A Physical Model for Tunable Patch Antennas

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Abstract
A model for tuning microstrip patch antennas with a controllable impedance “black box” is presented. These tunable impedance elements can be placed along the mid-line of the patch antenna to alter the impact of the tuning range on the antenna field pattern. Simulation results demonstrate the impact of this level of design control. Also highlighted is the improved ability to design beyond tunability with additional impedance matching and antenna area margins. Finally, the unique capability of the IMPATT diode for achieving these tunable impedance properties is discussed.

Keywords
Tunable antenna, IMPATT diode, impedance matching, microstrip, patch antenna

1. Introduction
Adaptive antenna arrays are extremely useful for overcoming wireless channel impairments such as attenuation, multipath fading, interference, and low signal-to-noise ratios [1]-[5] since they can be used to extract spatial information about the wireless channel and then be tuned to avoid or resist these effects. The antenna array is designed with a specific physical separation between each element, and this separation is exploited to spatially characterize the incidence of a signal-of-interest to and from the array. A combining network brings together each weighted antenna stream to electrically steer the total field pattern of the array and improve the performance of the wireless communications link.

Tunable adaptive antenna arrays are a specialized class of these antenna systems that offer two adjusting factors for adapting the total field pattern of the array: first by tuning the antenna element patterns and second by adapting the array weights for the combining network. Even further, we can imagine a tunable antenna array that foregoes the array weights and simply tunes the antenna elements themselves to achieve various beam patterns. Even though the antenna system would be more complex in this case, the hardware requirements could be significantly reduced as each antenna may potentially be combined before receiver and after transmitter RF hardware. This could be especially useful to handsets as it would double as cost and footprint savings.

Previously, we presented a theoretical method for tuning the antennas of an adaptive array by way of a dynamic “black box” impedance element [6]. Such an ideal scenario allowed us to explore the impact to the total array field pattern and present more evidence on the usefulness of tunable antenna elements for adaptive arrays. We now revisit the topic of tunable microstrip antennas to improve our ability to model the effects of the “black box” impedance elements on the individual antenna field pattern and introduce more flexibility for design and implementation of the patch antenna.

In addition to meeting the antenna array needs with a broader range of useable field patterns, this model for tunable antennas gives insight to other system-level benefits such as input impedance matching for overcoming resistive and capacitive losses or size constraints that limit antenna beamwidth and/or resonance frequency. The basis of our simulations is still an ideal impedance “black box”, but we maintain that the IMPatt Avalanche Transit Time (IMPATT) diode [7],[8] has shown the most promise as a real-world means for achieving tunable antennas.

2. Theory
The cornerstone of our tunable antenna model is the classic Pues and Van de Capelle [9][11] transmission line model for microstrip patch antennas. This methodology is well-known for being simple yet accurate. The transmission line model allows us to visualize the antenna system as a network of elements as demonstrated in Fig. 1.

Figure 1: Three-port network diagram for Pues transmission line model.

Procedurally, the Pues model computes effective parameters for line width \( W_e \) and length \( L_c \), dielectric constant \( \varepsilon_{\text{eff}} \), and loss tangent \( \delta_c \) that have been adjusted to compensate for the total dimensions of the strip, the strip thickness, and dispersion at the operating frequency. These parameters are then used to find the appropriate characteristic admittance \( Y_c \), propagation constant \( \gamma \), slot self-admittance \( Y_s \), and mutual admittance \( Y_m \). They combine via:

\[
Y_m = \frac{Y_e^2 + Y_i^2 - Y_m^2 + 2Y_e Y_i \coth(\gamma L) - 2Y_e Y_i \csch(\gamma L)}{Y_e + Y_i \coth(\gamma L)}
\]  

(1)

to yield an input admittance for the designed antenna at a feed line located at one edge of the strip. For simplicity, we will assume a lossless model (making \( \gamma=\beta \)) and ignore mutual coupling effects between the slots (\( Y_m=0 \)).

What this model also allows is the ability to visualize any element along the transmission line between the radiating slots of the antenna. Using this, we consider another way to tune the “black box” impedance and its effects: by changing
was designed with a resonance frequency at $f_0=2.4$ GHz. Horwath, A Physical Model for Tunable Patch...

$$Y_i = \frac{Y_e Y_s + Y_c \coth(\gamma L)}{Y_s + Y_c \coth(\gamma L)}.$$ (2)

Generally, the tunable impedance element provides a disturbance that, in turn, modifies the input impedance to the patch. Since we can see the relationship between input impedance and patch dimensions (in light of the documented Pues model and (1)), we can assume this tuned antenna system behaves just like a static antenna with a new $W$ and $L$. It is as if the tunable “black box” impedance can electrically stretch or squeeze the patch antenna. For the analysis, we utilize the following process:

1) Design a basic microstrip patch antenna to establish a baseline for the design
2) Choose a location for the tunable impedance element
3) Use (2) to find the transferred shunt impedance of the far radiating slot at the location of the “black box”
4) Combine the tunable and transferred slot impedances, and use (2) again to transfer to the patch input
5) Combine the new transferred impedance with the near radiating slot to get the new patch input impedance
6) Repeat the design process in reverse to find the tuned width and length

This procedure is used to evaluate the impact of the tuned impedance values from our “black box” at several different locations on the baseline antenna. Findings and discussion from this work are presented below.

3. Results

To begin our work, a baseline microstrip patch antenna was designed with a resonance frequency at $f_c=2.4$ GHz. The dimensions of the patch are $W=2$ cm and $L=4.1666$ cm with strip thickness $t=35 \text{ } \mu\text{m}$ on a substrate having $\varepsilon_r=2.2$ and height $h=0.1588$ cm. This design yielded an antenna with $Z_{in}=1774.3 \Omega$, $Z_c=16.7667 \Omega$, $Z_s=13.984 \Omega$, and $\gamma=j17.8004$.

Similar to our previous approach [6], we will assume that our tunable “black box” has two extremes: 1) positive resistance with inductance (extreme value of 30+j190 $\Omega$), 2) negative resistance with capacitance (extreme value of -5-j100 $\Omega$). Using the method described above for varying locations of our tunable element over the two scenarios, the resultant field patterns are calculated. It was quickly seen that, generally, the scenario (R+jol $\Omega$ vs. -R+1/joC) determined the type of influence on the field pattern while the location impacted the attenuation of the new pattern. For instance, the resulting field patterns for several different locations of the “black box” are plotted in Figs. 2 through 5.

Figs. 2 and 3 display the E- and H-field patterns, respectively, of tuning R+jol $\Omega$ and typically lead to a stronger, more focused beam leaving the patch than the baseline. It can be seen that placing the tunable element close to the middle of the line (@ $x=0.4$ times the patch length) yields almost no pattern difference, while the edges of the strip (@ $x=0$ and $x=L$) provide the largest pattern difference from the original, but ultimately the same field pattern. Similar discoveries for the –R+1/joC tuning scenario can be seen in Figs. 4 and 5, with the net effect being an attenuated version of the baseline field pattern.

![Figure 2: Magnitude of E-plane field patterns versus incident angle for designed patch antenna and 4 locations for tuned R+joL element.](image)

![Figure 3: Magnitude of H-plane field patterns versus incident angle for designed patch antenna and 4 locations for tuned R+joL element.](image)
scenario 1 and increasing in scenario 2. It is here that we can see some additional potential for tunable antenna elements beyond new and interesting field patterns: the ability to trim the dimensions of the implemented antenna and then compensate for it by tuning the “black box”.

Figure 4: Magnitude of E-plane field patterns versus incident angle for designed patch antenna and 4 locations for tuned -R+1/jωC element.

Figure 5: Magnitude of H-plane field patterns versus incident angle for designed patch antenna and 4 locations for tuned -R+1/jωC element.

The most interesting impact from relocating the tunable impedance element cannot actually be seen from the previous figures or discussion. Rather, it comes from investigating the resulting “tuned” input impedance. For example, in Figs. 2 through 5, when the tunable element is placed near the midpoint of the strip (x=0.4L), the resulting field pattern is the least effected. This makes sense since the patch impedance seen at the midpoint should be very close to zero and therefore disturbing at this location would not make much difference. Yet, when we evaluate the effective tuning impedance $Z_e$ (solving for disturbance given the original and tuned input impedances), we see the effect here is the greatest, $Z_e=410.11+j2107.6$ Ω vs. $Z_e=30+j190$ Ω for scenario 1 and $Z_e=-93.731-j1197.5$ Ω vs. $Z_e=-5-j100$ Ω for scenario 2.

This means that we can actually extend the tuning range of the “black box” by carefully selecting its location on the strip. Since scenarios 1 and 2 are our tuning value extremes, amplifying them adds to our tuning range at the sacrifice of tuning resolution. This extra capability is important if impedance matching (both for capacitive and resistive losses) is a design time concern in addition to pattern robustness.

4. IMPATT Diodes

To give this discussion some real-world credibility, we must discuss actual realizations of controlled impedance components. Several methods for tuning antenna elements have been proposed over the years, most notably the usage of varactors and/or specially-biased FETs [12]. These are often limited to positive resistance and capacitance (or inductance), require several tuning components, and tend to fall short for improving field pattern robustness.

The tuning range we have limited the “black box” to in this investigation is actually based in reality. These values have been achieved with the IMPATT diode [7,8], a promising method for achieving a range of impedance values through a single device. A DC bias, which should be well isolated from the RF signal, controls the avalanche frequency and hence the diode impedance. Fig. 6 shows the model for the IMPATT diode before and after the avalanche frequency.

Figure 6: Reactive part of IMPATT impedance as a function of frequency. Note the tuned avalanche frequency of the three distinct curves.

The impedance capabilities of the IMPATT diode range from $R+j\omega L$ to $-R+1/j\omega C$, as can be seen in Figs. 7 and 8. This means that when combined with a patch antenna, the field pattern can be tuned solely by the biasing of the
IMPATT diode and the required tuning range can be achieved by careful design of the diode dimensions. As discussed earlier, there are additional benefits to tunable impedance beyond modifying an antenna pattern. Resistive losses ($R_{\text{LOSS}}$) in an antenna can be compensated for by placing a negative $R_D$ component in parallel as long as $|R_D| > R_{\text{LOSS}}$. Also, in the case of the patch antenna, the total area on the top layer establishes a capacitance per unit length. Providing extra capacitance would allow for antennas with smaller areas while still maintaining a required total capacitance.

![Figure 7](image_url1)  
**Figure 7:** Reactive part of IMPATT impedance as a function of frequency. Note the tuned avalanche frequency of the three distinct curves.

![Figure 8](image_url2)  
**Figure 8:** Real part of IMPATT impedance as a function of frequency. Note the tuned avalanche frequency of the three distinct curves.

5. References


