# AUTOMATICALLY TUNING ANTENNA FOR SOFTWARE-DEFINED AND COGNITIVE RADIO

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## ABSTRACT

This paper discusses the approach and benefits of implementing an automatically tuning antenna for the further development of software defined radio (SDR). Electrically small antennas (ESAs) are utilized as tunable filters as well as radiating elements to simplify the RF front-end design, which has the potential to lower the cost of next generation commercial and military radios while simultaneously enhancing performance. The automatic tunability of the frequency selective antenna is achieved by a closed-loop automatic antenna tuning unit (ATU). In implementing the ATU, two different types of tunable matching networks are developed to match a more or less arbitrary load to a convenient impedance value, usually 50 Ωs. To generate feedback data that can be used to optimize the impedance synthesizer, the incident and reflected powers at the input to the impedance synthesizer are measured using a power detector comprising directional couplers, power detector diodes, and ADCs. In order to validate the design of the ATU, a hardware implementation of the ATU prototype has been demonstrated successfully.


## 1. INTRODUCTION

In this paper, we describe a new approach for allowing electrically small antennas (ESAs) to be used in multi-band, multi-mode radio transceivers and SDRs. The frequency selectivity inherent in ESAs can greatly simplify the RF front-end design by reducing the requirements for analog filters. The ESAs can be tuned to a specific narrow bandwidth over a much wider frequency range by reconfiguring its geometry using appropriate control elements such as RF switches or varactors. In principle, the control elements can be configured in an open-loop fashion based on a digital word received from the radio's baseband processor [1]. Open-loop tuning, however, cannot be used in practice because of limitations on the values of commercially available components, tolerances associated with physical components, and variations in the antenna's response due to environmental changes. These factors can cause the exact center of the antenna's narrow instantaneous bandwidth to fluctuate in an unpredictable way. Furthermore, open-loop tuning is not compatible with the ultimate goals of SDR and cognitive radio, where the radio can be re-programmed to cover new frequency bands and modes of operation simply by downloading new software. Thus, the implementation of a closed-loop automatic antenna tuning unit (ATU) is imperative.

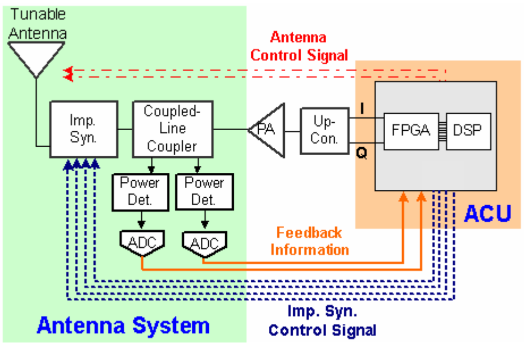


Figure 1: Block diagram of closed-loop automatic antenna tuning unit (ATU) for SDR transmitter.

The block diagram of the proposed ATU system is shown in Figure 1. The closed-loop system for antenna matching ensures that a narrowband antenna is

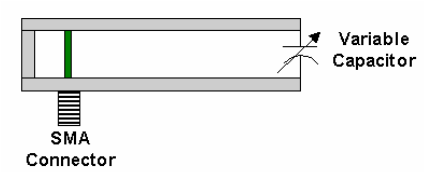


Figure 2: Geometry of SPA for reconfigurable antenna implementation.

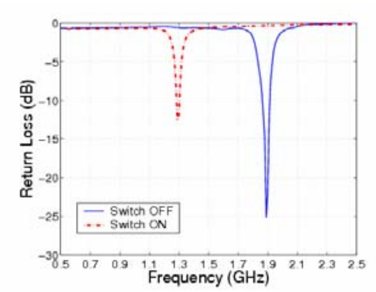


Figure 3: Measured return loss of the SPA tuned to two frequency bands.

automatically matched to any desired frequency under all environmental conditions using practical component values and tolerances. As the block diagram reveals, however, the antenna system is no longer simply an electromagnetic transducer, but a mixed-signal system that involves several microelectronics circuits as well as appropriate software algorithms running on one or more programmable logic devices (PLDs) such as field programmable gate arrays (FPGAs) or digital signal processors (DSPs).

Employing a PLD for the antenna control unit (ACU) provides the end users with compete control over the implementation of the impedance synthesizer and antenna. A search algorithm running on the ACU is used to efficiently find the impedance synthesizer state that results in minimum return loss at the given frequency and environmental conditions.

In order to design the impedance synthesizer, two different approaches have been implemented. One uses a tunable pi-matching network consisting of discrete components and PIN diodes. This approach is suitable for VHF/UHF bands, and up to about 2 GHz. At relatively high frequencies, such as S- and C-bands, a microstrip loaded-line type topology with varactor diodes is utilized.

In this paper we discuss a number of practical issues concerning the design and modeling of electrically small antennas, as well as their tunable matching networks and concomitant control circuitry and algorithms.

## 2. ELECTRONICALLY TUNABLE ATENNA

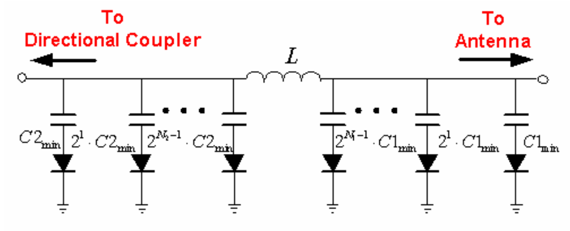


Figure 4: Impedance synthesizer configuration.

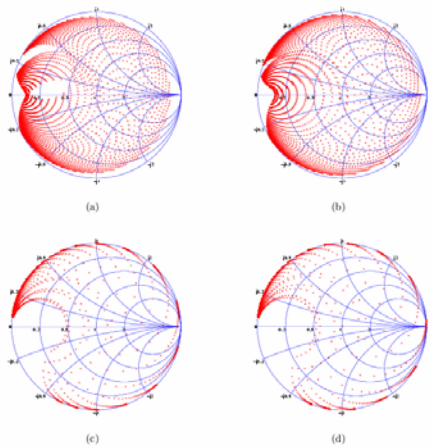


Figure 5: Simulated matchable domain with 12 capacitors ($N_1$=$N_2$ =6, $2^{12}$ = 4096 states) at (a) 800 MHz, (b) 900 MHz, (c) 1800 MHz, and (d) 1900 MHz. Ideal components are used in the simulation for the pi-network of Figure 5 with $L$ = 3 nH, $C1_{\min}$ = 0.5 pF, and $C2_{\min}$ = 1 pF.

An electronically tunable single patch antenna (SPA) was designed and fabricated in order to demonstrate the frequency selectivity of ESAs. The geometry of the SPA is shown in Figure 2 [1]. The SPA is designed with a layer of copper supported by FR4 over air as the main substrate. To feed the SPA, the outer conductor of the SMA connector is connected to the ground plane while the inner conductor is connected to the patch. The SPA is loaded with surface mount device (SMD) capacitors at the radiating edge to effectively change the electrically length of the antenna. Along with the capacitor, a PIN diode switch (to turn on off the load) and its associated bias network are mounted on the underside of the ground plane, i.e., FR4.

With the SPA fully fabricated and tested, the SPA is electronically tuned, and the measured return loss for each state is presented in Figure 3.

## 3. AUTOMATIC ANTENNA TUNING UNIT (ATU)

In this section, we discuss the major issues in ATU design from the perspective of current RF communication systems. These include the design, fabrication, and measurement of

 

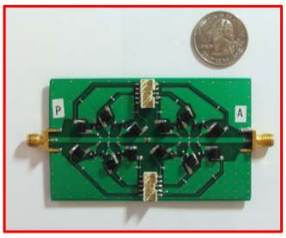

Figure 6: Photograph of the fabricated impedance synthesizer.

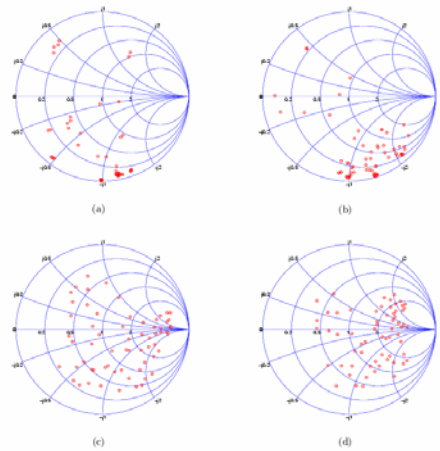

Figure 7: Measured matchable domains of the fabricated impedance synthesizer with 6 capacitors at (a) 800 MHz, (b) 900 MHz, (c) 1800 MHz, and (d) 1900 MHz.

the tunable matching network, RF power sensor, and analog and mixed-signal control circuitry.

### 3.1. Impedance Synthesizer

*3.1.1. Tunable pi-matching network*

To provide a complex-conjugate matching capability for a wide range of impedances and a variety of antennas that might be used under changing environments, a lowpass-type pi-matching network is considered due to its harmonic rejection capability and wide matchable impedance range [2], [3].

Figure 4 illustrates the basic topology of the tunable pi-matching network configuration [2], [4]. With a fixed inductor and binary capacitor arrays, the matching network is capable of generating a wide range of tuning possibilities. Although the matching network provides better tunability if a variable inductor is used, we eliminated the use of a tunable inductor to simplify the ATU design. The values of $L$, $C1_{min}$ and $C2_{min}$, and the numbers ($N_1$ and $N_2$) of capacitors in the configuration are determined by the desired operating frequency and matchable region.

It is important to note that any type of matching network is capable of producing a perfect match as long as

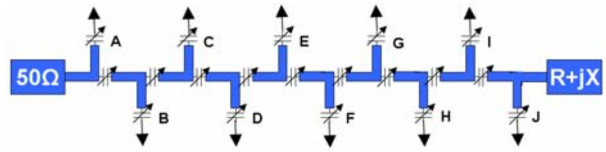


Figure 8: Ten stub reconfigurable RF impedance tuner.

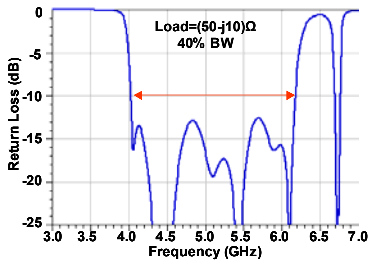


Figure 9: Simulated return loss of ten stub microstrip tuner.

its component values are variable from zero to infinity. However, the practical component values that can be realized are limited. Therefore, we determine the maximum matchable region for its conjugate matching within the practical ranges of the components values. A series of simulations has been performed by varying $N_1$, $N_2$, $L$, $C1_{min}$, and $C2_{min}$ in order to obtain reasonable dynamic ranges for the frequency range of 800 MHz to 1900 MHz. Figure 5 shows the matchable domains at different frequencies. Each dot on the Smith charts represents an antenna (or a load) impedance that can be matched exactly to the system impedance of 50 Ω.

The practical realization of the impedance synthesizer involves complicated trade-offs between the matching domain and physical limitations of components. The losses and parasitic effects associated with the PIN diode switches are one of the most important considerations when implementing the impedance synthesizer because they can deteriorate its performance drastically. However, in general, variations of antenna impedance due to the environmental conditions are limited to a certain region of the Smith chart. Thus, it is not necessary for the dynamic range of an impedance synthesizer to cover all the Smith chart area, but be sufficient to generate the complex conjugates of the antenna impedances confined to a certain region on the Smith chart. In other words, fabricating an impedance synthesizer for the purpose of matching a *particular* antenna (as opposed to *any* antenna) will require only a small tuning range of capacitors. Therefore, engineering trade-offs are necessary to determine the optimal number of matching states with an acceptable dynamic range. The compromise between large matchable domains and small losses led us to fabricate an impedance synthesizer with 6 switches ($N_1$=$N_2$ =3, $2^6$ = 64 states).

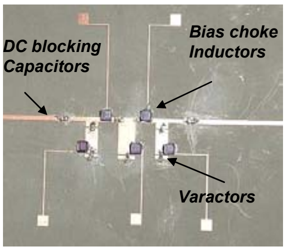


Figure 10: Photograph of three stub RF impedance tuner.

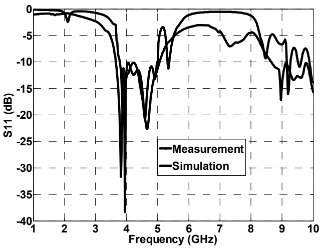


Figure 11: Comparison of measured and simulated results for fabricated three-stub tuner.

The photograph of the impedance synthesizer prototype fabricated on FR4 board is shown in Figure 6. The *S*-parameters of the fabricated impedance synthesizer were measured with the help of an automated measurement system using LabVIEW. Figure 7 shows the measured matchable domains of the fabricated impedance synthesizer at (a) 800 MHz, (b) 900 MHz, (c) 1800 MHz, and (a) 1900 MHz.

*3.1.2. Reconfigurable RF Impedance Tuner*

A broadband impedance tuner can be used at the input of ESAs and wireless devices in order to provide a significantly broader bandwidth or to reconfigure the impedance match spectrum. Another tuner configuration that uses a microstrip loaded-line circuit topology with varactor diodes at the end of the stubs and between resonator sections is shown in Figure 8. The impedance tuner is designed to provide wide instantaneous bandwidth (at least 40%) at a 5 GHz center frequency and be tunable to function with wide bandwidth for a diverse set of load conditions. Varactor diodes are employed due to their ability to provide continuous tuning, their wide availability, and their ease of implementation in fabrication of a prototype design.

The design of the tuner is based on a Chebyshev bandpass filter synthesis since the Chebyshev response gives the broadest bandwidth with the fewest number of sections [4]. Once the analytical design is complete, the tuner is further refined using optimization in Agilent Advanced Design System (ADS) [8].

A statistical optimization cost function has been developed to optimize the performance of the tuner by using the synthesized structure as a staring point. The cost function considers the frequency response in the tuning band (i.e., passband) as an entire set of points (i.e., a function), which is a significant factor in successfully designing and evaluating the impedance tuner. Figure 9 shows the simulated return loss for the ten-stub impedance tuner for the load impedance of 50-$j$10 Ω at 5 GHz .

To verify the circuit design and simulation approach, a prototype three-stub reconfigurable tuner with 30% bandwidth was designed, fabricated, and tested. The impedance tuner was fabricated a Rogers Corp. Duroid 6006. Figure 10 shows a photograph of the three stub tuner. This figure shows the tuner structure and the DC blocking capacitors. The overall length of this structure on a material of $\varepsilon_r$ = 6.15 is approximately 1100 mils. A coaxial double stub tuner was used to create the mismatched load cases for the measurements. For the 40+$j$50 Ω load, Figure 11 shows very good agreement between the measured and simulated results.

**3.2. RF Power Sensor**

To control the status of the impedance synthesizer, the ATU requires feedback data that allow it to determine the impedance mismatch corresponding to a given state. In certain applications (CDMA, for example), the incident power level is constantly being adjusted to optimize signal to interference plus noise ratio for all users. Hence, it is generally necessary to measure incident power levels as well as reflected power levels in order to be able to determine the input reflection coefficient. Here, we consider the design of a RF power sensor that can be used to detect the incident and reflected power levels at the input of the impedance synthesizer. Implementation of these sensors includes the design and fabrication of a three-line directional coupler, RF power detectors, and ADCs.

*3.2.1. Directional Coupler*

The main design issue of the directional coupler is to sense the incident and reflected powers (with a reasonable power level required for an RF power detector), while delivering the input power to the though-line output port with minimum loss, ideally, $S_{21} = S_{12} = 1$. For such weak couplings, a coupled line coupler is considered proper for the ATU system. The directional coupler was designed with the help of Ansoft HFSS.

*3.2.2. RF Power Detector*

An RF power detector is used to convert the power levels extracted from the three-line directional coupler to analog output voltage levels which are then used as an input to an ADC. The LTC5505-2 RF power detector (Linear Technology Corp.) is chosen here to detect the coupled power levels. The three-line directional coupler and the RF

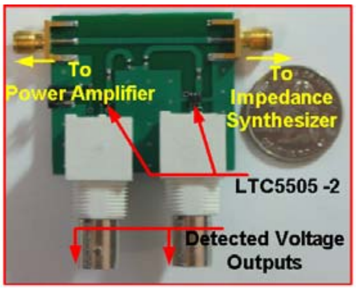

Figure 12: Photograph of the power detector combined with the three-line directional coupler.

power detector are combined on a single PCB as shown in Figure 12.

*3.2.3. ADC and Data Acquisition*

After detecting the incident and reflected power level with the RF power detectors, it is necessary to convert the analog signal to a digital signal for further digital signal processing of the ACU. The National Semiconductor's ADC1173 15Msps ADC is chosen to digitize the analog voltage signals from the outputs of the RF power detectors. To capture the digitized signal and feed the data into a microprocessor for further signal processing, the National Semiconductor's WaveVison™ Digital Interface Board is chosen and connected to the ADC1175EVAL Evaluation board.

### 3.3. Antenna Control Unit (ACU)

After the electronically tunable antenna is reconfigured by the open-loop ACU, the ATU adopts a closed-loop system to ensure that the coarsely tuned antenna is automatically matched to any given frequency under all environmental conditions. Based on the coupled incident and reflected signal levels, a search algorithm running on the ACU tries to minimize the impedance mismatch of the antenna.

A number of different types of search algorithms can be implemented according to [2], [5]-[7]. Here, we present a nearest neighbor search algorithm. The search process starts from an arbitrary point on the two dimensional plane. The algorithm compares the ratios of the incident and reflected power levels detected from this point and its eight nearest neighboring points. From among these nine points, the one that generates a minimum ratio of these power levels is selected as the new starting point. The search continues to iterate until it finds a starting point that produces a smaller mismatch than any of its nearest neighbors.

## 4. ATU PROTOTYPE AND TEST SETUP

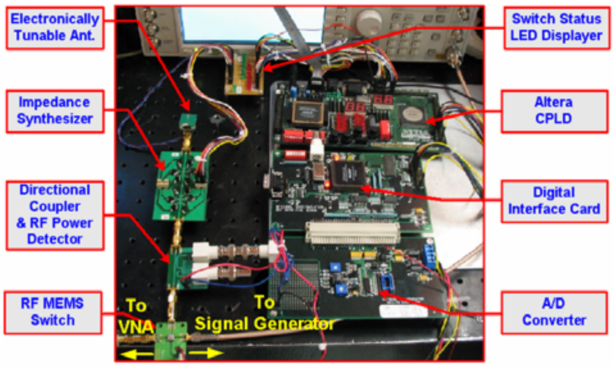

Figure 13: Photograph of the ATU demonstration setup.

To establish the feasibility of using the ATU in SDR and cognitive radio applications, an ATU system was constructed (see Figure 13) and demonstrated. The ATU demonstration setup is based on the block diagram shown in Figure 1.

The tunable pi-matching network of Figure 6 was placed next to the electronically tunable antenna. The power detector combined with the three-line direction coupler was inserted between the impedance synthesizer and an RF MEMS switch (Magfusion MagLatch™ RF Switch, Magfusion, Inc.). The RF MEMS switch is not a part of the ATU, but employed to automatically switch between an RF signal generator (Agilent E4432B Signal Generator) and VNA (HP-8510C Vector Network Analyzer). It should be mentioned that, in this ATU prototype, the ACU reconfigures the impedance synthesizer based on the reflected power level only. A 50 Ω matched load is connected to the output of the incident power level detector. But note that it is necessary to detect both the incident and reflected power level to be compatible with the dynamic power variation scheme in an RF communication system such as CDMA. Both the open-loop and closed-loop algorithms are programmed using VHDL and implemented using a FPGA device (Altera UP2 Education Board, Altera Corp.)

Consider the case where the frequency of an RF signal applied to the input of the directional coupler (output of the signal generator) is arbitrarily set to 1.87 GHz. First, the tuning circuit of the SPA is controlled by the open-loop ACU. The solid line on Figure 14 presents the measured return loss of the SPA which is reconfigured based on the frequency information received by the ACU. Then, the nearest neighbor search algorithm running on the FPGA tries to minimize the reflected power level in order to eliminate the impedance mismatch between the antenna and impedance synthesizer. Figure 14 shows the results achieved by the prototype. As can be seen in the figure, the ATU enables very narrowband tunability.

 

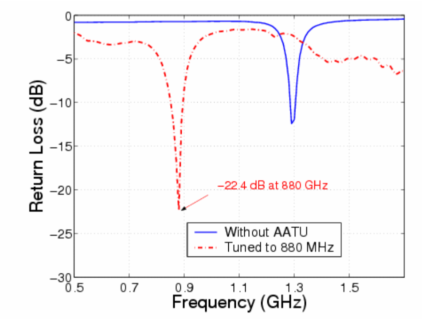


Figure 14: Narrowband tuning ability of the ATU. The SPA is tuned to 880 MHz.

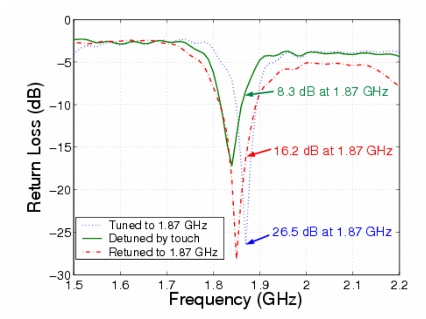


Figure 15: Automatic tuning ability of the ATU.

Handheld devices are generally used under constantly changing environment conditions. To demonstrate how well the ATU compensates for changing environmental conditions, the antenna is brought to close proximity of a human hand. Figure 15 shows the detuned response of the antenna when it is in contact with the human body. As can be seen, significant degradation of the antenna's performance occurs. Once the antenna is detuned, the search algorithm automatically reconfigures the impedance synthesizer to correct for this sudden environmental change. The retuned response, with the antenna still in contact with the hand, is shown in the same figure.

## 5. CONSIDERATIONS AND FUTURE WORK

With the successful demonstration of the ATU prototype, it is expected that the ATU could be beneficial to future commercial and military SDR platforms. However there are several issues to be considered for the ATU system to be deployed for use with these products. In order to meet needs of the fast developing wireless and mobile services, the design and optimization of the ATU antenna system are required to consider the following engineering design issues: high efficiency (low loss), low-power consumption, low profile, high-speed tuning, and spurious free radiation.

### 5.1. RF MEMS Switch Implementation

To realize RF front-ends that can function in multi-mode and handle wide frequency bands, the impedance synthesizers should contain components that have low-loss over a wide frequency range. However, the tunability and matching ability of the impedance synthesizers are mainly limited by the losses induced from RF switches, inductors, and varactors. Currently, reliability and packaging issues concerning RF MEMS switches are being resolved, and low cost production techniques are being developed. Based on these developments, we have COTS RF MEMS switches (TT712-68CSP, TeraVicta Technologies, Inc.) in hand and expect to be able to evaluate the performance of the pi-network impedance synthesizer realized with RF MEMS switches in the near future.

### 5.2. CMOS Implementation

The entire cognitive antenna self-matching system project targeted for commercial wireless communication systems, GSM-850, GSM-900, DCS-1800, PCS-1900, UMTS and ISM bands, will be implemented with integrated circuits (IC) in the near further. Currently a 54 dB detection range, 800 MHz - 2 GHz power detector is under development using 0.25u CMOS technology. Then the other parts, including directional couplers, impedance synthesizers, and ADCs will be migrated to silicon chip. The expected benefits include low power consumption, small size, robustness, and low cost.

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