Mini-Project #2: Yagi-Uda Antenna Design Using *EZNEC*

Introduction

There are many situations, such as in point-to-point communication, where highly directional antennas are very useful. Many types have been developed, but one of the most widely used is the Yagi-Uda array, named after the two Japanese engineers who first proposed it in the 1920s [1, 2]. As shown in Figure 1, a Yagi-Uda array (often shortened to just "yagi") consists of several parallel wires or metallic tubes approximately $\lambda/2$ in length. Only one element, called the *driven element*, is actually connected via a transmission line to a transmitter or receiver. The other elements interact with the driven element and each other via electromagnetic coupling to induce currents in them with specific phase relationships. The result is akin to an end-fire phased array with a high degree of directionality. The spacing between the elements is usually 0.1–0.3λ. Yagi antennas are very easy to construct and mount on masts or other support structures. They are also mechanically robust, so they are good choices for use in harsh environments. However, they can be difficult to design without the aid of modern antenna analysis software. In this min-project you will use the software package *EZNEC* to design a Yagi-Uda array. Later you will construct the antenna and measure its performance. The assigned project groups are listed at the end of this handout.

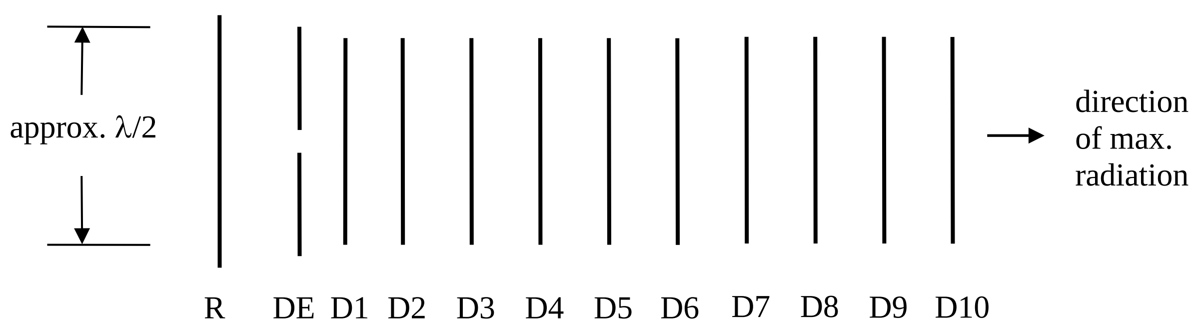

Figure 1. Geometry of a typical Yagi-Uda array. Although the array you will build has 12 elements, others can have as few as two or as many as 40 or more. The first element is a *reflector* (R); the second is a *driven element* (DE); and the remaining elements are *directors* (D1 through D10 in this example).

Theoretical Background

As shown in Figure 1, yagis have three different types of elements. One element is directly connected to a transmitter or receiver (or transceiver) via a transmission line. The currents along the other elements are induced by intercepted radiation coming from the driven element (transmitting case) or by an incoming plane wave (receiving case). This is usually referred to as *parasitic excitation*, and the non-driven elements are called *parasitic elements*, or *parasites*. The current distributions along the parasitic elements are approximately sinusoidal like that of the driven element. The yagi thus operates much like a phased array. The relative magnitudes and phases of the parasitic current distributions depend on the lengths of the elements, their distances from the driven element, and their proximity to the other elements in the array. If the dimensions are adjusted so that the element currents have just the right magnitudes and phases, the antenna will radiate most strongly (transmitting) or be most sensitive (receiving) in the direction along the axis of the antenna toward the directors. (That is why they are called "directors.") Like all reciprocal antennas, the radiation patterns for the transmitting and receiving cases are the same.

The reason only one reflector element is used is that the majority of the radiated field propagates away from the reflector (transmitting case). The directors are immersed in a stronger field and therefore have stronger currents induced in them than would any additional reflectors. Consequently, if one element is to be added to the antenna, it is almost always more advantageous to put it on the director side rather than on the reflector side if one reflector is already in place. A similar argument can be made for the receiving case. Extra reflectors are rarely added and only to handle unusual situations, such as to strongly suppress a troublesome back lobe.

Experience has shown that the overall length of a Yagi-Uda array is the most significant factor in determining its gain and that for a given length a sufficient number of elements should be used so that the spacing between the elements is on the order of 0.1–0.4λ. Shorter spacings are sometimes used for one or two elements near the driven element, usually in an attempt to control the input impedance. Spacings and element dimensions affect not only the gain of the antenna but also the input impedance, the impedance matching bandwidth, the gain bandwidth, and other important parameters. Thus, the design of this type of antenna can be a complicated optimization exercise involving interrelated and often conflicting constraints. Even though yagis have been in use for over nine decades, researchers continue to investigate their properties, develop more effective design procedures, and optimize them for specific applications.

<u>Experimental Procedure</u>

The tasks you will need to complete are listed below. Please note that the fabrication lead time for some of the antenna parts could be a week or more. The required deliverables are listed as bold-faced item numbers below. Scores will be quantized as indicated next to each item number. Items are due at the time(s) indicated on the Laboratory page at the course web site.

- Open the program *EZNEC*. It should be installed on all of the computers in Dana 307 and in the Maker-E but probably not anywhere else. If you are not already familiar with *EZNEC*, select "Contents" under the "Help" menu. This accesses the online manual. You may read as much of it as you wish, but you should begin with the sections entitled "Introduction to Modeling" and "Modeling with *EZNEC*" in the "Building the Model" chapter.

- Proceed to the "Test Drive" chapter. The four sections constitute a tutorial to help you learn the software. Work through as much or as little of the tutorial as you wish, but the more of it you complete, the better you will be able to take advantage of the program's features.

- The primary focus of this project is for your group to design a Yagi-Uda array that will allow you to receive programming from the Public Broadcasting System (PBS) television affiliate WVIA in Wilkes-Barre/Scranton, PA. The US Federal Communications Commission (FCC) has assigned physical channel 44, which spans 650–656 MHz, to the station. (WVIA's "virtual" channel is the same as the physical channel, which is not always the case; WVIA's virtual channel has always been 44, but it was assigned to physical channel 41, which spans 632–638 MHz, a few years ago.) ATSC television signals, the new digital TV standard in the United States, occupy roughly 6 MHz of bandwidth as did the old analog NTSC standard.

- Once you are ready to begin designing your array, set the following parameters in *EZNEC* to the indicated values. The default values for the other parameters should be okay.

Frequency: 653 MHz	Plot type: Azimuth
Ground Type: Free space	Elevation angle: 0°
Alt SWR Zo: 50 ohms	Step size: 1°

  Bring up the "Sources" window, and place a source on wire #2 (the DE) located 50% from the wire end. Make sure the "Type" is set to "V" (for voltage source) and the "Amplitude" to 1 V. The phase can remain at the default 0°. The type and amplitude of the source are not critical, but comparisons will be simpler if all project groups use the same specification.

- Enter into the "Wires" table the geometry of a 12-element Yagi-Uda array with the following initial dimensions and characteristics, which apply at 653 MHz: [CHANGE DIMENSIONS]

  - Element diameter: 3/16" (4.76 mm)
  - Reflector length: 220 mm, oriented parallel to *y*-axis, centered on *x*-axis
  - Driven element (DE) length: 202 mm, oriented along *y*-axis, centered on origin
  - First director length: 194 mm, parallel to *y*-axis, centered on *x*-axis
  - Director #2 through #10 lengths: all 192 mm, parallel to *y*-axis, centered on *x*-axis
  - DE-to-reflector spacing: 0.2λ (92 mm)
  - DE-to-first director spacing: 0.05λ (23 mm)
  - First-to-second director spacing: 0.25λ (115 mm)
  - Director spacing beyond second director: 0.3λ (137.7 mm)
  - No. of segments per element: any odd number between approx. 21 and 41
  - **Save the antenna description!**

  For this particular design it does not matter where the array as a whole is located relative to the origin, as long as the proper inter-element spacings are maintained and the element centers lie along the same line. However, you are being asked to use a common driven element location (at the origin) and element orientations (parallel to the *y*-axis and spaced along the *x*-axis) in order to facilitate design comparisons with those of other groups. If you wish, you may use a large number of segments per element in order to improve accuracy, but the number should be odd in order to place the feed point at the center of the driven element. The more segments you use, the slower the solution will be, although this is not be much of an issue with the lab computers. Accuracy will actually suffer if more than approximately 40 segments per half wavelength are specified since the matrix used to calculate the element currents becomes ill-conditioned under such circumstances.

- Click on the "FF Plot" button to plot the "azimuth" radiation pattern (i.e., gain vs. ϕ), and record the gain in the direction of maximum radiation. The pattern should be symmetrical, the gain should be very close to 13 dBi, and the first sidelobe level should be around 7 dB below the gain (ugly!). With the element orientations given above, the direction of maximum radiation should be in the $+x$ direction, which corresponds to $\phi = 0°$ and $\theta = 90°$ in the standard spherical coordinate system (in *EZNEC*'s sytem, "azimuth" = 0 and "elevation" = 0). Print out the radiation pattern for this first design iteration, and highlight the gain.

- Click on the "Src Dat" button to obtain the calculated input impedance as well as other information regarding the feed point. The input impedance should be close to 50 Ω with only a few ohms of reactance. The SWR (relative to 50 Ω) should therefore be close to 1. Historically, yagi antennas made with standard dipoles for the driven element had very low input impedances, typically in the 15-25 Ω range. However, recent research (see [3], for example) has shown that moving the first director very close to the driven element can raise the input impedance to 50 Ω or 75 Ω or even higher. With careful design it is possible to maintain a good impedance match over a wide bandwidth (5% or more). The closely spaced first director used in the WVIA yagi here is an example of this technique.

- Using "intelligent" trial-and-error (guided by trends noted by careful observation!), adjust the element lengths and perhaps some of the spacings to increase the gain, but keep the overall boom length at or under approximately 2.75λ (1.3 m) since there is limited space on the antenna's boom (central support structure). You should also maintain the input impedance at a value close to 50 Ω even though the standard impedance for television systems is 75 Ω. The specified value of 50 Ω is necessary because that is the impedance for which all of our test equipment is designed. There will be trade-offs between gain and input impedance, but you should be able to optimize both. The lengths of the elements closest to the DE will have the most effect on the input impedance. If you can, you might also try to obtain a pattern that has suppressed side lobes and attempt to keep the SWR well below 2 (even better, below 1.5) across the WVIA spectrum from 650 MHz to 656 MHz. If you run an SWR frequency sweep, be sure that the reference impedance Z_o is set to 50 Ω.

  The element length and spacing changes that you make should be very small, on the order of 1% or less per iteration. It helps to keep good records while you are doing this. None of the elements should be greater than approximately 0.55λ or less than approximately 0.38λ in length. Any element outside that range is not likely to significantly affect the performance of the antenna. To minimize the number of variables to optimize, you can use constant spacings for most of the directors, and groups of adjacent directors can have the same lengths.

  It should be possible to adjust the input impedance by tuning only the DE and first director lengths. You might also have to adjust the spacing slightly. Changes in the lengths of the DE and first director should have only a very minor effect on the gain (not enough to be considered significant). Thus, consider optimizing the gain first and then working on the impedance by adjusting the DE and first director.

  With a little effort you should be able to increase the gain by at least 2 dB above the initial unoptimized value. After you have optimized the gain, **save the antenna description**.

- Print out the azimuth radiation pattern plot for your optimized antenna. Also plot an "elevation" pattern (gain vs. "elevation" angle) for the appropriate azimuth angle so that the pattern cut includes the direction of maximum gain. The elevation angle in *EZNEC* is equal to $\theta - 90°$ in the standard spherical coordinate system; that is, the elevation angle is measured from the horizon, which in *EZNEC* is assumed to be in the $\theta = 90°$ plane. Think about why the elevation pattern does not look the same as the azimuth pattern.

- Click the "Src Dat" button in the main *EZNEC* window, and record the input impedance of your final design on one of the radiation pattern plots.

- Save a record of the element lengths and spacings using the Excel spreadsheet template available at the course Moodle site. The length data will be given to the Project Design Lab (PDL), where the technicians will manufacture the elements to your specifications.

  Item #1 [0, 10, 20, 30, 40%]: Hard copy of azimuth and elevation radiation patterns of unoptimized and optimized yagi antenna with input impedances indicated and copy of the *EZNEC* file for the optimized design.

  Item #2 [0, 5, 10, 15, 20%]: Hard copy of spreadsheet with element lengths and spacings.

- We will schedule times for assembling and testing your yagi around the obligations for your other courses. Instructions will be given as needed.

  Item #3 [0, 5, 10, 15, 20%]: Fully assembled yagi antenna.

  Item #4 [0, 5, 10, 15, 20%]: Plot of measured radiation pattern.

References

[1] H. Yagi, "Beam Transmission of Ultra-Short Waves," *Proceedings of the IRE*, vol. 16, pp. 715-740, June 1926.

[2] S. Uda and Y. Mushiake, *Yagi-Uda Antenna*, Saski Printing and Publishing Co., Ltd., Sendai, Japan, 1954.

[3] J. Breakall, "The Optimized Wideband Antenna (OWA) and Its Applications," *Proc. 12th Annual Review of Progress in Applied Computational Electromagnetics*, vol. 1, March 18-22, 1996, pp. 33-39.

Group Assignments

The assigned groups for this project are listed below:

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