# Final Report

# New Indoor Smart Antenna System Using a Single-Wire Interface

*NAB FASTROAD FTP-3*

Submitted to

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# 1 Introduction

This is a non-proprietary version of the final report for the National Association of Broadcasters (NAB) Flexible Advanced Services for Television and Radio on All Devices (FASTROAD) project FTP-3 entitled "New Indoor Smart Antenna System Using a Single-Wire Interface". This report does NOT include detailed circuit schematics, circuit descriptions, and other potentially sensitive information that was included in the original proprietary version. The omission of this information has caused the page and section numbering to differ from the original.

The NAB Request For Proposals (RFP) for this program was issued in the fall of 2007. The Antennas Direct team responded by submitting Proposal NAB_FT3-RFP-9/28/07 on October 31, 2007. After reviewing proposals, NAB requested that the Antennas Direct team submit a revised proposal with reduced scope and cost that focused on development of a compact VHF/UHF reconfigurable antenna and a two-wire to single wire CEA-909 test fixture. Antennas Direct subsequently prepared and submitted Proposal NAB_FT3-RFP-9/28/07-Rev-1 on December 14, 2007.

NAB initiated funding of the ten-month effort on March 2, 2008 with period of performance to run through January 2, 2009. Scheduling delays precipitated by unanticipated technical challenges and economic conditions prevalent in the fall of 2008 resulted in a "no cost" continuation of the effort through February 9, 2009.

## 1.1 Deliverables

As specified in the proposal, deliverables for this project are as follows:

1. Brief written monthly status reports throughout the course of the program.
2. Final technical report summarizing all relevant results, calculations, analyses, computer simulations, design notes, test results, etc. This report will essentially be an edited compilation of the monthly reports with additional clarifications and narrative added as necessary to properly present the material.
3. Two complete working prototype systems for each of the funded development efforts.

Item 1 was been met by submission of status reports throughout the course of the program. Item 2 is satisfied by this document. The prototypes of Item 3 were delivered to NAB headquarters in Washington, D.C. on February 6, 2009.

## 1.2 Report Overview

Subsequent sections of this report detail the thinking and analysis that went into development of the antenna architecture and the selection of the tunable microstrip element. The discussion is supplemented by laboratory test data and computer simulation results obtained using a state-of-the-art Finite Difference Time Domain (FDTD) field solver. Also included is a discussion on the CEA-909 implementations encountered in commercially available receivers currently on the market and the impact their non-conformance may have on the viability of supplying smart antennas to the existing base of receivers.

## 1.3 Acknowledgement

The Antennas Direct engineering teams are committed to research, development, and commercialization of smart antenna technology. Both organizations are grateful for the generous financial support provided by NAB in their quest to improve the art of television and radio reception.

# 2 System Overview

## 2.1 Overview of Indoor Smart Antenna System

During the course of this program, Antennas Direct's, Viamorph engineering team made substantial and unique advances in the art of smart antennas for DTV reception using CEA-909 and CEA-909A enabled receivers. The smart antenna systems delivered to NAB under this program are still at the prototype phase of development and therefore have room for considerable improvement in performance, cost, manufacture, and aesthetics before they are ready for commercial deployment. Despite their limitations, these prototype antenna systems may be the most technologically advanced antennas ever developed for indoor television reception.

The Antennas Direct NAB smart antenna system is based on a unique low-profile dual-polarized tunable microstrip element. Details on design of this element are presented in subsequent sections. Up to two elements can be connected to achieve beam or spatial diversity. Each element offers both Vertical and Horizontal polarization and the ability to tune across the post 2009 UHF DTV frequency band.

The use of a tunable element is made possible by the CEA-909/CEA-909A Mode-A transfer which provides digital channel information to the antenna. By using “tunable bandwidth” to achieve frequency agility, the design constraints involving size, gain, efficiency and bandwidth are relaxed permitting the construction of smaller, yet higher performing antennas for DTV reception. An important side benefit of the tunable bandwidth approach is that it suppresses reception of interfering channels and signals from non-television sources. This is akin to having the antenna function as an automatic pre-selector ahead of the broadband receiver to reduce noise and make it easier for the receiver to select and receive the desired channel. While the Antennas Direct engineering team has previously developed prototype antennas with this capability for niche military applications, such functionality has heretofore been unavailable in any commercially available antenna for television.

The prototype NAB smart antenna, shown in Illustration 1, consists of a master/slave pair of low-profile dual-polarized tunable microstrip elements mounted in wooden picture frames that are hinged on one vertical edge. The assembly is suitable for placement on a bookshelf which was the intention of the size requirement set forth by NAB. We note that the second prototype used smaller picture frames than the one shown due to limited availability of the larger frames at our local supplier.

A plastic shell housing produced using a fused deposition rapid prototyping machine was also supplied to NAB to illustrate one possible method of producing a commercial incarnation of the antenna. A computer rendering of such a shell is shown in Illustration 2.

The master element is fitted with a CEA-909A enabled coaxial (F-connector) input/output, as well as the standard 6-wire CEA-909 smart antenna connector to enable interface agility and backward compatibility with the older standard. A separate AC/DC power supply is not required since all power is supplied via the CEA-909/909A connections.

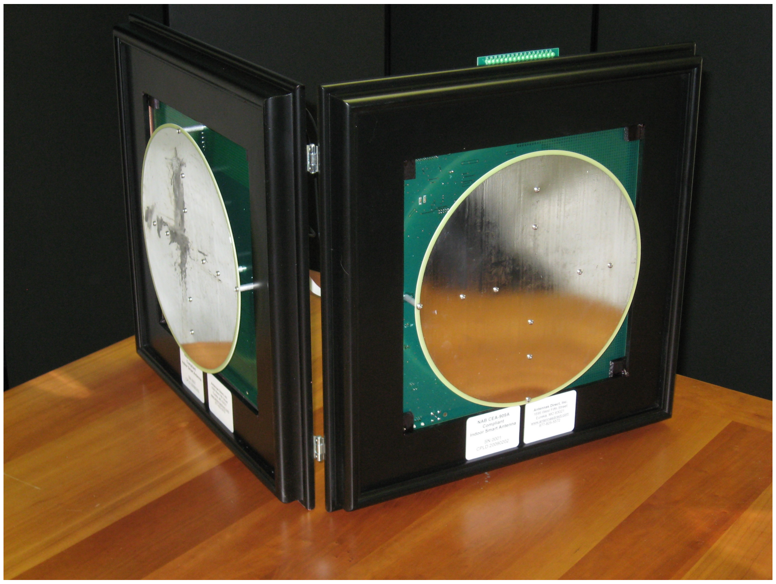


*Illustration 1: Prototype NAB Smart Antenna.*

*Illustration 2: Conceptual plastic housings.*

The master element contains the electronics and decoder logic required to interpret both 909 and 909A data transfers from the receiver and configure the tunable microstrip disc elements employed in both the master and slave units. Each microstrip element offers up to 16 UHF tuning states for each polarization. The tuning state is selected depending upon channel information supplied by the CEA-909/909A enabled receiver. A four way RF switch is used to select the strongest signal from among the polarization states available in each panel. The two-panel solution provided to NAB is capable of directing a beam in two different directions depending on orientation and hinge angle. Beam coverage for each panel is roughly 70 degrees so a two panel configuration offers considerable flexibility while limiting costs and size.

We expect future versions to support up to three slave elements to enable coverage of additional directions, or to enable enhanced reception through spatial diversity. The current system does not implement a phasing system for gain enhancement but this function could also be added to future revisions.

In addition to logic and decoding circuitry, the master element is also fitted with a high quality low-noise pre-amp to boost signal levels without introducing Intermodulation Distortion (IMD). The pre-amp has a a gain of 17 dB, a noise figure of approximately 2 dB and a Third-Order Intercept point of approximately +28 dBm (100 kHz tone spacing). The pre-amplifier circuit is the same one used in the Antennas Direct CPA-19 pre-amplifier and integrated into the master panel as a daughter board. For commercialization, an amplifier will need to be integrated on the same board as the master element.

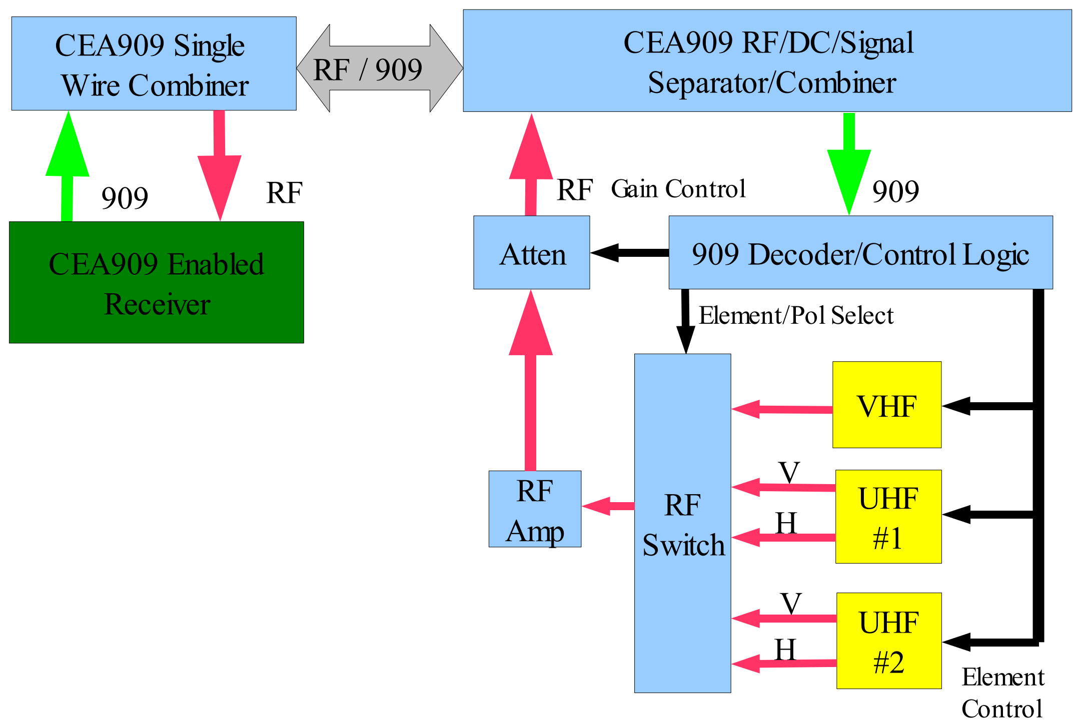
Gain settings sent via CEA-909/909A signals are used to configure an attenuator ahead of the pre-amp to help prevent overloading the gain stage. The amplifier is followed by an additional attenuator that when enabled can reduce signals by 6 or 12 dB to help prevent receiver overload.

VHF reception is enabled by connecting the reflector / backplanes of the UHF elements into a broad band plate dipole configuration. The laws of physics combined with the size constraints imposed by NAB precluded the possibility of a high gain / high performance option for the low VHF band. It would be easy to modify the design to allow for connection of an external low-band VHF element for cases where element size is not an issue.

## 2.2 Conceptual Block Diagram

A conceptual block diagram of the CEA909A single wire smart antenna operating with a CEA-909 enabled receiver is shown in Drawing 1. The CEA-909 Single Wire Combiner combines the RF and CEA-909 6-wire signals to the 909A single wire standard. On the antenna, the combined signals are separated into DC, CEA-909 and RF components. The CEA-909 signals are decoded and control logic selects the proper element and polarization, adjusts the attenuator, and tunes the selected element for optimum performance on the selected channel. The diagram shows only one VHF and two UHF elements for brevity but additional elements are easily accommodated with commensurate increase in size and cost. Depending on implementation, the polarization selection switch may be resident on the element. Element tuning can be limited to particular elements or eliminated all together depending on performance and cost objectives. A phasing module to control beam steering could be added in an advanced implementation. Subsequent sections discuss the system design and element selection.

We note that the CEA-909 Single Wire Combiners supplied as deliverables on this program did not include a second F-Connector, blocking cap and isolation choke since the intent was to use the combiner for to test 909A control only and not full-up RF testing.




*Drawing 1: Conceptual Block diagram of CEA909A single wire enabled smart antenna system with existing CEA-909 enabled receiver.*

# 3 Design Requirements and Considerations

The Antennas Direct proposal to NAB specified that a CEA909A compliant reconfigurable antenna would be developed and that it would fit within the NAB specified form factor and provide NAB specified levels of performance. The actual architecture of the underlying antenna elements was however unspecified. One of the first tasks in completing the NAB indoor antenna initiative was to identify appropriate antenna architectures that could meet the NAB specifications.

This section discusses some of the factors such as cost, performance, aesthetics, size, ease of manufacture, etc. that were considered in establishing the antenna system architecture and in selecting the form of the reconfigurable element.

## 3.1 NAB Requirements

The NAB Indoor Smart Antenna must meet the following requirements:

1. Shall be in full compliance with the CEA-909A single wire control interface standard.
2. Shall operate across all Post 2009 DTV bands.
3. Shall provide performance equal or better than a tuned rabbit ear antenna (approximately 0 dBi) on VHF bands. There are no other performance criteria on any bands.
4. Shall fit in a form factor smaller than 20 in x 10 in x 12 in or equivalently 50.8 cm x 25.4 cm x 30.5 cm. (The intent of this size requirement is to limit the antenna to something that would fit on a typical book shelf.)

## 3.2 Electrical Size Considerations

The US Domestic Television Channel allocations are listed in Table 1. Channels 52 through 69 are listed for reference, but are slated to be abandoned after February 17, 2009. The last column lists the electrical wavelength (m), $\lambda$, at the video carrier frequency used by the analog transmitters.

A simple dipole must be approximately $\lambda/2$ for resonant operation. Dipoles that are smaller than resonant size are generally less efficient, have lower gain, narrower fractional bandwidth and are more difficult to match than resonant dipoles. These principles hold for all other antenna elements including commonly used monopole, loop, slot, and microstrip elements.

**US Domestic TV Band Allocations**

| Channel | F-Low (MHz) | F-High (MHz) | F-VCarrier (MHz) | Band | lambda @ F-VCarrier (m) |
|---|---|---|---|---|---|
| 2 | 54 | 60 | 55.25 | VHF-LO | 5.23 |
| 3 | 60 | 66 | 61.25 | VHF-LO | 4.72 |
| 4 | 66 | 72 | 67.25 | VHF-LO | 4.3 |
| 5 | 76 | 82 | 77.25 | VHF-LO | 3.74 |
| 6 | 82 | 88 | 83.25 | VHF-LO | 3.47 |
| 7 | 174 | 180 | 175.25 | VHF-HI | 1.65 |
| 8 | 180 | 186 | 181.25 | VHF-HI | 1.59 |
| 9 | 186 | 192 | 187.25 | VHF-HI | 1.54 |
| 10 | 192 | 198 | 193.25 | VHF-HI | 1.49 |
| 11 | 198 | 204 | 199.25 | VHF-HI | 1.45 |
| 12 | 204 | 210 | 205.25 | VHF-HI | 1.41 |
| 13 | 210 | 216 | 211.25 | VHF-HI | 1.37 |
| 14 | 470 | 476 | 471.25 | UHF | 0.61 |
| 15 | 476 | 482 | 477.25 | UHF | 0.61 |
| 16 | 482 | 488 | 483.25 | UHF | 0.6 |
| 17 | 488 | 494 | 489.25 | UHF | 0.59 |
| 18 | 494 | 500 | 495.25 | UHF | 0.58 |
| 19 | 500 | 506 | 501.25 | UHF | 0.58 |
| 20 | 506 | 512 | 507.25 | UHF | 0.57 |
| 21 | 512 | 518 | 513.25 | UHF | 0.56 |
| 22 | 518 | 524 | 519.25 | UHF | 0.56 |
| 23 | 524 | 530 | 525.25 | UHF | 0.55 |
| 24 | 530 | 536 | 531.25 | UHF | 0.54 |
| 25 | 536 | 542 | 537.25 | UHF | 0.54 |
| 26 | 542 | 548 | 543.25 | UHF | 0.53 |
| 27 | 548 | 554 | 549.25 | UHF | 0.53 |
| 28 | 554 | 560 | 555.25 | UHF | 0.52 |
| 29 | 560 | 566 | 561.25 | UHF | 0.51 |
| 30 | 566 | 572 | 567.25 | UHF | 0.51 |
| 31 | 572 | 578 | 573.25 | UHF | 0.5 |
| 32 | 578 | 584 | 579.25 | UHF | 0.5 |
| 33 | 584 | 590 | 585.25 | UHF | 0.49 |
| 34 | 590 | 596 | 591.25 | UHF | 0.49 |
| 35 | 596 | 602 | 597.25 | UHF | 0.48 |
| 36 | 602 | 608 | 603.25 | UHF | 0.48 |
| 37 | 608 | 614 | 609.25 | UHF | 0.47 |
| 38 | 614 | 620 | 615.25 | UHF | 0.47 |
| 39 | 620 | 626 | 621.25 | UHF | 0.47 |
| 40 | 626 | 632 | 627.25 | UHF | 0.46 |
| 41 | 632 | 638 | 633.25 | UHF | 0.46 |
| 42 | 638 | 644 | 639.25 | UHF | 0.45 |
| 43 | 644 | 650 | 645.25 | UHF | 0.45 |
| 44 | 650 | 656 | 651.25 | UHF | 0.44 |
| 45 | 656 | 662 | 657.25 | UHF | 0.44 |
| 46 | 662 | 668 | 663.25 | UHF | 0.44 |
| 47 | 668 | 674 | 669.25 | UHF | 0.43 |
| 48 | 674 | 680 | 675.25 | UHF | 0.43 |
| 49 | 680 | 686 | 681.25 | UHF | 0.42 |
| 50 | 686 | 692 | 687.25 | UHF | 0.42 |
| 51 | 692 | 698 | 693.25 | UHF | 0.42 |
| 52 | 698 | 704 | 699.25 | UHF | 0.41 |
| 53 | 704 | 710 | 705.25 | UHF | 0.41 |
| 54 | 710 | 716 | 711.25 | UHF | 0.41 |
| 55 | 716 | 722 | 717.25 | UHF | 0.4 |
| 56 | 722 | 728 | 723.25 | UHF | 0.4 |
| 57 | 728 | 734 | 729.25 | UHF | 0.4 |
| 58 | 734 | 740 | 735.25 | UHF | 0.39 |
| 59 | 740 | 746 | 741.25 | UHF | 0.39 |
| 60 | 746 | 752 | 747.25 | UHF | 0.39 |
| 61 | 752 | 758 | 753.25 | UHF | 0.38 |
| 62 | 758 | 764 | 759.25 | UHF | 0.38 |
| 63 | 764 | 770 | 765.25 | UHF | 0.38 |
| 64 | 770 | 776 | 771.25 | UHF | 0.37 |
| 65 | 776 | 782 | 777.25 | UHF | 0.37 |
| 66 | 782 | 788 | 783.25 | UHF | 0.37 |
| 67 | 788 | 794 | 789.25 | UHF | 0.37 |
| 68 | 794 | 800 | 795.25 | UHF | 0.36 |
| 69 | 800 | 806 | 801.25 | UHF | 0.36 |

*Table 1: US Domestic Television Channel Allocations*

### 3.2.1 Low VHF Band (54 to 88 MHz)

For channel 2 a resonant dipole is 2.61 m in length. This is significantly larger than the size specified by NAB. This fact essentially guarantees that low VHF band performance is a design compromise. A physically small reconfigurable element offers little or no advantage in this band. A smart impedance matching solution may be useful but was not requested by NAB.

### 3.2.2 High VHF Band (174 to 216 MHz)

For Channel 7 the resonant dipole is 0.825 m in length. This structure is too large to fit directly into the NAB specified volume without some design compromises. A physically small reconfigurable element may offer a small advantage in this band but will not provide high gain due size limitations. A smart impedance matching solution may be useful for this band but was not requested by NAB.

### 3.2.3 UHF Band (470 to 698 MHz)

A dipole resonant on Channel 14 is approximately 0.3 m in length and easily fits within the NAB specified form factor. Additional structures resonant on UHF such as loops, slots, microstrip elements, etc. can also fit within the NAB form factor.

With careful engineering, multiple UHF elements can fit within the NAB form factor to allow for tunable bandwidth or electronically steered beams using various switching and phasing methods.

Reconfigurable UHF elements may also be possible which offer higher performance in smaller form factors than their fixed geometry counterparts. The increased costs of reconfigurable elements may however prove to be cost prohibitive if multiple UHF elements are employed. The NAB however requested a reconfigurable element, and the UHF band offers promise, given the form factor requirements.

### 3.2.4 Physical Size, Form Factor and Aesthetics

Physical size, form factor and aesthetics are the main drivers when consumers consider purchasing an indoor antenna. The prime directive shall be to reduce size as much as possible. When given the choice, the design shall prefer elements with a slim-low profile over elements that have a lower height / width to thickness ratio. A thin high performance antenna element that could be mounted on a wall or placed behind a photo would have significant market appeal. Antennas that can be disguised to or made to function as decoration are also an advantage in the marketplace.

### 3.2.5 Amplification

Most indoor antenna solutions on the market include a pre-amplifier. Manufacturers often make outrageous and misleading claims as to the capabilities of such products. In one case, a simple pair of rabbit ears was touted as having 55 dB gain! This is of course false since a true 55 dB antenna such as the one located at the National Radio Astronomy Observatory in Green Bank, West Virginia is several hundred feet in diameter!

The conundrum here is that even though many of the claims are obviously false, the average consumer does not have any knowledge of antennas and amplifiers and is likely to base a purchase decision based on a single number where bigger is better. In short, it is unlikely that a smart antenna can be a success in the marketplace unless it includes some amplification circuitry in order to compete against the claims of other manufacturers.

While the benefits of an amplifier for an indoor installation are not as great as for an outdoor antenna, most receivers on the market have noise figures somewhere in the range of 6 to 8 dB. This means that a well executed low noise amplifier of modest gain (~ 10 dB to at most 20 dB) and low noise (~2.5 dB or less) can substantially lower the noise floor of the receiver system and improve reception. The key is that the amplifier must be well designed so that it is both low noise and resistant to overload. Balanced performance like this does not come cheap however, and the amplifier could be a significant cost component of the final design.

### 3.2.6 Selectable Gain Settings

The CEA909A standard allows two bits for adjustment of gain. With a well designed amplifier, the gain adjustment can be made using attenuators placed after the amplifier. The gain settings will then help keep the antenna/amplifier combination from overloading the front end of the receiver. In some cases, extraneous signals may be so strong as to overload even a well designed amplifier. In this case, selectable attenuation ahead of the amplifier can reduce the amplitude of the offending signal and improve reception.

### 3.2.7 Polarization Selection

The CEA909A standard allows one bit for adjustment of polarization. Most DTV signals are broadcast with horizontal polarization (H). There are some stations that have recognized that vertically polarized (V) signals have advantages for mobile applications and have moved to radiate either Circular Polarization (CP) or combinations of V and H to improve reception.

Regardless of the polarization radiated from the transmitter, indoor signals are often significantly depolarized due to the multiple reflections and diffractions encountered between the transmitter antenna and the indoor antenna.

It therefore seems logical that including the ability to switch polarization may be advantageous for an indoor antenna, and such capability should be added, if the cost and technical risks are reasonable. Selectable polarization may also prove advantageous in suppressing undesired signals relative to desired signals and improve reception in some circumstances.

### 3.2.8 CEA-909 Interface

The NAB program requires a CEA909A single wire interface, however at the time the initial proposal was submitted there were no receivers on the market that supported this interface. Therefore, the proposal included funds to develop a CEA-909 to CEA909A single wire converter test fixture to enable testing of the CEA909A single wire antenna interface. The dongle was designed and constructed to be a test fixture only and not a commercial grade product. Samples of the test fixture were submitted as part of the deliverables shipped to NAB.

The original intent of the test fixture was to provide the ability to issue CEA-909 signals to the smart antenna. Since there were few if any commercially available CEA-909 enabled receivers on the market at the time the proposal was submitted we envisioned having a PC drive the dongle. Subsequent to the start of the program however several Coupon Eligible DTV converter boxes came on the market that offered CEA-909 functionality through the 6-wire interface. With the availability of these receivers it was redundant to then design in the PC functionality into the converter test fixture, since a simple and cheap converter box could be used to effectively drive the antenna.

To simplify testing, the smart antennas support both the CEA-909A single wire interface as well as the older 6-wire standard.

### 3.2.9 CEA-909 Transfer Mode

The CEA-909 standard allows for two modes of communication. In Mode A the receiver provides a bit stream that contains channel information, gain, coarse and fine direction, and polarization to the antenna. The mode B transfer is more sophisticated and can allow additional information such as signal level, Bit-Error-Rate (BER), antenna configuration state to flow to and from the antenna. Unfortunately, the Mode B transfer is not standardized and is subject to variation depending on the firmware implemented on the receiver and within the antenna. Given the wide variation in firmware exhibited in the currently available CEA-909 enabled receivers it was determined that it was not feasible to use Mode B, and that the NAB demonstration antenna would be compatible only with the standard Mode A transfers.

## 3.3 Incompatible CEA-909 Receivers

To date we estimate that there have been several million CEA-909 enabled converter boxes sold. Though this is a relatively small number, this existing base of CEA-909 receivers will almost certainly require that any commercially successful smart antenna implement the 6-wire interface. If the 909A interface is eventually adopted as well, antennas must then support both modes.

Through the course of the program we have evaluated several CEA-909 enabled converter boxes and have discovered problems that may impact adoption of CEA-909 smart antenna technology. Antennas Direct engineers were dismayed to find that many of the commercially available converter boxes do not rigorously implement the CEA-909 data signal specifications. Their tests have clearly documented cases of receivers that omit start bits or otherwise do not conform to the CEA-909 specifications.

These discrepancies impacted the design schedule of the NAB smart antenna and associated dongle adapters. They will also impact any attempt to develop and commercialize smart antennas for television by increasing costs of engineering and components.

## 3.4 Firmware Implementations

In addition to the signaling issues, there is also a wide variation in the firmware used on the converter boxes used to control the CEA-909 enabled smart antenna. Antennas Direct engineers have learned that some models do a very good job in executing a channel scan / search. However, others omit search parameters or issue antenna commands too quickly making it impossible for the receiver to settle properly to evaluate signal conditions. Various models provide features to manually control some or all features of the antenna, while others offer no manual controls whatsoever. Almost universally the current crop of CEA-909 enabled receivers do not provide an easy way to adjust the smart antenna for best signal. Some of our notes on this issue are discussed in  Appendix A - CEA-909 / 909A Enabled Receiver Data.

Like the 909 signaling issue, the lack of consistent firmware functionality in the current crop of converter boxes will also impact the development of future smart antennas. While the firmware on most converter boxes will support a simple antenna (i.e. switched dipole), the support for an advanced smart antenna such as the ones developed on this program vary widely. Since firmware functionality and compatibility is not defined in the current CEA-909A standard, we suggest that the success of smart antenna technology in the marketplace may hinge on establishing standards for this key component of the smart antenna system.

# 4 Antenna Element Selection

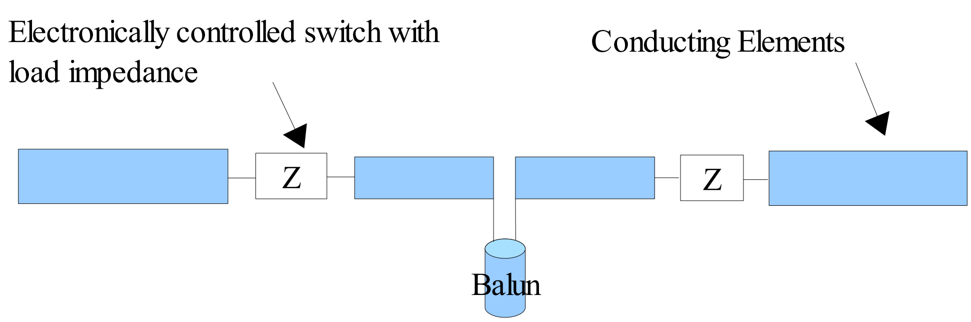
This section discusses the relative merits of several basic reconfigurable elements and the logic that lead to the selection of the tunable microstrip disc element for the final design. We first review some basic reconfigurable antenna elements. Subsequent sections discuss various arrangements and methods of utilizing these elements in conjunction with other fixed geometry elements to construct antenna which meets NAB requirements or other commercially relevant objectives.

## 4.1 Reconfigurable Dipole Element

As seen in Drawing 2, this element has wire segments inter-connected with one or more electronically controlled switches or loads (Z) to allow the element to tune across one or more bands. A balun is needed to suppress undesired radiation from currents that arise on the outer conductor of coaxial feed lines. The balun, not necessarily  of the 75:300 ohm variety, may also assist in matching the impedance of the antenna to the feed line.

The basic dipole does not provide a lot of gain, but with proper loading it can operate reasonably efficiently in one or more of the DTV bands. Depending on the target band, the form factor can be relatively small as compared to most of the alternative elements. The dipole can be bent if necessary to fit into a more compact form.

While the principle of operation is relatively simple, it is generally difficult to accurately predict coupling to control, power, and ground lines and account for those effects in the design process. It is therefore more difficult to implement a reconfigurable dipole than it is to implement some of the other reconfigurable elements that are discussed later. The reconfigurable dipole was therefore not pursued further under this program.



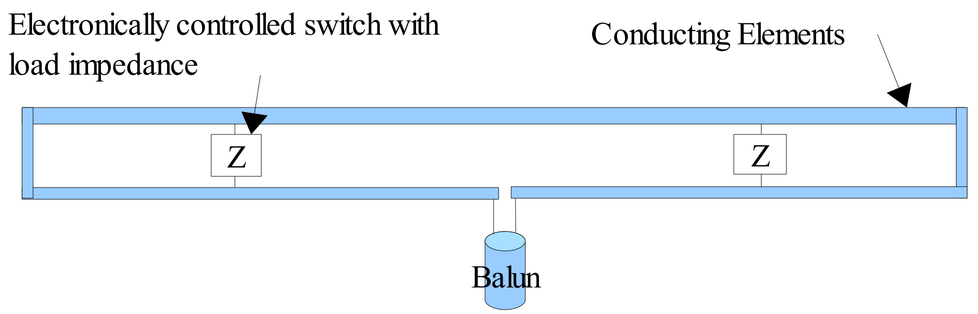

*Drawing 2: Schematic representation of reconfigurable dipole antenna.*

## 4.2 Reconfigurable Folded Dipole Element

This element is similar to the reconfigurable dipole element, except that instead of serially connecting radiating elements, the switches and loads are placed in parallel across the folded dipole element. A cartoon diagram is shown in Drawing 3.

The folded dipole naturally has broader bandwidth than the equivalent size dipole for each state. The enhanced bandwidth for each state may help make this option more forgiving than the simple dipole. The step up ratio of the folded dipole can be adjusted to help improve impedance match if necessary.

The folded dipole element still suffers from the same basic problem of accounting for coupling to the control, power, and ground lines in the design process and is thus less attractive than other reconfigurable elements discussed later. As a result this element was not considered further under this program.

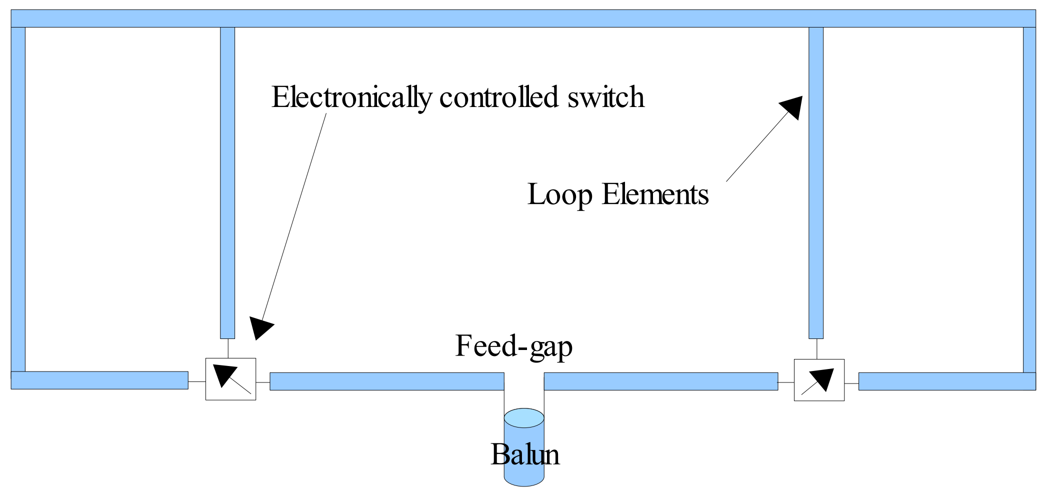



*Drawing 3: Schematic representation of reconfigurable folded dipole antenna.*

## 4.3 Reconfigurable loop-reflector element

A cartoon drawing of a reconfigurable loop element is shown in Drawing 4. Here, electronically controlled switches are used to select loops of various sizes. Switches can be located at various locations to effect multiple loop structures as necessary.

The loop structure will provide slightly better gain and possibly better bandwidth than the reconfigurable dipole elements, but it still suffers from the coupling issue during the design phase. Based on their past experience with other projects the design team believed that it may be possible to place switching elements in such a way such that the coupling of control, power and ground lines is minimized so this concept was explored further, but only when combined with a reflector as discussed in the next section.



*Drawing 4: Schematic representation of reconfigurable loop element.*

## 4.4 Reconfigurable Loop – Reflector Element

The idea of combining the reconfigurable loop element with a suitably sized reflector is a natural extension of the commercially successful Antennas Direct Clearstream and Lacrosse Micron antennas which are targeted at the UHF and High VHF bands.

One of the design challenges in the ClearStream models was to balance the dimensions of a tapered loop element with the loop-to-reflector distance. Moving the loop close to the reflector improves gain, but narrows bandwidth. A design compromise resulted in a spacing of about 11.4 cm for the UHF ClearStream elements. This separation is quite large and removes about 1 dB or so from the theoretical maximum peak gain of about 9 dB.

The design team believed that by employing a reconfigurable loop the separation distance between the loop & reflector could be reduced substantially while maintaining or even increasing gain slightly by about 1 dB (to about 9 dBi) for a single loop. Previous experience suggested that the beam width of such an antenna should be near 70 degrees. It also suggested that narrow spacing would decrease bandwidth, but that this could be compensated by selecting different size loops in order to meet the frequency coverage requirements.

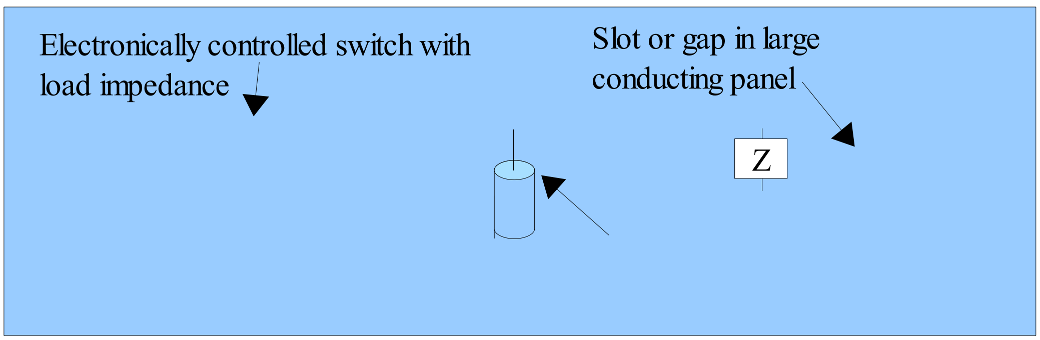
For such an antenna, the number of states would be determined based on the bandwidth of each state and the width of the UHF band. While a thickness near 1 inch (~ 25mm) would be most desirable, it may prove to be impractical due to bandwidth and impedance issues.

Even though the reconfigurable loop-reflector element seemed to offer numerous advantages, it still had the disadvantage that coupling must be accounted for in the design process. A balun is also required at the feed point.

Early in the design phase, numerous reconfigurable loop-reflector element configurations were evaluated using the Remcom, Inc. X-FDTD simulator. Unfortunately, none of the configurations investigated exhibited impedance curves that could have been made workable for a thin UHF element. For brevity therefore, further discussion of the investigation into this element type is omitted from this report.

## 4.5 Reconfigurable Slot Radiator

The reconfigurable slot geometry is shown in Drawing 5. The slot is the electromagnetic dual of the dipole and its polarization and radiation patterns are different from the dipole. This must be considered when orientating the slot.




*Drawing 5: Schematic representation of reconfigurable slot antenna cut in large conducting panel.*

The slot does not necessarily need to be linear, and it can be shaped as necessary to achieve the desired pattern and bandwidth. The slot radiates equally to both sides of the panel.

Depending on configuration, it may be possible to provide a 75 ohm impedance directly without the need for a balun. This can improve efficiency by ½ to 2 dB depending on frequency and may reduce costs.

The natural shielding of the slots helps to decouple the control, power, ground lines from the radiating element. This should help considerably in the design process.

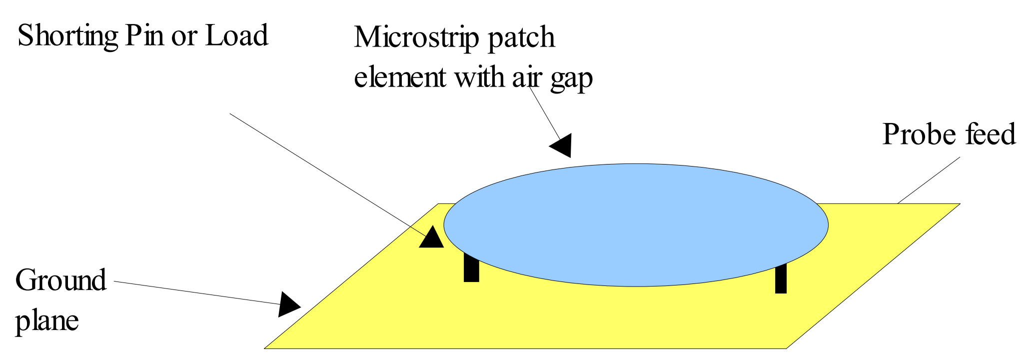
The conducting panel must however be as large as possible to ensure that the enclosed slot operates properly. Small conducting panels will result in pattern distortion and detuning of the slot due to reflections and radiation from the edge of the panels. For this application, the size requirements are such that the slot will need to be designed and tuned for a specific panel dimension.

Numerous open (i.e. non-cavity backed) slot configurations were investigated as part of this program. Unfortunately, none of them were deemed to be of substantial value for the NAB effort. For brevity, discussion of these null results are omitted from this report.

## 4.6 Reconfigurable Microstrip Element

Microstrip antennas are widely used in the military and in microwave communications and networking equipment due to their compact size and low profile. Historically they have not seen wide use in reception of terrestrial broadcast televisions due to their inherently narrow bandwidth. The availability of tuning controls from a television receiver, however, opens the door to utilizing tunable microstrip elements for broadcast reception.

The basic geometry of a microstrip element is shown in Drawing 6. A disc patch is shown, but other patch geometries such as squares, rectangles, ellipses, triangles, etc are allowable. The shape selected for a particular application is determined by the desired pattern, polarization and bandwidth subject to size constraints.




*Drawing 6: Schematic representation of reconfigurable microstrip disc antenna.*

While a microstrip geometry can be created for nearly any frequency band, the size limits imposed on an indoor television antenna limit the concept to UHF applications where electrical sizes are manageable. The disc shaped patch has some advantages from the standpoint of symmetry and bandwidth over other options, but other shapes may offer superior performance. Due to the limited time available in this investigation, only the disc shape was extensively analyzed for use as a reconfigurable UHF element.

To achieve usable bandwidth for UHF television the microstrip element is suspended above a ground plane with an air gap. Microstrip elements are commonly fed using microstrip lines from the side or from beneath using probe feeds. The bandwidth of the element decreases as the gap decreases. Increasing the gap size however increases the probe inductance which detunes the element. The inductance can be compensated by including a series capacitance with the probe. The capacitor is often implemented as a parallel plate capacitor placed at the top of the probe. Probe inductance can also be decreased by increasing the diameter of the probe or using conical probes. Conical probes are of course more costly to manufacture than a simple wire probe.

The input impedance of the element can be increased or decreased by adjusting placement of the probe relative to the edge of the disc. Feed locations near the edge have generally higher impedance than those nearer the center.

The microstrip element can be tuned by using one or more shorting pins located at various points on the element. If the tuning is to be done electronically, the base of each shorting pin is connected to an electronically controlled switch such as a FET, PIN diode, MEMS switch or mechanical relay. Switch selection is key to developing an antenna with good performance. Design trade offs based on cost, power handling and acceptable switch time and losses must be considered.

Shorting a pin to ground (the reflector) causes the resonant frequency to increase. Pins near the center cause small shifts in resonant frequency, while pins near the edge cause larger shifts. Shorting more than one pin causes an additive effect in the frequency shift.

In the case of the disc, shorting pins are generally set along a line that passes through the feed point and the center of the disc.

Placement of too many shorting pins near the feed point detunes the device and prevents proper operation. Practical designs use as few pins as possible and make use of locations on both the same side and the opposite side as the feed location.

Dual polarization operation is possible by placing additional feed and shorting pins on a line orthogonal to the first. Performance is generally unaffected provided that the feed port and shorting pins for the unused polarization are open.

Unlike the other reconfigurable elements such as dipoles and loops, the control, power and ground traces used to drive the switching elements are electrically shielded from the radiating element by the ground plane. This isolation of electronics and radiating element greatly simplifies the design of the antenna since the performance is no longer highly dependent on placement and routing of traces used in the electronics. This decoupling of the electronics layout from the element radiation characteristics was the key factor in selecting the reconfigurable microstrip element for use in the NAB demonstration antenna.

Numerous fixed and reconfigurable microstrip configurations were thus examined as part of this program. Details are provided only on configurations that are substantially similar to those employed in the final design.

### 4.6.1 Example: Four State UHF Reconfigurable Microstrip Disc

For UHF television applications, a ground plane of approximately 25 cm x 25 cm is usable, but the small size complicates designs due to edge effects and coupling to the antenna element. Investigation of a simple circular patch with an air gap of 50 mm showed that the bandwidth of each state is relatively wide and suggested that it may be possible to cover the whole UHF band using only two switches. Plots of the VSWR and directivity for such antenna is shown in Illustration 3. Since this antenna was thicker than desired, it was not further optimized for performance.

Additional investigations revealed that decreasing the air gap to 25 mm substantially narrows the bandwidth and greatly increases the number of required tuning states. Decreasing air gap also increases the lowest resonant frequency. As a result, the size of the disc and ground plane must be increased to compensate for the smaller air gap.

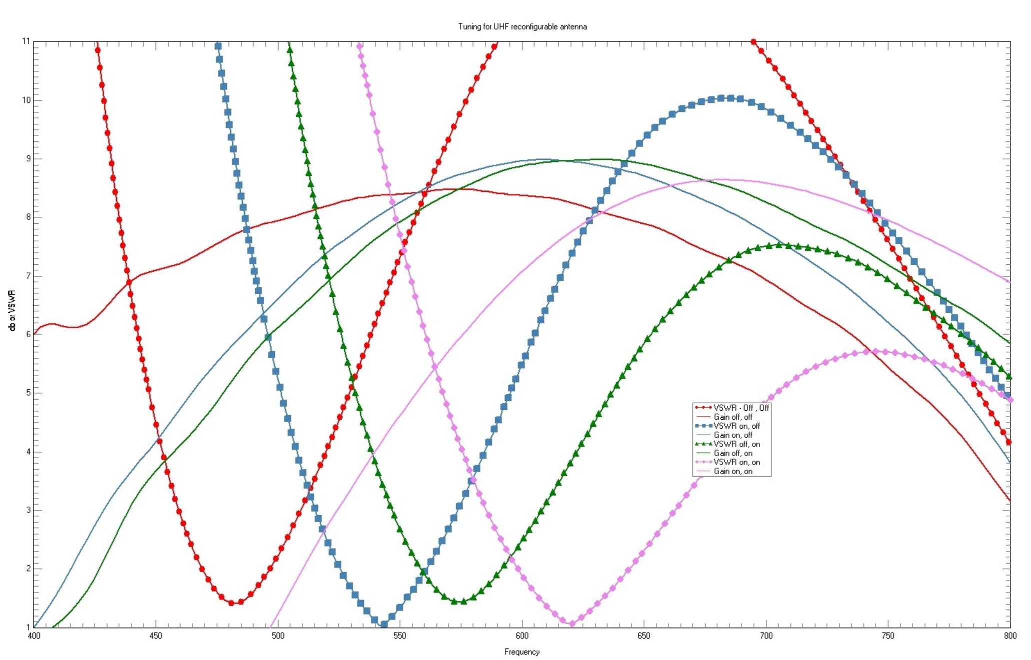


*Illustration 3: Computed tuning states for UHF reconfigurable disc antenna with 50 mm air gap.*

### 4.6.2 Example: 16 State Dual Polarized UHF Reconfigurable Microstrip Disc

Numerous computer simulations were performed to determine that 30 mm was the minimum practical gap size for the reconfigurable microstrip disc. With this thickness, a ground plane size of 300 mm x 300 mm is required to allow the element to tune to the lowest end of the UHF band.

The geometry for a UHF reconfigurable element fitting this form factor is shown in Illustration 4. It provides separate feeds for Vertical and Horizontal polarization and uses 4 switches for each polarization for a total of 8 switches per element. The switches provide 16 tuning states for each polarization to cover the UHF band from 470 to over 698 MHz. The tuning state VSWR and directivity are shown in Illustration 5. Computed VSWR for each state less is than 2:1 relative to 75 ohm. Typical directivity (dB) for each state is between 7.5 and 9 dB.

Performance of this reconfigurable element is superior to the T-bar fed cavity backed slot yet it occupies only about 70% of the volume of that element and provides pre-selection at the antenna to further improve performance. If successfully implemented, this design should compare favorably to the ClearStream 1 / Lacrosse Micron even though it occupies only about ¼ of the volume of those elements. This element would have strong appeal for use as a building block in sophisticated CEA-909 enabled smart antennas that require high performance in low profile and aesthetically pleasing form factors.

The multiple narrow band states of this element may prove advantageous in improving effective dynamic range of the receiver system, since signals significantly away from the desired channel are attenuated.

This example design was used as the basis for developing the prototype NAB Reconfigurable Antenna. Additional details on analysis, construction, testing of this element are provided in subsequent sections.

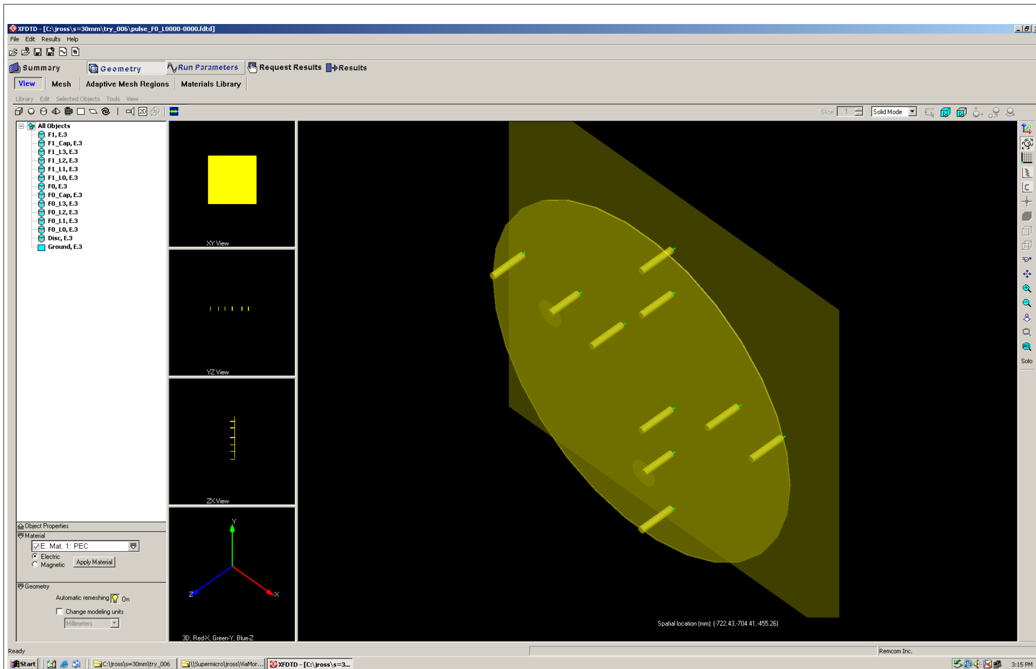


*Illustration 4: Geometry of Rev 001 UHF Reconfigurable element. Pins with top had capacitor are feed locations. Remaining pins control tuning.*

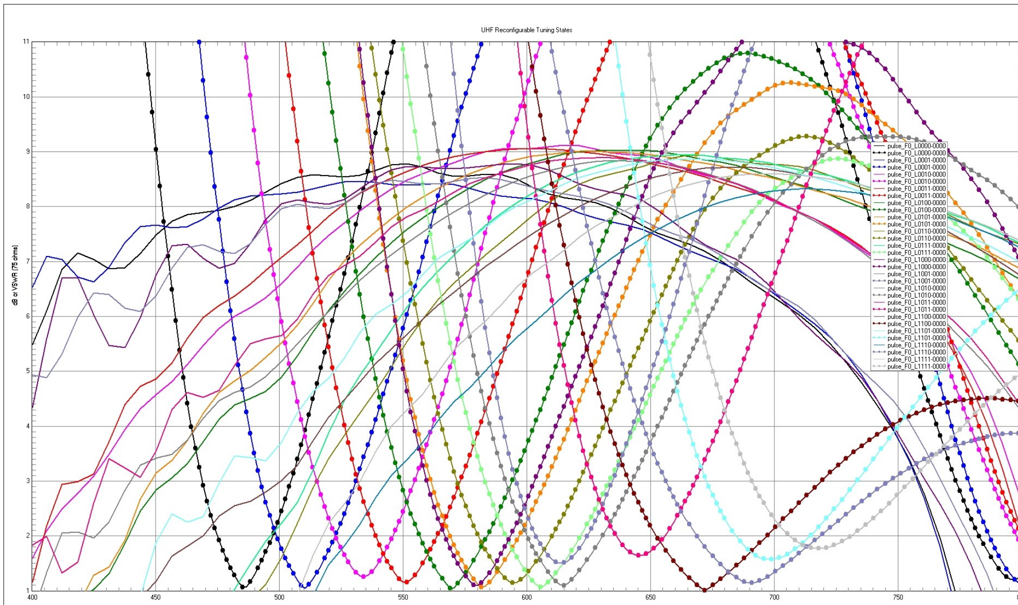



*Illustration 5: Computed tuning states of Rev 001 UHF Reconfigurable element. Solid lines are gain. Dotted lines VSWR relative to 75 ohms.*

## 4.7 Prototype Reconfigurable Microstrip Disc

This section outlines the development of the reconfigurable microstrip disc element.

### 4.7.1 Prototype 0 – PIN diode switches

Based on the simulations shown in the previous section a prototype antenna was produced that used electronically controllable PIN diodes at the base of each shorting post. The diodes were chosen over other switch types due to their low cost. The PIN diodes were manually controlled using a switch box to allow testing of the element. Lab testing revealed that the PIN diode switch did not offer sufficient OFF isolation. A second board was fabricated using jumpers to validate the tuning principles demonstrated in the initial simulations.

### 4.7.2 Prototype 1 – Jumpers

VSWR measurements of the jumper prototype, shown in Illustration 6, demonstrated that the antenna element offered tunable bandwidth roughly in accordance with the principles shown in the simulations, but that the measured frequency was lower than predicted by the simulator. Measurements were performed indoors using an HP 8569A spectrum analyzer with an HP 8444A Opt 59 tracking generator and Eagle Return Loss bridge. Pasternack precision matching pads were used to reference line impedance to 75 ohms.

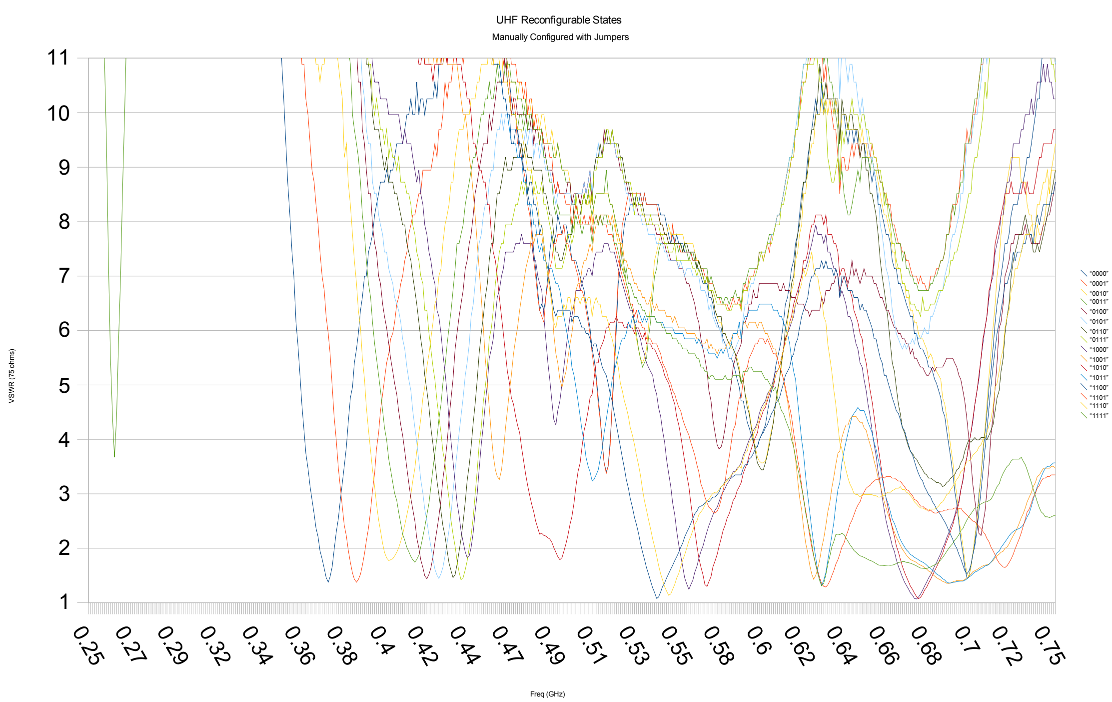



*Illustration 6: Measured VSWR for jumper prototype.*

## 4.8 Prototype 1 – RF Relays

The Antennas Direct team had previously used COTO RF Relays in other smart antenna related design efforts with good success. Despite the relatively high cost of the relays, the team determined relays offered the best chance of achieving the desired performance for the purpose of the NAB demonstration program. Like the diodes, the relays were configured using a manual switch box for test purposes. Measured VSWR performance of the various states is shown in Illustration 7. While the curves do not match the simulations of the initial design simulations, they do demonstrate the desired tunable bandwidth characteristics using an electronically controlled element.

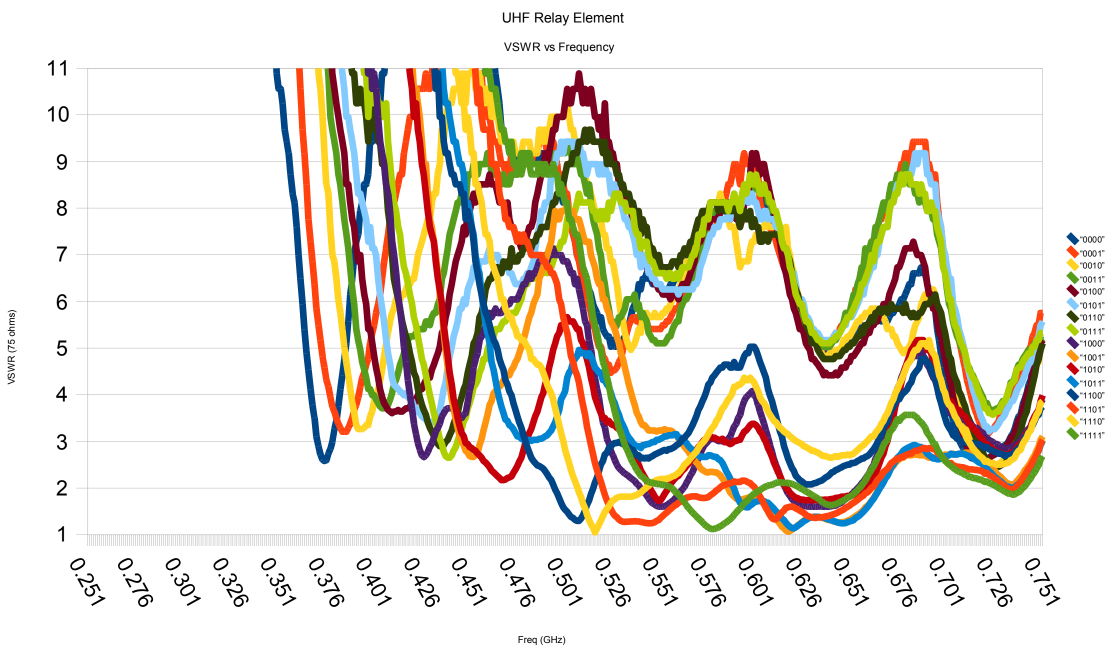



*Illustration 7: Measured VSWR for Relay Prototype 1*

As in the case of the jumper prototype, the resonant frequency is lower than predicted by the computer simulations. Therefore, more accurate computer models were constructed with refined accuracy in the region of the shorting pins taking account of the physical and electrical distance from the center of the pins to the point where the relays actually connected to the reflector. The enhanced accuracy of the computer models caused simulation times to increase substantially, with simulation of a single switch configuration requiring 18 to 24 hours to produce a gain and VSWR versus frequency plot. A complete analysis of the 16 configurations available for one polarization could require more than two weeks to complete depending on availability of license threads and computer up-time.

Due to the extensive time required for computer simulations, laboratory experiments were also undertaken in order to get a better understanding of the various factors that impact the performance of the antenna. Investigations were performed to examine the effect of the top hat capacitor on the feed post, the element-reflector spacing, and also the removal of some of the shorting pins. Configurations employing the cross-polarized switches (normally left open) were also investigated to determine if impedance matching could be improved. For brevity, only results from the final configuration are shown in the following section.

## 4.9 Slave Element with RF Relays

In the end, it was determined that an element configuration with 25mm spacing would increase resonant frequency to compensate for the longer electrical distances between the shorting pins and reflector. This was a welcome find since the main goal of the design was to decrease size. It was also found that impedance matching was generally improved by completely removing the top hat capacitor and directly connecting to the disc.

VSWR measurements of the Slave Element are shown in Illustration 8. The resonances are not quite as uniform as the initial design, but the design is clearly tunable across the whole UHF band. Additionally, lower frequency resonances not apparent in the initial design are also seen. While there is the possibility that these lower frequency resonances may be useful for high band VHF reception, the resonances are narrow band so no attempt was made to exploit them in this design.

X-FDTD simulation results of the Slave panel in the same configuration are shown in Illustration 9. The simulations are definitely not a perfect match to the laboratory data, but they do exhibit similar trends and grouping of resonant frequencies. We believe that much of the discrepancy between the simulation and measurement lies with the performance and modeling the RF relay.

Measurements of the RF relays in a test fixture showed less than ideal performance at UHF frequencies. Attenuation can be high above 500 MHz and RF leakage to power, ground and control lines was demonstrated. The RF leakage is exceedingly difficult to model in a computer simulation and something that must be minimized for proper operation of the element. Future revisions of the microstrip element will therefore employ RF switches such as FET's that do not exhibit the coupling and loss problems. There was not sufficient time during this program to redesign the element to use an alternative switch.

We note that it is generally difficult to get a good agreement between simulation and measurement on input impedance and VSWR. Computed pattern results generally agree better with measured data due to the fact that radiated fields are computed based on an integration of RF current over the whole of the antenna. The integration therefore acts as a smoothing function minimizing the results of errors in current. Input impedance or VSWR on the other hand, is dependent on the accuracy of the current solution at a single point, hence the greater variability.

Antennas Direct does not currently own an anechoic range, so we rely on simulation data for patterns and confirm VSWR by laboratory measurement. Weather permitting, we also perform signal strength tests outdoors, but time constraints and winter weather conditions at all available locations (Salt Lake City, State College, PA and St. Louis, MO) have limited testing of the smart antennas to indoor VSWR measurements and reception validation.

Computed broadside gain versus frequency plots for excitation of the vertical group of feed / shorting pins is shown in Illustration 10 and Illustration 11. Gain is not as high as predicted by the initial design, but it is still effective for a compact indoor antenna. Polarization is generally V, but some cross-polarization is evident, especially between 500 and 550 MHz. Measurements and simulations of the reconfigurable microstrip element show that good VSWR and gain is possible across the whole post 2009 television band. Maximum performance will be obtained however only by properly programming the CPLD logic chips used to control the antenna. The truth table used to build our initial set of CPLD logic programming is shown in Illustration 12. The states were determined based on laboratory VSWR measurements. F0 (LSB) is pin between center and feed. F3 (MSB) is pin on outside edge near feed. F2 is on edge opposite feed while F1 is between center and F2. X pins use same scheme. Eventually, the antenna should be reprogrammed to use measured through signal data for each polarization.

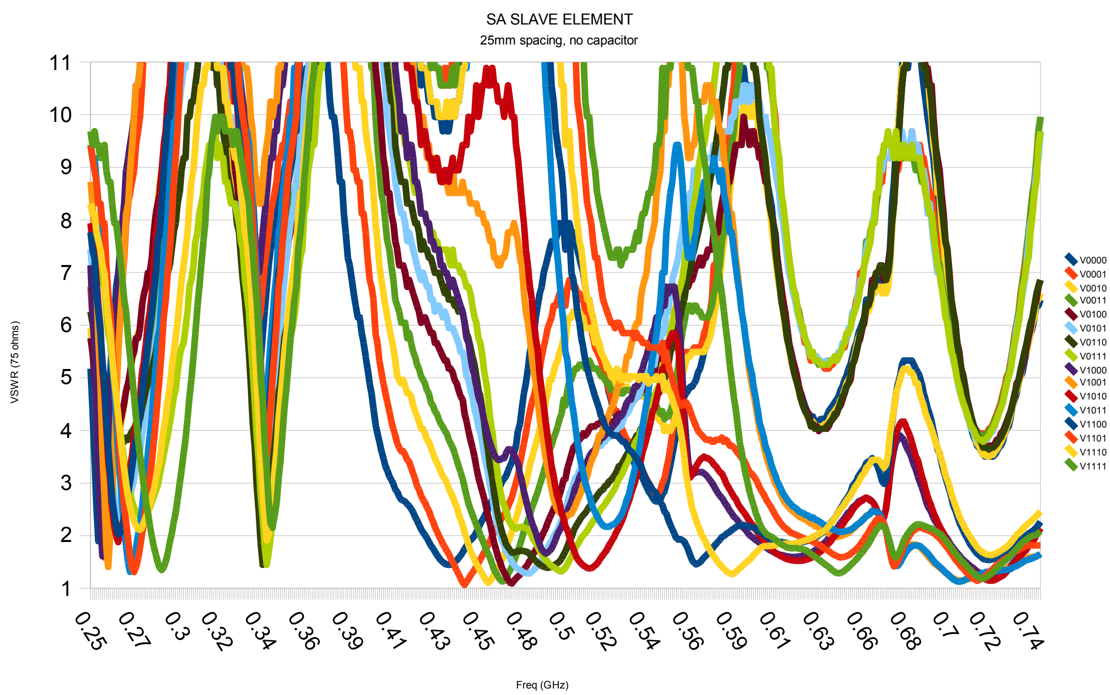



*Illustration 8: Measured VSWR versus frequency for Slave Element with Relays*

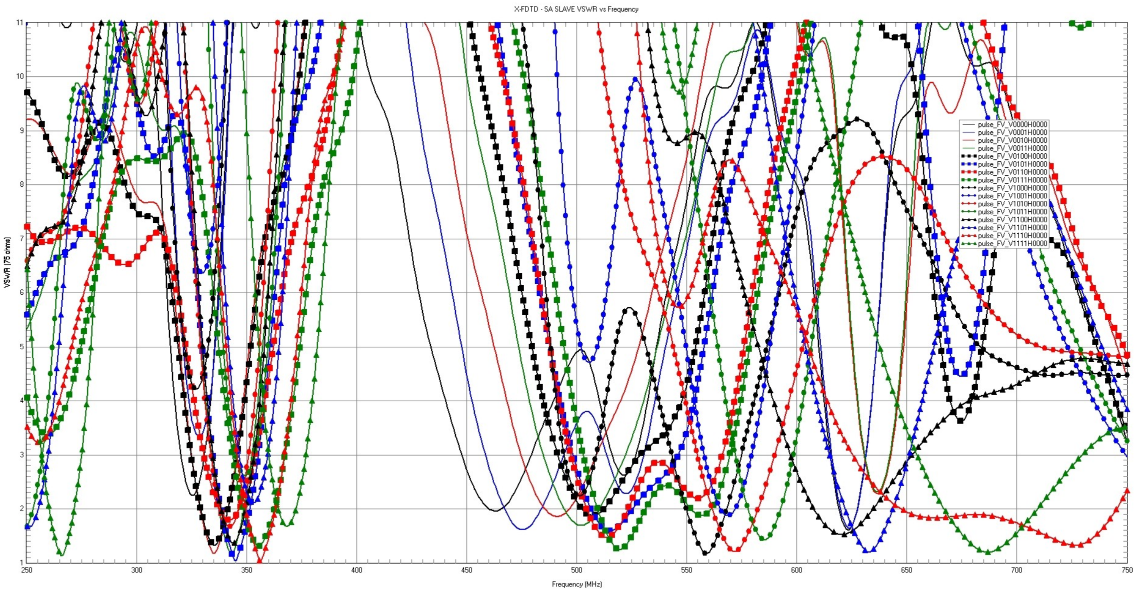



*Illustration 9: X-FDTD results. VSWR versus frequency for Slave Element with Relays.*

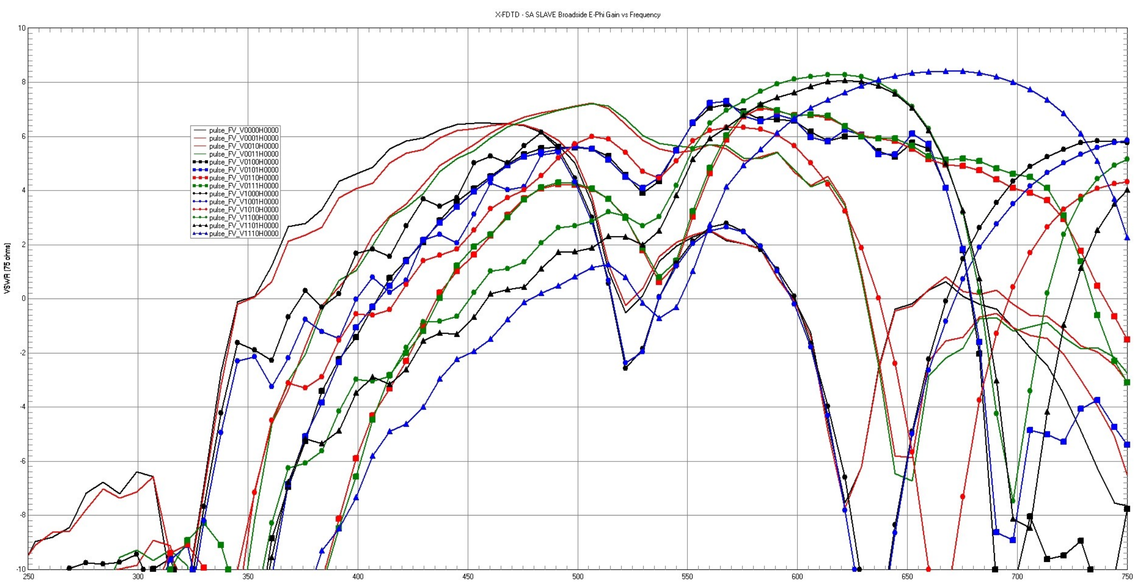



*Illustration 10: X-FDTD Broadside E-phi (V) gain versus frequency for vertical group feed and shorting pins.*

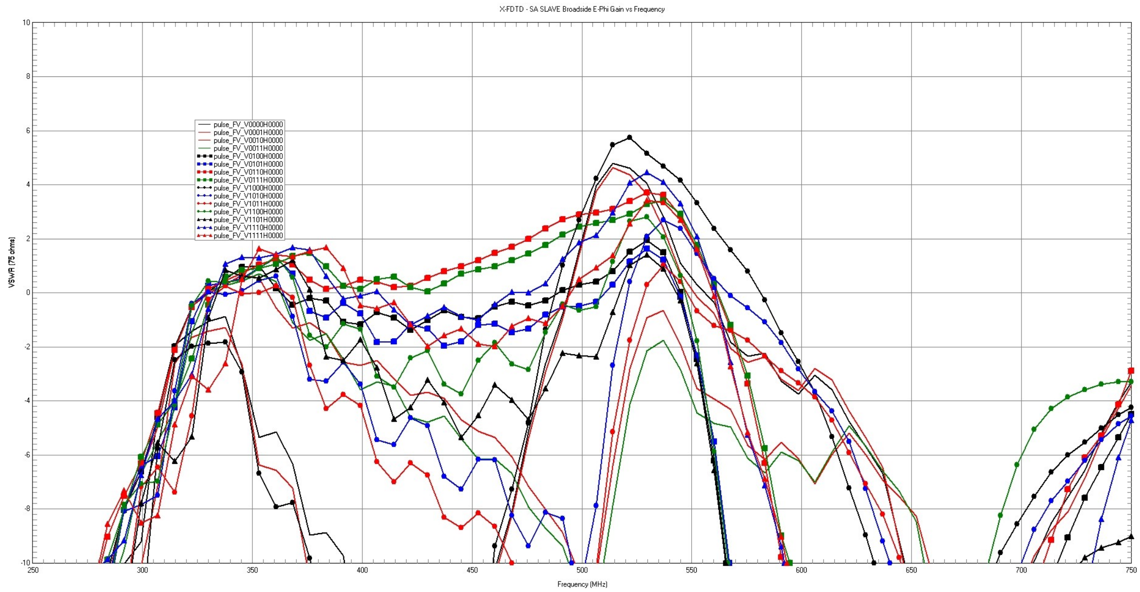



*Illustration 11: X-FDTD Broadside E-theta (H) gain versus frequency for vertical group feed and shorting pins.*

| | | | | | Feed Group Switches | | | | Orthogonal Group Switches | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Channel** | **F Low** | **F High** | **Band** | **Band Select** | **F3** | **F2** | **F1** | **F0** | **X3** | **X2** | **X1** | **X0** |
| **2** | 54 | 60 | VHF-LO | VHF | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **3** | 60 | 66 | VHF-LO | VHF | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **4** | 66 | 72 | VHF-LO | VHF | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **5** | 76 | 82 | VHF-LO | VHF | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **6** | 82 | 88 | VHF-LO | VHF | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **7** | 174 | 180 | VHF-HI | VHF | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **8** | 180 | 186 | VHF-HI | VHF | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **9** | 186 | 192 | VHF-HI | VHF | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **10** | 192 | 198 | VHF-HI | VHF | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **11** | 198 | 204 | VHF-HI | VHF | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **12** | 204 | 210 | VHF-HI | VHF | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **13** | 210 | 216 | VHF-HI | VHF | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **14** | 470 | 476 | UHF | UHF | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| **15** | 476 | 482 | UHF | UHF | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 |
| **16** | 482 | 488 | UHF | UHF | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 |
| **17** | 488 | 494 | UHF | UHF | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 0 |
| **18** | 494 | 500 | UHF | UHF | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| **19** | 500 | 506 | UHF | UHF | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| **20** | 506 | 512 | UHF | UHF | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| **21** | 512 | 518 | UHF | UHF | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| **22** | 518 | 524 | UHF | UHF | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| **23** | 524 | 530 | UHF | UHF | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| **24** | 530 | 536 | UHF | UHF | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| **25** | 536 | 542 | UHF | UHF | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| **26** | 542 | 548 | UHF | UHF | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| **27** | 548 | 554 | UHF | UHF | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| **28** | 554 | 560 | UHF | UHF | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| **29** | 560 | 566 | UHF | UHF | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| **30** | 566 | 572 | UHF | UHF | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| **31** | 572 | 578 | UHF | UHF | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 |
| **32** | 578 | 584 | UHF | UHF | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 |
| **33** | 584 | 590 | UHF | UHF | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 |
| **34** | 590 | 596 | UHF | UHF | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 |
| **35** | 596 | 602 | UHF | UHF | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 |
| **36** | 602 | 608 | UHF | UHF | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 |
| **37** | 608 | 614 | UHF | UHF | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 |
| **38** | 614 | 620 | UHF | UHF | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 |
| **39** | 620 | 626 | UHF | UHF | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 |
| **40** | 626 | 632 | UHF | UHF | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| **41** | 632 | 638 | UHF | UHF | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| **42** | 638 | 644 | UHF | UHF | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| **43** | 644 | 650 | UHF | UHF | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| **44** | 650 | 656 | UHF | UHF | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| **45** | 656 | 662 | UHF | UHF | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| **46** | 662 | 668 | UHF | UHF | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| **47** | 668 | 674 | UHF | UHF | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| **48** | 674 | 680 | UHF | UHF | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| **49** | 680 | 686 | UHF | UHF | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| **50** | 686 | 692 | UHF | UHF | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| **51** | 692 | 698 | UHF | UHF | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |

*Illustration 12: Initial CPLD Truth Table based on VSWR measurements.*

# 5 System Architectures

This section outlines some of the thinking that went into choosing the two-panel hinged design for the NAB smart antenna.

## 5.1 VHF Component

The VHF solution can be either fixed geometry or reconfigurable. In either case, size limitations will ensure that it will provide low gain and little directive advantage. It will also likely either be narrow band or exhibit low efficiency. A reconfigurable or tunable element may allow increased bandwidth and efficiency. If a reconfigurable or tunable antenna is used, it will likely require a multiplicity of states to cover the required frequency ranges. A fixed geometry antenna with an automatic impedance matching network may also meet the requirements for this element.

After the completion of the digital transition in February 2009, roughly 75% of the stations will remain on UHF as such, UHF performance shall have priority over VHF.

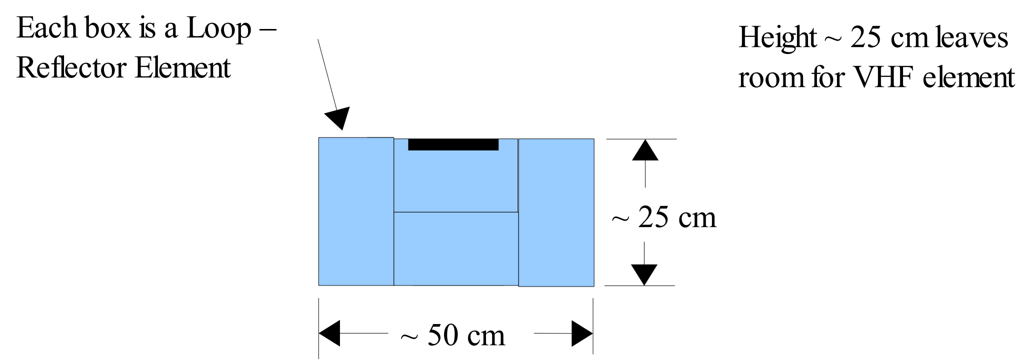
## 5.2 UHF Component

The UHF requirements can be met by using one or more fixed geometry solutions in a switched or phased array configuration to accomplish beam steering and / or diversity reception. Reconfigurable UHF elements may also be used to produce a lower profile solution. Several UHF options using fixed geometry antennas are discussed below.

### 5.2.1 Solutions with Fixed Geometry Elements

#### *5.2.1.1 Switched Directional Sectoral UHF Antenna*

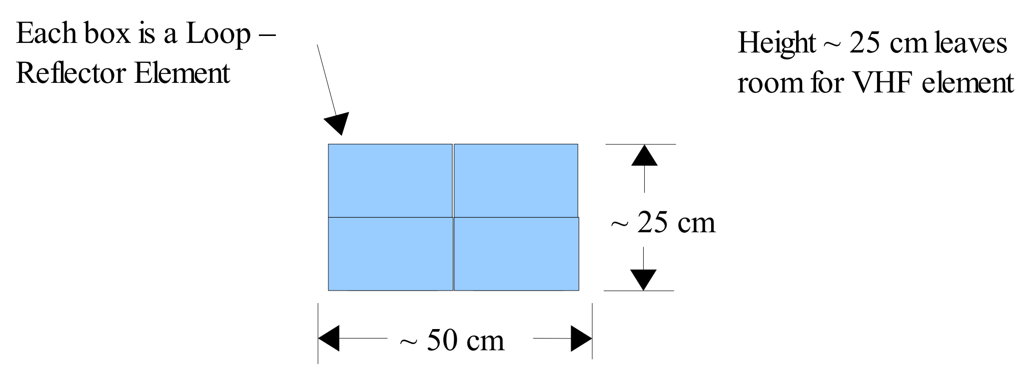
The loop-reflector geometry used in Lacrosse Micron is difficult to beat for high performance in a small and inexpensive package. It is possible to configure a switched directional sectoral UHF antenna using these elements as shown in Drawing 7. Here, two elements are placed back to back and two more are used as “book ends” to complete an array that covers four quadrants. Each of the elements has a -3dB beamwidth of 70 degrees. They are down 6 dB at 90 degrees, so there may be some slight degradation at some angles. Some work may be required to account for the deeper effective baffle on the middle two elements. The overall size of this configuration is roughly 50 cm x 25 cm x 25 cm. This leaves some room on the top or bottom to integrate the reconfigurable VHF element.




*Drawing 7: Top view of switched directional sectoral UHF antenna using existing loop-reflector elements.*

### *5.2.1.2 Bi-directional Diversity or High Gain UHF Antenna*

An alternative that may provide higher gain in only two directions is shown in Drawing 8. The elements in this configuration could be phased to allow higher gain in one of two directions. Alternatively, a diversity scheme could be used to simply select the antenna with best reception. Diversity may be as effective as beam steering indoors due to propensity for phase cancellations and multi-path in that environment.




*Drawing 8: Top view of switched bi-directional UHF antenna using existing loop-reflector elements.*

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### 5.2.2 Solutions Employing Reconfigurable Elements

The low-profile reconfigurable microstrip element provides enhanced performance and additional geometrical configuration options.

#### *5.2.2.1 Bi-directional reconfigurable using Lacrosse Micron Motif*

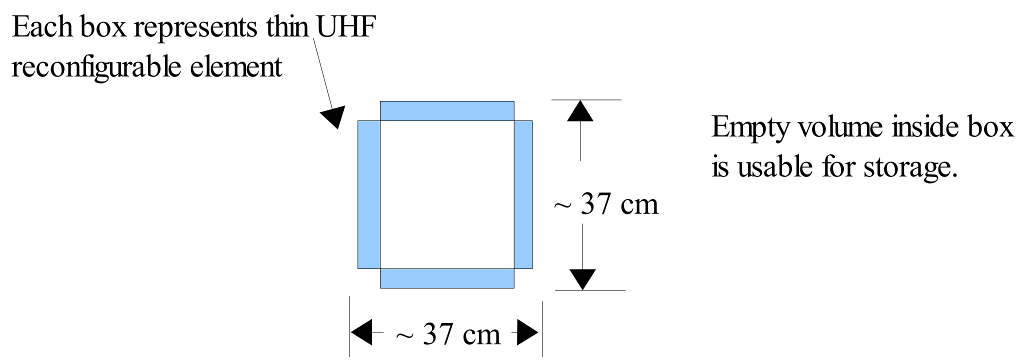
With the UHF reconfigurable shown in the previous section, it is possible to integrate two low-profile elements into a structure similar to the U shaped Lacrosse Micron shell. The elements could point in opposite directions and give the same performance as the current Micron with the ability to select two directions.

The bi-directionality and switchable polarization may be a big improvement on the current Lacrosse Micron which has only one direction, is horizontally polarized, and is manually pointed.

Another possible advantage is that the space within the "U" shape could then be used as a letter holder. A vase or plant holder style antenna would also be possible. We note that the UHF reconfigurable element shown in the previous section is larger than the current Lacrosse Micron shell so some re-tooling will be required, but the design motif can be retained.

#### *5.2.2.2 Quad Element Sectoral UHF in Small Cube*

An alternative embodiment might be to combine four of the basic elements into a cube and select between 4 directions. While this option may be cost prohibitive, it does allow the inside of the antenna box to be used for storage or perhaps as a plant holder. A similar option with three elements to form a triangle could also be constructed.



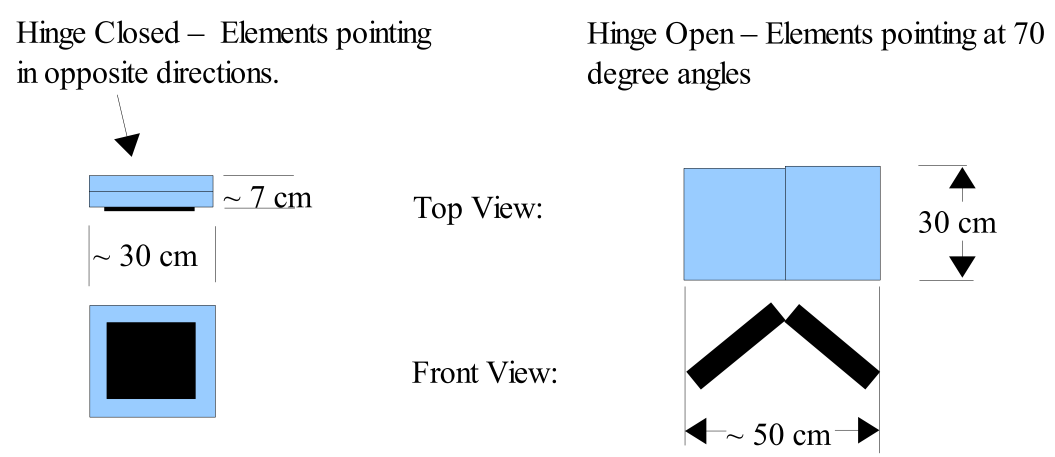

*Drawing 9: Top view of switched directional sectoral UHF antenna using thin reconfigurable elements.*

### 5.2.2.3 *Dual or Quad Element Flat Panel*

Two reconfigurable UHF elements can fit side by side in a 30 x 60 cm 3.5 cm panel. The array would have a gain of 9 to perhaps as much as 12 dB, depending on spacing. It may be possible to add phasing to this configuration to allow beam steering with the higher gain array, or we could simply do a diversity switching scheme which may solve most indoor problems. Adding a second set of elements on the opposite side of the center conducting panel would cover the opposite hemisphere with a package only 7 cm thick.

### 5.2.2.4 *Hinged Two Element UHF reconfigurable*

The reconfigurable UHF element opens the door to a picture frame style solution using two elements hinged together. Using two elements instead of four reduces size and costs. The 909 interface will control tuning and polarization of each element and select the element with the stronger signal. Using a sensor in the hinge, it may be possible to sense when the element is set flat and to perform phasing rather than switching for enhanced gain. Drawing 10 depicts the elements in a closed position where they are facing opposite directions, or in a deployed position where the beams are separated to allow reception from widely separated towers.




*Drawing 10: Hinged panel with two UHF reconfigurable antennas in picture frame type format.*

The approach used to develop the NAB Reconfigurable antenna was to first develop a high performance UHF reconfigurable element and then develop a VHF solution that did not significantly degrade performance of the UHF element while offering improved reception in the VHF bands. The hinged two-element solution was chosen based on cost, size and performance capabilities.

# 6 Electronics Description

## 6.1 Terminology

The SA (Smart Antenna) design is closely tied to the CEA-909A interface specification. Because this 'A' revision of the CEA-909 specification added a “coax only” interface solution, we shall refer to the F-connector data interface as '909A' . The modular jack data interface shall be referred to as the '909' interface. While the 909A interface includes power, data, and RF signal, the 909 interface refers only to power and data. For the 909 interface the use of the F-connector for the separate RF signal path is assumed.

## 6.2 Block Diagram

The block diagram shown in Illustration 13 depicts the functional elements of the SA design. This implementation addresses  several design goals as facilitated by the CEA-909A specification.

### 6.2.1 Interface Agility

Interface agility is defined as two different physical interfaces between the SA and the TV receiver or set-top box. These are the 909 modular data interface, utilizing a separate F-connector for the RF signal interface, and the 909A interface which combines power, data and RF signal onto the F-connector, circumventing the modular jack.

### 6.2.2 RF Signal Agility

RF signal agility is defined as the ability to provide four combinations of RF signal path gain by utilizing a preamplifier and two attenuators. The intent is to avoid overload compression and the corresponding cross-modulation and distortion for both the preamplifier component and the TV tuner or set-top box.

### 6.2.3 Directional Agility

Directional agility is defined as the ability to provide spacial diversity. For the purposes of this design, two separate SA panels provide the directional agility. A 'MASTER'  panel contains the 909 and 909A interfaces and the SA decoding and control circuitry. An additional 'SLAVE'  panel provides directional diversity, while reducing duplication cost and complexity.. Both the MASTER and the SLAVE panel provide a horizontal and a vertical polarization feed. The physical separation of the MASTER and SLAVE panels also allows the additional electrical length required to support VHF reception

### 6.2.4 Frequency Agility

Frequency agility is defined as the ability to tune the SA elements to better match COI (channel-of-interest) wavelength and exclude energy other than the COI. Excluding this unwanted spectrum, as well as the SA panel directionality, are primary attempts to maximize gain while avoiding RF signal compression.

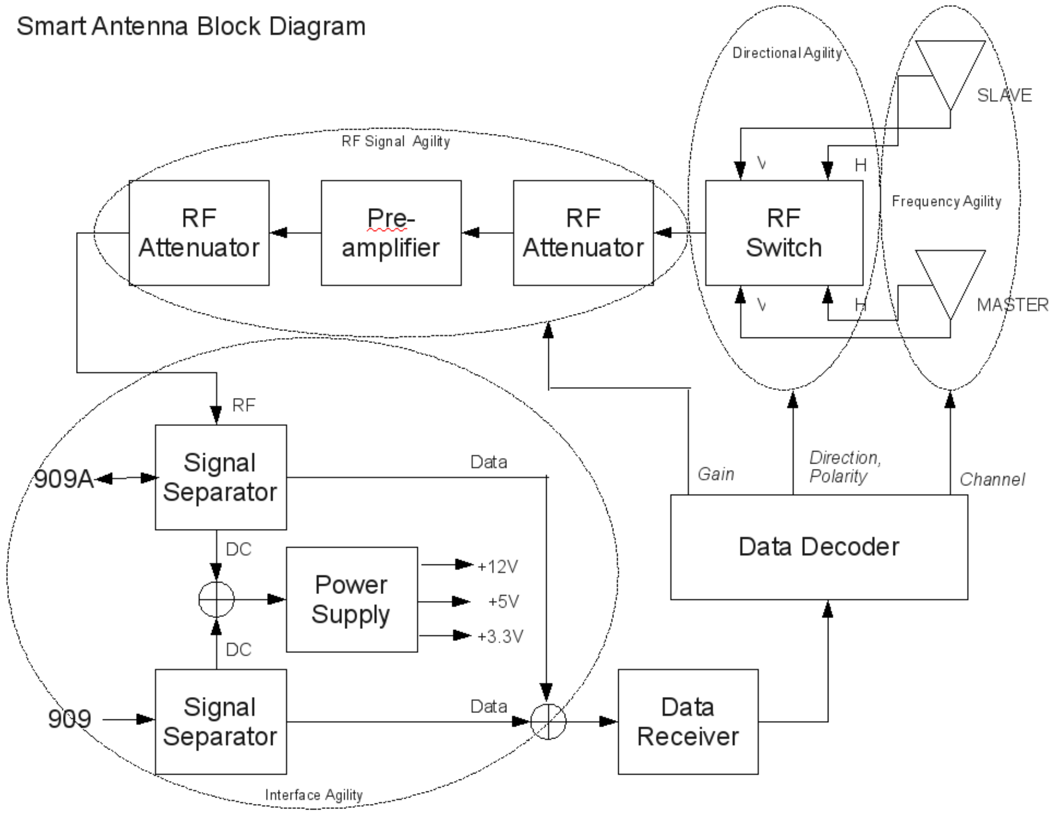



*Illustration 13: Smart Antenna Block Diagram*

## 6.3 Future Refinements

This section summarizes some of the future goals for the SA implementation.

### 6.3.1 Minimize SLAVE Panel Interface

We wish to reduce the SLAVE panel electrical interface to one ribbon cable and one coax cable. By including a polarization switch on the SLAVE panel, the horizontal and vertical feeds could be multiplexed prior to exiting the SLAVE panel. This would eliminate one coax cable and its connector. This would also allow the two additional 4PST switch inputs to be used to connect 2 additional SLAVE panels, providing additional directional agility. The problem is that to expand the ribbon control cable for this additional signal, means the number of conductors increases from ten to eleven. Eleven is not a standard size ribbon cable, In fact, twenty is the next standard size, however, custom sizes are possible. Ultimately, a data-over-signal approach similar to 909A would allow us to shed the ribbon cable altogether.

### 6.3.2 Polarized SLAVE Coax Cable Connector

We wish to identify an inexpensive, polar connector for where the SLAVE panel coax interface connects to the MASTER panel. Something other than the standard F connector would avoid configuration confusion. This interface could be BNC, since the RF interface is 50 ohm at this point.

### 6.3.3 Expand the 909/909A Interfaces to Include Non-Standard Timing

Late in the process of refining the 909A signal processing integrity, we discovered the SA only worked reliably with the Typical Unit #1set-top box. We were relying on the fact that the Typical Unit #3 could be used to manually configure the SA for performance verification. It became necessary to investigate why this test approach did not work. The largest deficiency of the Typical Unit #1 is that it does not dither the POLARIZATION bit in any scanning mode. It also does not allow manual control of SA settings.

Illustration 14 provides a snap-shot of the 909 data transmission, using an oscilloscope, for a failed Typical Unit #3 message. Illustration 15 from the CEA-909A specification shows the expected data signaling format. Note that the Typical Unit #3 is missing a pulse in the START bit position. In Illustration 14 it is unknown whether there is additional off screen bit, making a for delayed START, or a fully missing START bit. Further analysis requires an edge time-tagging logic analyzer.

To further develop the SA, we require a deterministic 909 data source. Our plan is to use our CPLD development test bed to develop a manual 909 signal generator. This would consist of switches to set the data pattern and a pushbutton to activate a single message transfer. This will allow the configuration control we need to perform better design verification testing and the design refinement necessary for cost reduction.

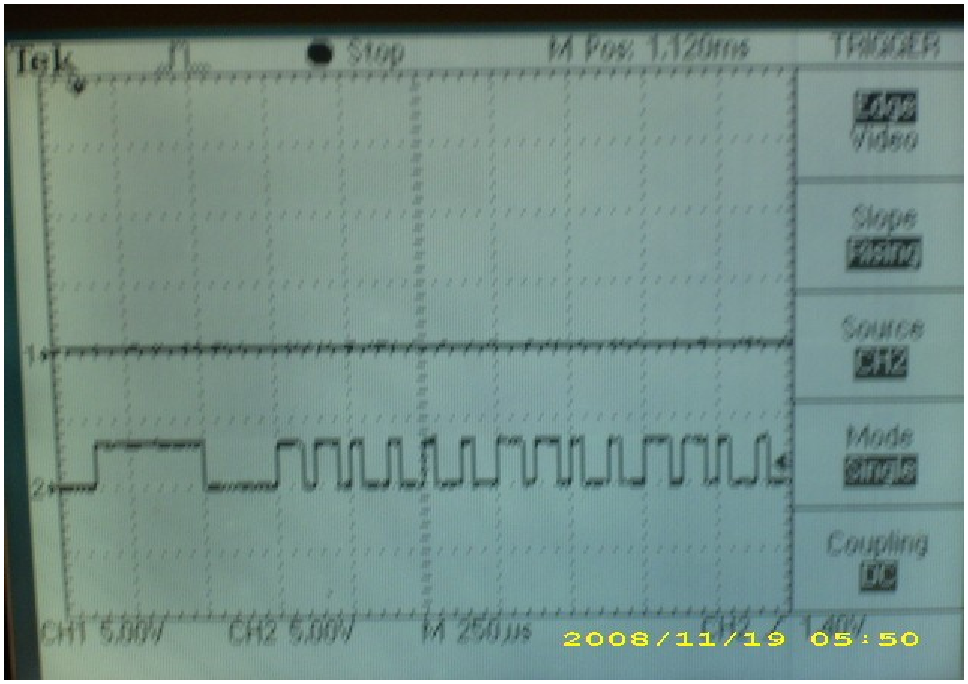
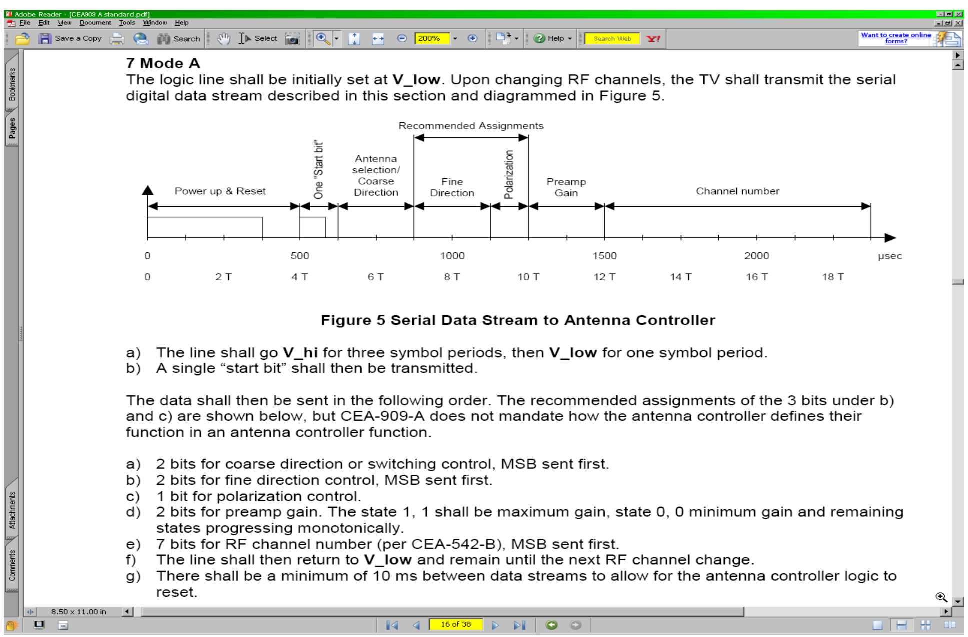



*Illustration 14: Typical Unit #3 Oscilloscope Trace of a Failed 909 Message*



**7 Mode A**

The logic line shall be initially set at **V_low**. Upon changing RF channels, the TV shall transmit the serial digital data stream described in this section and diagrammed in Figure 5.



**Figure 5 Serial Data Stream to Antenna Controller**

a) The line shall go **V_hi** for three symbol periods, then **V_low** for one symbol period.
b) A single "start bit" shall then be transmitted.

The data shall then be sent in the following order. The recommended assignments of the 3 bits under b) and c) are shown below, but CEA-909-A does not mandate how the antenna controller defines their function in an antenna controller function.

a) 2 bits for coarse direction or switching control, MSB sent first.
b) 2 bits for fine direction control, MSB sent first.
c) 1 bit for polarization control.
d) 2 bits for preamp gain. The state 1, 1 shall be maximum gain, state 0, 0 minimum gain and remaining states progressing monotonically.
e) 7 bits for RF channel number (per CEA-542-B), MSB sent first.
f) The line shall then return to **V_low** and remain until the next RF channel change.
g) There shall be a minimum of 10 ms between data streams to allow for the antenna controller logic to reset.

*Illustration 15: CEA-909A Data Timing Specification*

# 7 Appendix A - CEA-909 / 909A Enabled Receiver Data

This section contains notes on the various CE-909 / 909A enabled receivers used during the course of this program.

All testing was performed with an antenna attached to the set-top-box (NO DTV detected).

NOTE: Dithers all bits of a function, Direction(4-bits)/Polarity(1-bit)/Gain(2-bits)/Channel(7-bits), unless otherwise stated below.

NOTE: Channel bit patterns are ALL limited to 2 to 69 (7-bits => 0 to 127)

## 7.1 Typical Unit #1 Converter Box

This receiver provides signaling compliant to CEA-909 and offers extensive search capability. Manual control of the antenna through firmware is not possible.

### 7.1.1 Power Behavior

SA is powered in STANDBY(off) mode as well as ON mode.

### 7.1.2 Initial Startup (ex: from FACTORY RESET)

Unless you can detect ONE channel in the INITIAL scan you can NOT access the detailed setup MENU Can ONLY select language and do INITIAL scan! (forced into channel scan MENU, ex: LEVEL1 ++> LEVEL3 normally, LEVEL2 options: LANGUAGE/POWER_SAVER/ANTENNA/TIME_ZONE/ SYSTEM_RESET are NOT available until after finding a channel in the initial scan). Don't know if this is true fresh from BOX!?

### 7.1.3 Channel Scanning:

- 2 modes of scanning LONG/SHORT
  - SHORT
    - Scans with 5 or 8 states using 3 MS bits of Direction and Channel only.
    - Directional states are:
      - 0000
      - 0100
      - 1000
      - 1100
      - 1010
  - LONG
    - Scans with Gain/Direction/Channel
    - NOTE: Polarity is NEVER changed.

## 7.2 Typical Unit #2 Converter Box

Firmware is similar to others tested here. Allows manual control of antenna.

### 7.2.1 General

SW Version: X1.00-01222008
HW Version: 0000
Loader Version: 11558
Firmware/chipset appears much like TU#4.
Firmware/chipset appears much like TU#3.

### 7.2.2 Power Behavior

SA is powered in ON mode ONLY.

### 7.2.3 Smart Antenna Detection

`Differentiates between SA and NO SA!
Smart antenna is powered, but exactly what modes generate communications do not appear straight forward.

### 7.2.4 Channel Scanning

Manual Channel/Direction/Polarization/Gain.
Automatic Channel/?/?/?(11 states)
Sends 11 - 2.5mS messages with 2.5 mS between them (as all scanning combinations) for each frequency scanned. Suspect the 2.5 mS dwell is too small for antenna settling and converter lock.
Messaging is 2.24V into data receiver, proper detection is possible!
Exact scanning control MENU behavior is confusing.

## 7.3 Typical Unit #3 Converter Box

Widely available at Best Buy. Firmware has manual control options. Problems with CEA-909 compliance.

### 7.3.1 General

SW Version: X1.00-06132008
HW Version: 001
Loader Version: 11230
Firmware/chipset appears much like TU#4.

### 7.3.2 Power Behavior

SA is powered in ON mode ONLY.

### 7.3.3 Smart Antenna Detection

Differentiates between SA and NO SA!

Smart antenna is powered, but exactly what modes generate communications do not appear straight forward.

#### 7.3.4 Channel Scanning

Manual Channel/Direction/Polarization/Gain.
Automatic Channel/?/?/?(11 states)
Sends only 1 - 2.5mS message with 250+mS dwell (up to 1000mS?) mS between them.
Message only 2.0V into data receiver, DOES NOT CROSS signaling threshold!
Direction/Gain/Polarity appear fixed to the last values set in the smart antenna manual configuration menu.
NOTE: Appears to sets polarity bit (manual ONLY).
NOTE: Gets into a mode where the start bit is missing and the SA never qualifies the message (need SYNC and START to qualify data)
Exact scanning control MENU behavior is confusing.

#### 7.3.5 Other

NO +/- channel buttons on box itself (remote ONLY)

### 7.4 Typical Unit #4 Converter Box

Firmware and signaling similar to TU#3 models.

#### 7.4.1 General

SW Version: X1.00-02252008
HW Version: 0000
Loader Version: 11746
Firmware/chipset appears much like TU#3.
Manual/Automatic SA tuning

#### 7.4.2 Power Behavior

SA is powered in ON mode ONLY.
Smart antenna (SA) detection:
Differentiates between SA and NO SA!
Smart antenna is powered, but exactly what modes generate communications do not appear straight forward.

#### 7.4.3 Channel Scanning

Manual Channel/Direction/Polarization/Gain.
Automatic Channel/?/?/?(11 states)
Sends 11 - 2.5mS messages with 2.5 mS between them (as all scanning combinations) for each frequency scanned. Suspect the 2.5 mS dwell is too small for antenna settling and converter lock.
Messaging is 3.4V into data receiver, proper detection is possible!
Exact scanning control MENU behavior is confusing.