a traditional re-configurable antenna or phased array system. The state database could hold as many configurations as required to have bearing information for a wide range of frequencies.

Antenna for Software Defined Radio

To enable communications and interoperation between the military, homeland security, and state and local responders, the Department of Defence is developing new programmable radios that enable any communications waveform or protocol to be used over a wide frequency range. The SSA technology could enable the SDR to extend programmability and adaptability beyond the RF connector and to the antenna and thus allow the SDR to cover extreme frequency ranges with reduced size, weight and cost. Similar SDR systems are being developed for a variety of modern commercial communications systems including wireless LAN and HDTV.

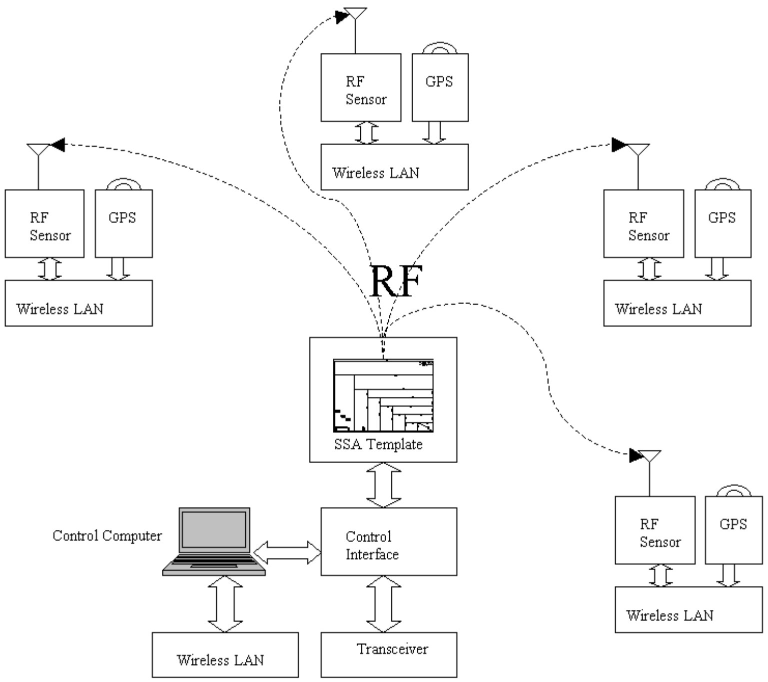

Figure 12. Conceptual diagram of SSA used as a factory or field-programmable re-configurable antenna. Feedback of signal received at each sensor is sent back to control computer via wireless LAN. GPS used to accurately locate each sensor for bearing and distance.

Summary

The SSA is a new class of adaptive antenna that offers substantial advantages over traditional fixed antennas, phased-array, and re-configurable antennas. The SSA concept breaks the old paradigm of antenna design that required a complete understanding of antenna performance to be established prior to deployment. By allowing the antenna to adjust its shape as needed to maintain optimal performance, the SSA can make the most of its environment and signal conditions at all times. Whereas a fixed antenna can become essentially useless when subjected to damage, the SSA can still provide functionality using whatever portions of the template remain intact after damage is sustained. The result of this change in philosophy is that antennas can be built that will have wider bandwidth and better performance on a wider range of platforms than ever before. Moreover, these advances will be done faster and at lower cost than can be achieved by traditional antennas that require substantial engineering prior to deployment.

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