The Yagi-Uda Antenna

Fig. 1. Shintaro Uda: (Courtesy of Library of Tohoku University, Sendai, Japan.)

The Inventor-Uda
Presentation Agenda

Part 1
• Introduction
• Motivation
• Description/Key Characteristics
• Qualitative Theory of Operation
• Conclusions

Part 2 (date TBD)
• Design Approaches
• Yagi Impedance
• Matching
• Conclusions

Presenter-Tom KJ6PST

Look For The bottom line
Introduction-The Yagi-Uda Antenna

• A Layman’s Curiosity For A Popular Ham Antenna
• Disclaimers
  – I’m an electrical engineer, but
  – I’m not an antenna engineer
    • Don’t use a Yagi, wish I could (HOA would not approve)
    • Have not analyzed or designed a Yagi
    • Have searched on-line publications as the basis for this presentation
“Tower of Yagi Arrays” on Preston Road

Yes, there are 6 Yagi antennas

This arrays owner should be presenting!
Introduction-A Few Yagi-Uda Antenna Uses

The Yagi Antenna has found a number of applications:

- Commercial Ham Tri-bander
- Military Search Radar
- Commercial Antenna often used by utility companies
- 1950 rooftop TV antenna
Some Commercial Ham Yagis

Cushcraft A3S Yagi

- **Model**: A3S
- **Frequency Ranges**: 28, 21, 14
- **Forward Gain, dBi**: 8
- **Front to Back Ratio, dB**: 25
- **2:1 Bandwidth KHz**: >500
- **Power Rating, Watts PEP**: 2000
- **3 dB Beam Width, Deg. E Plane**: 60
- **Boom Length**: 14 (4.27 ft)
- **Boom Diameter, In (cm)**: 1.5 (3.81 cm)
- **Longest Element, ft (m)**: 27.75 (8.45 m)

HyGain TH3-MK3

- **Electrical**:
  - **Gain (ave.)**: 5.8 dBd (8.0 dBi)
  - **Front-To-Back Ratio (max.)**: 25 dB
  - **Maximum Power**: 1500 Watts PEP
  - **VSWR at resonance**: Less than 1.5:1
  - **Input Impedance**: 50 ohms
  - **Matching System Beta (DC Ground)**

*Note key electrical characteristics: Directivity (Gain), F/B, SWR*

VSWR CURVES

These VSWR curves are typical for this antenna mounted between 30 and 100 feet above the ground. DO NOT TRY TO TUNE THIS ANTENNA FOR LOW VSWR AT GROUND LEVEL.

**Figure 9**

2:1 SWR BW~ 3-4%
Units Specifying Yagi “Gain” and F/B

- The dB = 10*log_{10}(P1/P2)
- If P1/P2=100, in dB, (P1/P2)dB = 20 dB
- If (PF/PB)= 25dB, then (PF/PB)=316, a ratio of power densities
- The directive gain of an isotropic antenna is 0dBi (i for isotropic)
- The directive gain of a dipole antenna is ~2.15dBi=dBd

An antenna’s directivity (gain) can be expressed in dBi or dBd

Ideal Dipole Antenna
Pmax= 1.65 (Po/4pi)
dBd=10*log ((1.65 Po/4pi)/(Po/4pi))
10log (1.65)=2.15dBi=dBd

Isotropic Antenna (theoretical)
power density, Po/4pi is equal at every point on the sphere
Po= antenna radiated power
Motivation

• MARC uses 20, 15 & 10 meter Yagis (mono-banders) for Field Day
• Yagi gain enhances opportunity for successful contacts
• Although widely used; operational principles sometimes vaguely understood

Presentation goal- to present basic Yagi operation and appreciate a remarkable antenna
The Yagi construction is elegantly simple— one driven element with one or more parasitic elements. The Yagi operation is simply complicated due to inter-element coupling.

The radiation pattern is determined by all element currents.
Yagi Key Characteristics

Primary

• Radiation Pattern
  – Directive Gain
  – Front-back Ratio
  – Sidelobes
• SWR Bandwidth

Secondary (Part II Presentation)

• Input Impedance (Driving point impedance)

Designers select the pattern characteristic that is most important to their operating requirements
How Does The Yagi Work?

- The driven element (DE) current radiates an electric field
- That field induces currents on the passive (parasitic) elements (reflector and directors) - mutual coupling
- **Those element currents in turn radiate fields**
- All parasitic fields combine by phase adjustment with the DE field to create the radiation pattern with a beam (constructive and destructive interference)

The Yagi element fields add as vectors to produce the array’s gain, F/B ratio and sidelobes
Yagi Radiation Pattern Illustration

What produces this pattern? - E-field Vector Addition

This pattern is the same for both Tx and Rx

Interfering signal

Desired signal

Main lobe acts like a “spatial filter”

Back lobe

Side lobes
What’s A Vector And Vector Addition?

Definition-A quantity with magnitude and direction. It can be represented by an arrow whose length indicates magnitude and whose tip represents direction.

Map coordinates

<table>
<thead>
<tr>
<th>Direction</th>
<th>Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>N (0° or 360°)</td>
<td>0°</td>
</tr>
<tr>
<td>E (90°)</td>
<td>90°</td>
</tr>
<tr>
<td>S (180°)</td>
<td>180°</td>
</tr>
<tr>
<td>W (270°)</td>
<td>270°</td>
</tr>
</tbody>
</table>

Roadmap Example

- $V_1 = 2E$
- $V_2 = .5E + 1N$
- $V_1 + V_2 = V_3 = 2.5E + 1N$
- $\delta \sim 70°$
- $\phi \sim 63°$

Vector Voltage coordinates

- $V_1 = V_2 + V_3$
- $V_2 = R^*i$
- $V_3 = jXl^*i$
- $V_1 = V_2 + V_3$

Circuit Voltage Example

- $V_1$, $V_2$, $V_3$
- $\phi$ indicates phase lag of current $i$ relative to $V_1$
- Assume $R = 2$, $Xl = 1$
- $V_2 = V_1 * (.8 - j.4)$
- $V_3 = V_1 * (.2 + j.4)$

Vector addition includes both magnitude and direction (phase)
What’s About E-field Vector Addition?

The phase, $\phi$, indicates that the vector magnitudes do not occur simultaneously just as we observed with the circuit voltages.

Here phase $\phi$ indicates relative direction or phase rotation between $E_1$ and $E_2$.

$$E_3 = E_1 + E_2$$

$$|E_3| = [E_1^2 + E_2^2 + 2E_1E_2\cos \phi]^{\frac{1}{2}}$$

See Casler, Vectors/phasors Nov. 2020 QST Page 34-37,

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E-field Example

E fields add as vectors
Vector Addition Phase Effect-Constructive/Destructive Interference

Phase angle indicates vector peak amplitude relationship
How Is A Beam Formed? 2-Driven Elements Example

A "beam’ is formed by constructive interference Its all in the phase
The Radiation Fields, $E_\theta$ & $H_\phi$ Of A Current Element

The electric field is proportional to element current amplitude and phase

$E_\theta = I_z \ast G(r, \phi, \theta)$

$E_\theta$ is directly proportional to the magnitude and phase of $I_z$.

$G(r, \phi, \theta)$ describes the radiation spatial pattern

Where $Iz = |I_z| \text{ang}(\psi)$, $\psi = \text{phase}$
Phase $\phi_1$ is the first design parameter to choose and vary.
The 2\textsuperscript{nd} Critical Phase, $\phi_2$, Varies With Element Length

The designer iteratively varies $\phi_1$ and $\phi_2$ to achieve the best compromise between gain, F/B ratio and sidelobes.

Director length, $L_2$
$L_2 < \lambda/2$
Port $Z_{22} = R + jX_c$, length dependent

$\phi_2 = \text{atan}(X_c/R)$

$I_2$ is produced by $V_2'$
$I_2 = V_2'/Z_{22} = -V_1'/Z_{22}$
$i_2 \sim \phi_1 + \phi_2$

$E_2$ is produced by $i_2$
Therefore, $E_2 \sim \phi_1 + \phi_2$
All mutual coupling must be included to determine the array element currents
Thiele’s Mutual Coupling Analysis Determined All Parasitic Element Current Amplitudes and Phases

DE

Director spacing = 0.33 \lambda

The DE current amplitude is the largest, the director current amplitudes are approximately equal. All the currents produce E fields resulting in the radiation pattern (vector addition)
The Maximum Radiated E Field Is Limited By Each Director’s Phase, Vector Addition

Note: Because each director’s E field has a different phase, the array’s max E field is less than the ideal (all in phase)!
Element Field Vector Phases Produce The F/B Ratio Example

\[ \text{Eb} = \text{Er} + \text{Ede} + \text{Edir} \]

\[ \text{Ef} = \text{Er} + \text{Ede} + \text{Edir} \]

\[ \text{F/B} \sim \frac{|\text{Ef}|^2}{|\text{Eb}|^2} \]

The element electric field vector phases are key to make \( \text{Ef} > \text{Eb} \)
Conclusions-Part 1

• The Yagi Array:
  – Provides gain with 1 driven element and several parasitic elements
  – Relies on judicious element-element spacing and element length-directly affects E-field phase
  – Pattern is a result of E-field vector addition
  – Has a “beam” radiation pattern that provides spatial filtering;
  – Is relatively simple to construct- only 1 driven element

• The Yagi performance:
  – Is based on complex inter-element coupling
  – Depends upon element length and inter-element spacing
  – Depends on the choices of the critical phases (\(\phi_1\) & \(\phi_2\))

Bottom line: It is a winner
References

3. “Yagi Antenna/ Yagi-Uda Aerial”
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8. Wortman, Bill, N6MW, “ The Hairpin Match”
9. vu2nsb.com/antenna/yagi-antennas/
10. ARRL Antenna Handbook