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Tunable Antenna for Handsets

Self-Structuring Antenna (SSA) Technology

1. Description

Monarch's patented Self-Structuring Antenna (SSA) technology is the result of many years of development and is being used in both the civilian and military sector of the economy. With several advancements since its first inception, the SSA technology has proven its value by improving reception in demanding conditions, as well as reducing power consumption. SSA is a reconfigurable adaptive antenna which optimizes its aperture based on feedback from the radio to maximize the signal quality as shown in Figure 1. The SSA technology allows for simultaneous tuning of (1) frequency, (2) beam pattern and (3) input impedance, dynamically. The antenna aperture is electrically altered by using solid-state or micro-electromechanical relays to maximize RF link quality. Though the optimization is based on the received signal, the reciprocity of the electromagnetic wave dictates that the same optimization also holds for the transmitted signal. This is accomplished by identifying the most relevant switch combinations in the antenna design phase, to produce the greatest efficiency. These switch combinations provide a sufficient number of degrees of freedom to allow for dynamic frequency, pattern and impedance tuning of the antenna. It is important to note that no separate impedance tuning circuitry is needed as that is taken care of by the self-structuring of the aperture and hence, SSA is immune to detuning. SSA requires feedback from the radio for optimum performance but could be operated in sub-optimal plug-in fashion with the aid of a self-tuning circuit.

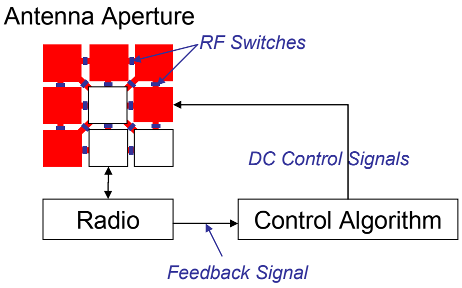


Figure 1: Self-Structuring Antenna (SSA) technology.

2. Benefits

1. Aperture tuning allows for frequency tuning of the antenna, which results in a single antenna for multiple frequency bands and hence lower component count.
2. A narrow-band frequency tunable antenna is always more efficient than a wide-band or multi-band passive antenna due to conservation of energy since the product of bandwidth and efficiency must remain approximately constant from antenna to antenna.

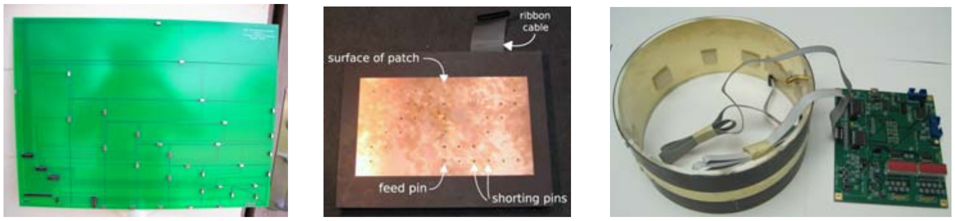
3. SSA reconfigures its aperture to compensate for detuning of the antenna instead of a separate impedance tuning circuitry and aperture tuning results in more efficient antenna than impedance tuning circuit since the electric current is spread over larger space.
4. Both the frequency tuning and the aperture tuning will result in a higher efficiency antenna, which means:
   a. Amplifier does not have to work hard and less current is drawn from the battery for transmitting the signal, hence longer battery life
   b. With a narrow band antenna, the filter can be cheaper grade and hence lower price for the component.

3. SSA vs. Competing Technologies

There are stark differences between the SSA and the other competing technologies, and how they achieve Antenna Tuning is summarized in the table below:

SSA	COMPETITION
Antenna Architecture	Antenna
Substrate Agnostic	Substrate Dependent
Reconfigurable Aperture	Impedance Matching Circuit
Operates on Sub-Resonant Elements	Combining Resonant Elements
Digital Control	Analog Control
High Power Efficiency	Low Power Efficiency
Large Tuning Range	Small Tuning Range
Uses ON/OFF Relays	Uses Varactors
Standard Board Manufacturing	Non-standard/Exotic Materials
Specific Absorption Rate (SAR) Friendly	Is not SAR Friendly

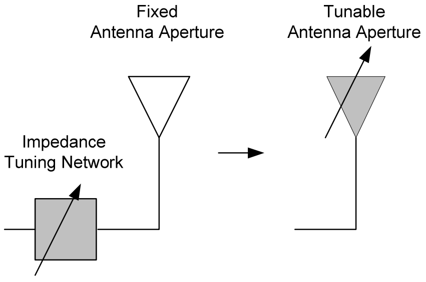
1. SSA is an architecture and method of reconfiguring the aperture of the antenna using ON/OFF relays. It could take the form of switching in and out sub-resonant lengths of conducting wires, short-circuiting (electrically connecting?? a microstrip patch to ground at various locations inside its cavity or grounding one edge of a microstrip line with a shunt capacitor at various locations along its length (see Figure 2).



(a) (b) (c)

Figure 2: (a) Wire-loop SSA developed for HDTV applications, (b) a proof-of-concept Patch SSA with shorting pins, and (c) Leaky Wave SSA for 360 coverage configured using shunt switches along a microstrip.

2. SSA is substrate agnostic and could be manufactured using any standard substrate. SSA can be a planar antenna printed on a substrate or 3D antenna printed realized using standard 3D circuit printing techniques.
3. SSA reconfigures the aperture of the antenna, instead of adding an impedance matching circuit to an existing antenna (see Figure 3). The vast majority of today's smart phones employ multi-band passive antennas, which offer suboptimal performance across all frequency bands of interest and are susceptible to detuning; hence they are being phased out and being replaced by tunable antennas. Few phone models today carry what is typically called "impedance tuners" placed between the antenna and the power-amplifier (PA), as shown in Figure 3(a), to primarily compensate for detuning of the antenna. Some manufacturers are gearing up to provide similar circuit components for also switching between frequency bands over large ranges (700-2,700MHz) for global LTE roll out. SSA takes the antenna tuning technology to a higher level by reconfiguring its aperture to tune the antenna over large frequency ranges as well as to recover from severe detuning. SSA also does this without requiring the additional circuit component called the Tuning Network. SSA offers solid-state and MEMS-enabled products in the design, to compensate for fluctuations in antenna input impedance. This improves performance when the phone is handled during use and/or when the phone is operating over different frequency bands. Other solutions fall short of satisfying performance requirements since (1) the impedance tuners exhibit high Quality Factor (Q), which contribute to high RF losses and (2) the antenna aperture remains detuned and hence the solution is suboptimal.



(a) (b)

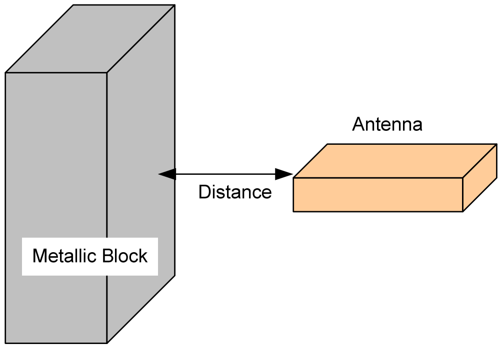
Figure 3: (a) Conventional approach where a tunable impedance network is placed before the antenna and (b) Monarch's approach where the antenna aperture is tuned instead.

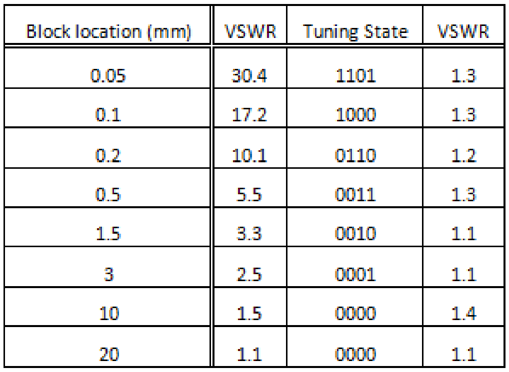
Monarch's SSA solution is a "tunable aperture", where the aperture is reconfigured to: (1) alter its input impedance to recover from detuning, (2) to tune the antenna to operate at a different frequency band, and (3) to alter its polarization.

Tuning the aperture is more beneficial than adding tuning circuits for many reasons:

- The antenna aperture itself is reconfigured to generate 50ohm input impedance, making it more efficient
- The electric current is spread over a much larger real-estate with a much lower density resulting in the solid-state switches having to carry much smaller current levels thereby avoiding the non-linear region and the harmonics.

The points mentioned above have been validated using simulated data. An antenna design for 2.4-2.5GHz operation measuring, 10mm x 10mm x 2.4mm in size, and using four SPST relays to alter its aperture produced fine-frequency tuning to individual channels and recovery from detuning, dynamically. Figure 4 demonstrates the advantage of *aperture tuning* over *impedance tuning*. As shown in Figure 4(a), The antenna has been simulated using HFSS software, where the distance between a metallic box and the antenna is varied from 20mm to 0.05mm and the worsening VSWR is computed at 2.45GHz (at the center of the frequency band). As shown in table in Figure 4b, as the metallic box is brought closer to the antenna, the antenna detunes and the VSWR (efficiency) worsens as would be expected (increases from 1.1 to 30.4). The table also lists the switch logic states that recover VSWR to 1.4 or less. Recovering from a VSWR of 30.4 is significant, since typical *impedance tuning* circuits (utilizing the same number of switches) could only provide detuning compensation from VSWRs as high as 5 only. This testifies to the power of *aperture tuning*. It also enables improved performance, which increases battery life or allows for smaller battery with equal performance.





Block location (mm)	VSWR	Tuning State	VSWR
0.05	30.4	1101	1.3
0.1	17.2	1000	1.3
0.2	10.1	0110	1.2
0.5	5.5	0011	1.3
1.5	3.3	0010	1.1
3	2.5	0001	1.1
10	1.5	0000	1.4
20	1.1	0000	1.1

(a) (b)

Figure 4: (a) The geometry of the metallic block in proximity of the antenna, (b) Resultant VSWR worsens as metallic block to antenna distance decreases, and recovered VSWR values with corresponding switch logic states.

4. SSA reconfigures the aperture of the antenna by connecting and disconnecting “sub-resonant” pieces as opposed to combining individual “resonant” antennas. This separates it from legacy approaches such as “antenna combining” and “phased arrays” as practiced in cell phone towers.
5. The SSA achieves aperture tuning via digital control and can therefore be seamlessly integrated into the next generation Front End Modules (FEM) via RFEE or other module control standards.
6. SSA uses hard-switching by employing Single-Pole-Single-Throw (SPST) ON/OFF relays, which are widely available from multiple suppliers.
7. SSA offers higher power efficiency than passive antennas and passive antenna-impedance tuner combinations. Antenna with higher efficiency will extend the battery life since less power will be used by the electronics as illustrated in Figure 5.

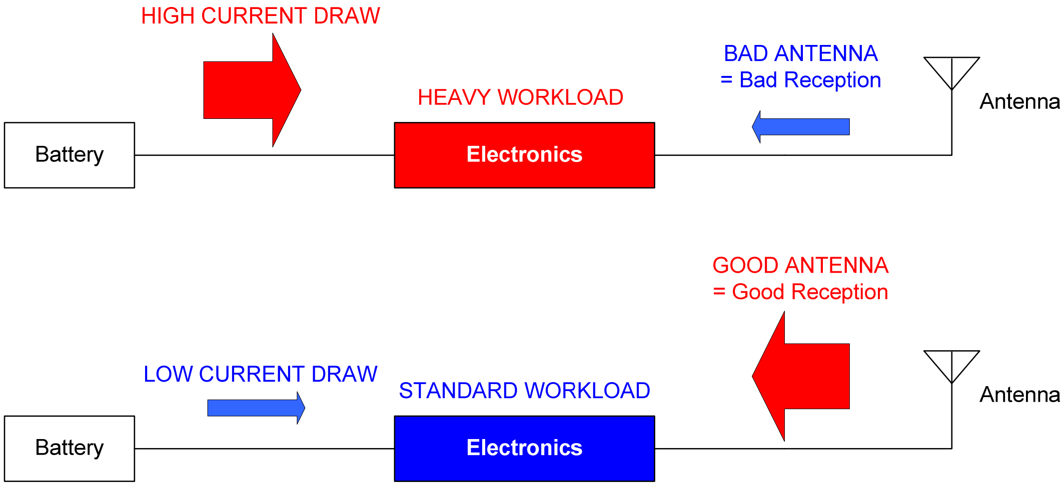


Figure 5: Effect of antenna performance on the battery life.

8. SSA can be designed to have very low Specific Absorption Rate (SAR), which is a measure of electromagnetic energy radiated by the phone and absorbed by the human body. There are serious concerns about long term health effects of cell phones and numerous studies have been completed and many are ongoing. Current SSA prototype developed by Monarch always radiates away from the body and hence offers very low SAR numbers and an SSA can also be operated to maintain low SAR numbers under different operating conditions dynamically.

4. Tunable Handset Antenna for LTE Global Roaming Band (2.3-2.7GHz)

1) Design and Manufacturing

The reconfigurable antenna design described here is based on a printed half patch antenna and is shown in Figure 6. The entire antenna geometry (including the feed network) measures 16mm x 16mm x 4mm with a patch radiator measuring only 10mm x 5mm. As the name suggests, the size of this antenna is half of a regular patch. The reduction in size is achieved by shorting one end of the antenna to ground at the expense of the antenna efficiency. To increase the instantaneous bandwidth, the antenna is manufactured using a 150 mil dielectric substrate. Figure 6 shows the photograph of the back side of the assembled antenna readied for measurement. Antenna tuning is achieved by 4 RF switches producing a total of 16 states (logic states 0000 to 1111). The switches are controlled via 4 DC control lines. A 0V signal (with respect to a -3.3V supply voltage) means the switch is ON and -3.3V signal means the switch is OFF. To suppress possible RF contamination in the control lines, single layer capacitors are installed in the vicinity of the switches and both the switches and the single layer capacitors are mounted using wire-bonding.

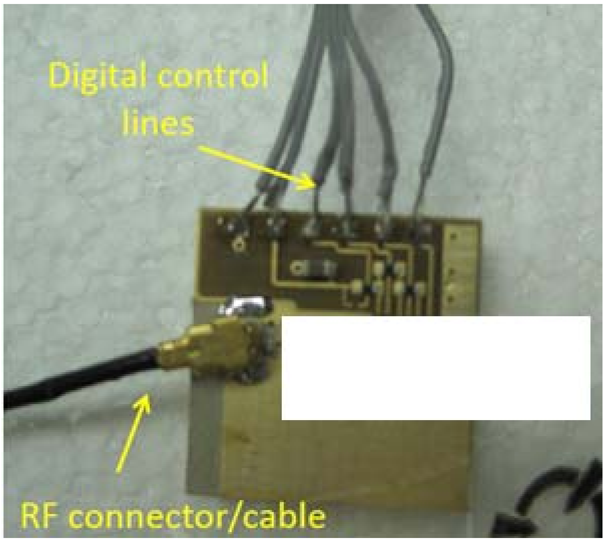


Figure 6: 4-bit prototype antenna completely assembled and ready for testing.

2) Return Loss (S11): Measured vs. Simulated

The performance of the antenna was first simulated using HFSS and then validated with measurements. Figure 7 depicts the S11 (return loss) measurement setup. Since the dielectric constant of the Styrofoam is close to 1, it is used as a structural support material for the antenna without altering antenna properties. Tuning is achieved by manually connecting digital control lines to 0V or -3.3V on the breadboard. The traces are then recorded using the vector network analyzer.

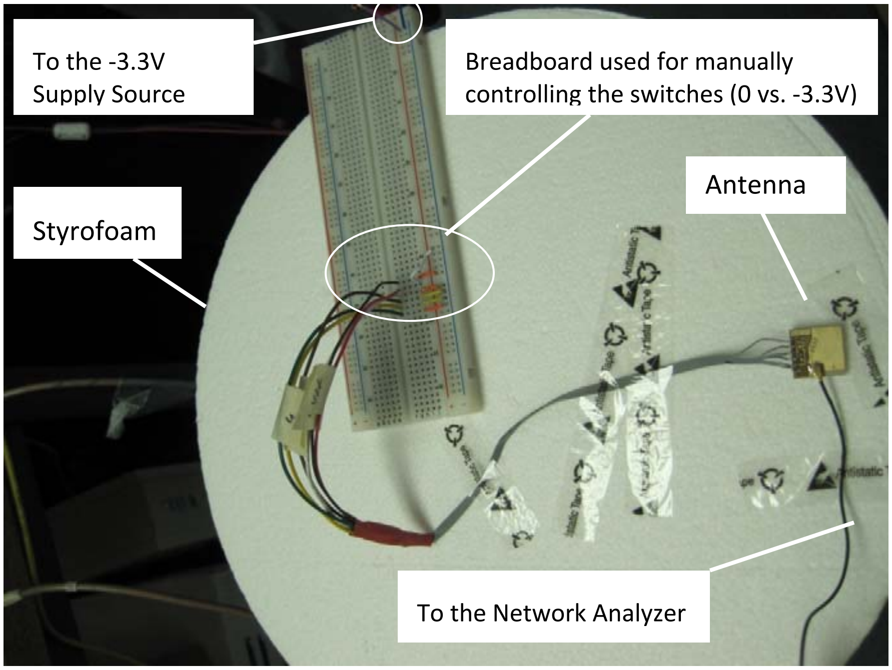
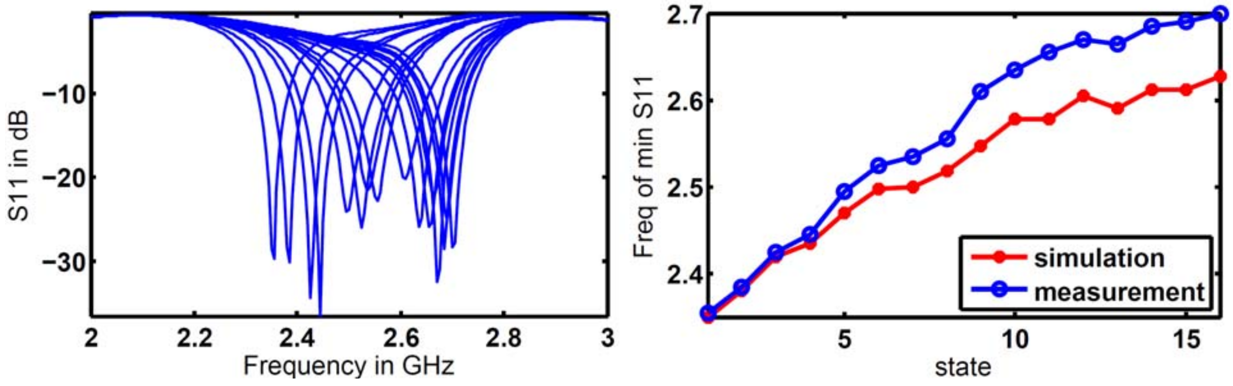


Figure 7: Setup for S11 (return loss) measurement.

Figure 8(a) shows the S11 curves for all 16 states. As can be seen, the resonant frequency can be tuned almost uniformly between 2.35 GHz and 2.7GHz. Figure 8(b) compares the simulated and measured tuned frequency of the antenna as a function of the switch states and validates the design process. Considering much of the parasitics associated with the solid-state switches are not available to the simulation, this is an excellent agreement.



(a)

(b)

Figure 8: (a) S11 vs. Frequency for all 16 states as recorded on the Network Analyzer. The frequency can be tuned from 2.35 GHz to 2.7 GHz to cover the global roaming band 2.3-2.7GHz, (b) Simulated and measured Tuned Frequency vs. State. Sate 1 is logic state 000 (corresponding to -3.3V on all 4 lines) and State 16 is logic state 1111 (corresponding to 0V on all control lines). Supply voltage (Vdd) is at 0V with respect to ground. Considering typical tolerances involved in prototyping, there is excellent agreement between simulation and measurement..

3) Measured Gain Patterns

After the Return Loss (S11) performance was validated, three states (at the edges and middle of the tuning range) were picked for the gain pattern measurements. Table 1 lists the maximum achievable gain for three logic states: 0000, 0111 and 1111, which tune the antenna to lower end, middle and the higher end of the roaming band, respectively, as measured in the anechoic chamber. Figure 9-8 display patterns along three principal planes of the antenna for 0000, 0111 and 1111 switch logic states, respectively. Gains of -4dBi and -5dBi are very good numbers for this antenna, considering it has a half-patch radiator of 5mm wide, which is 1/12th of the size of the full size air-filled half-patch radiator measuring 60mm and having 9dBi gain. The on-state switch resistance of 6ohms also contributes to the negative gain numbers.

Switch Logic State	Measurement Frequency (MHz)	Maximum gain (dBi)
0000	2357	-4.44
0111	2591	-5.29
1111	2695	-3.57

Table 1: Measured maximum Gain for three switch states.

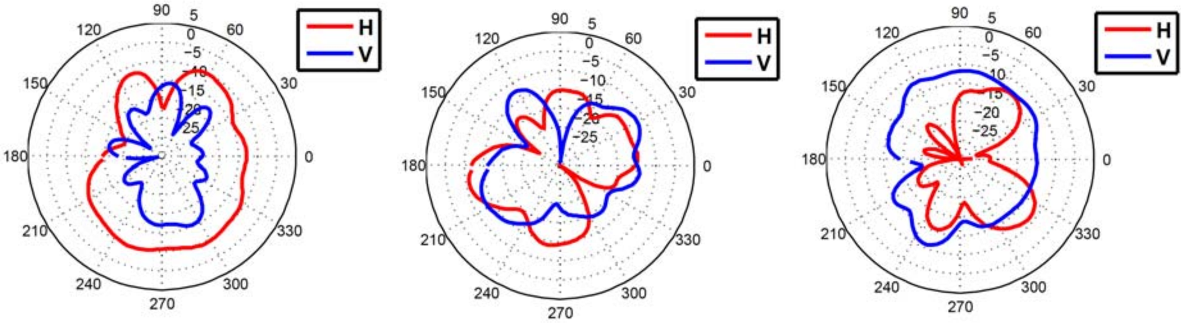


Figure 9: Gain patterns for 0000 logic state at 2357 MHz along three cuts.

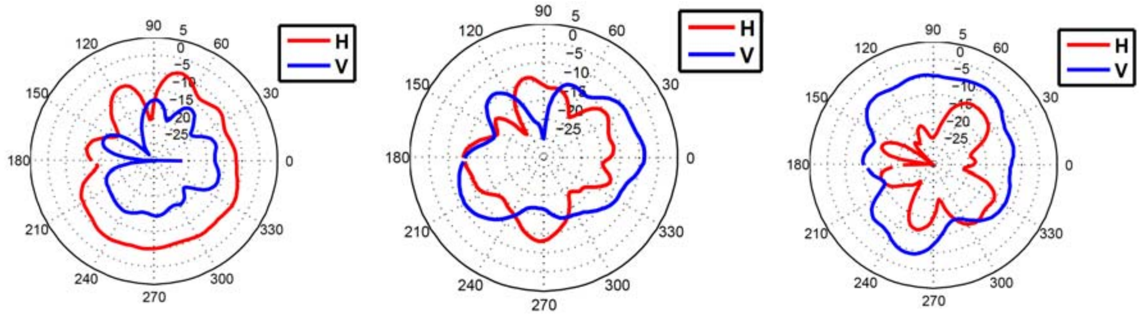


Figure 10: Gain patterns for 0111 state at 2591 MHz along three cuts.

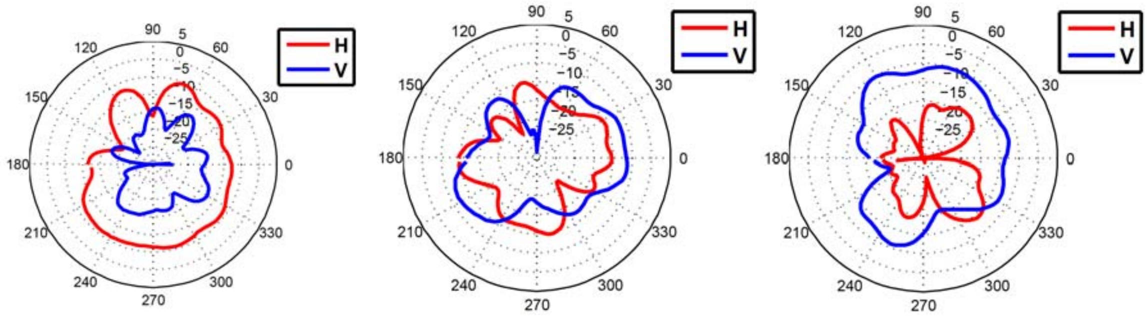


Figure 11: Gain patterns for 1111 state at 2695 MHz along three cuts.