# Security of Wireless Networks
# Cantenna Exercise

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**Abstract**

The goal of this lab was to design a directional antenna with a high gain. This report discusses our experiences and findings from experiments with Yagi-Uda antennas.

## 1 Introduction

The task of this exercise was to build a high-gain, directional antenna for WiFi frequencies (2.4-2.5 GHz). We chose to build a Yagi-Uda antenna (named after its inventors Hidetsugu Yagi and Shintaro Uda), because this design allows both good directivity and a high gain, and we expected it to be reasonably simple to build.

A disadvantage of the Yagi antenna is however, that its bandwidth is rather limited. Since we want a frequency range of 2.4 to 2.5 GHz, we have a bandwidth ratio of 1:24.5 (ratio of bandwidth to center frequency). On the other hand, a small bandwidth can of course also be seen as an advantage, as it limits out-of band interference to a minimum.

### 1.1 Acknowledgements

We would like to thank Michael Lerjen from the CTL for kindly helping us with measurements, as well as with antenna theory, and for generously allowing us to use the CTLs lab equipment.

## 2 Theory

The typical Yagi antenna consists of one driven element, one reflector and several directors, as seen in Figure 1.

### 2.1 Driven Element

For the driven element either a simple dipole is used, or a folded dipole. This dipole is the only actively driven element. It consists of two align conductors of length approximately $\lambda/4$ (i.e. a dipole). One is connected to the shield of the coax cable and the other to the signal.

To achieve good resonance, the length of the dipole element, must be one half of the wavelength. It is therefore determined by the frequency the antenna should work on. For our frequency of $f = 2.45\,\text{GHz}$ the

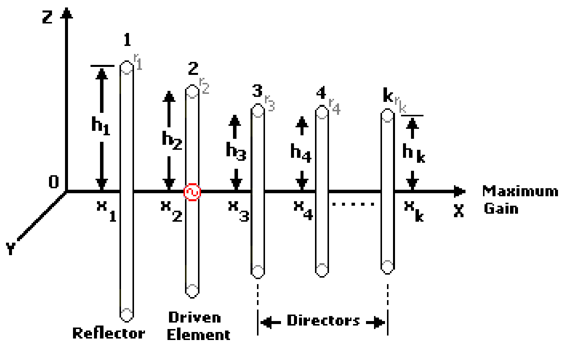



Figure 1: Yagi antenna with $k$ directors [2].

wavelength is $\lambda = \frac{c}{f} = 122.4\,\mathrm{mm}$. This yields a length of the dipole element of 61.18 mm.

In the experimentally found designs, this length is usually somewhat lower. This is because of the matching of the antenna to the coax cable, which is a very important point. A poor matching results in a high reflection coefficient and therefore in bad performance, because a big fraction of the power is reflected back into the WiFi card, instead of being transmitted into the air. Therefore it is easily possible to build an antenna which is far worse than no antenna at all. This is important especially for the transmitting mode (in reception mode, a poorly matched antenna loses both signal and noise power, which is loss of a problem).

In Figure 2 the input impedance of a dipole can be seen. For the optimal $\lambda/2$, both the real and imaginary part are not near the required $50\Omega$. Therefore one chooses the point where the imaginary axis crosses zero, which is at approximately $0.47\lambda$. At this point the real part will be around $60\Omega$, which is not too bad.

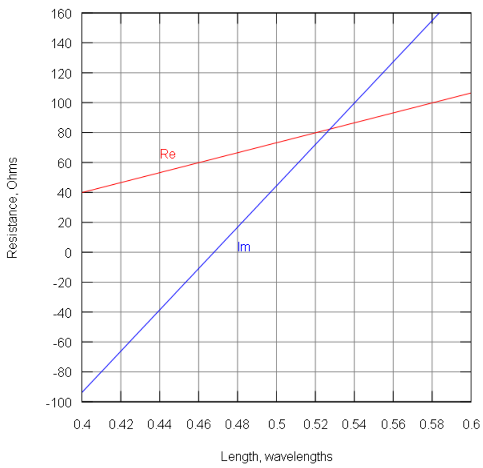



Figure 2: Impedance of a dipole [7].

## 2.2 Directors

The directors are used to make the antenna directional. They are excited by the field of the driving element and produce fields of their own, which are phase-shifted to the dipole. The phase-shift is determined by the elements length and position on the boom.

The far-field of the antenna is a superposition of all elements contributions. In the direction of the boom there is a constructive interference of the different fields, whereas in the direction perpendicular to the boom, the interference is destructive. Of course this destructive interference is not perfect and there will always be some minor side lobes, but nevertheless a good directionality is achieved.

The spacing of the director elements influences the bandwidth of the antenna. For equally spaced elements of equal length, the gain may be better, but only at a very small frequency band. Varying both, the lengths and the spacings, makes the bandwidth larger and the antenna more usable. Good results are achieved by continuously increasing the spacings by a constant factor and decreasing the lengths by another factor.

## 2.3 Reflector

The reflector element is placed on the opposite side of the dipole. Compared to the dipole it has a lower resonant frequency and is therefore longer. The function of the reflector is to produced a wave, which cancels the backward wave from the dipole by destructive interference [3]. This leads to a radiation pattern with very little power being transmitted backwards.

# 3 Design

There are no simple formulas to calculate the Yagi antenna in an analytical way. Most designs, like for example the ones proposed after extensive research by the National Bureau of Standards (NBS) [6], use an experimental approach by continuously optimizing the element lengths and spacings.

For our design, we used the values provided by a JavaScript Yagi Calculation Application [5]. For the center frequency of our antenna we chose 2.45 GHz. This corresponds approximately to the wireless channels 8 and 9 (see [1] for channel frequencies). The lengths suggested by this application are listed in Table 1.

One problem with Yagi antennas at such high frequencies is the required accuracy of all element dimensions. The JavaScript application specifies a minimum accuracy of 0.4 mm. For the lengths this can be achieved by precise cutting and grinding. But to position them with such accuracy on the boom is nearly impossible using hot glue.

Because of this and because most Yagi antennas need to be tweaked manually, we chose a design which would allow us to move the different elements along the boom. With this construction we would not only be able to position the elements very precisely, but also test different spacings and check out what happens, if certain elements are removed from the boom.

| | Position | Length |
|---|---|---|
| Reflector | 0 | 57.8 |
| Dipole | 24.47 | 54.68 |
| D1 | 33.65 | 47.03 |
| D2 | 55.68 | 45.98 |
| D3 | 81.98 | 45.00 |
| D4 | 112.58 | 44.13 |
| D5 | 146.84 | 43.38 |
| D6 | 183.55 | 42.74 |
| D7 | 222.09 | 42.18 |
| D8 | 262.47 | 41.7 |
| D9 | 304.69 | 41.28 |

Table 1: Element lengths and positions (dimensions in mm).

# 4 Construction

Our goals for the construction of the Yagi-Uda antenna were the following ones:

- Low cost – it should be possible to build our antenna from cheap, off-the-shelf parts.
- Non-metallic material only – although Yagi antennas can be built using metal parts (e.g. a metal boom), the metal makes the theoretic considerations more complex and great care has to be taken not to influence the antenna performance.
- Adjustable element position – as Yagi antennas usually have to be tuned manually, we must be able to adjust the position of our reflector and the director elements on the boom.

After looking at different parts available at a local hardware store, we chose the following list of materials:

- 16 mm diameter wood rod for the boom
- Plastic pipe clamps to fix the elements on the boom
- 2.5 mm diameter copper wire for the dipole, the reflector and the directors
- Hot glue to mount the elements onto the pipe clamps

As we were uncertain, whether rigid Aluminium sticks (with a diameter of 3mm) might be better suited as director and reflectors, we chose to build a second antenna, with this option.

In total, the cost of the material for one antenna sums up to about CHF 20.00, which was well within our budget.

For the connection, we soldered the coax cable directly to the dipole, connecting ground to one dipole element, and the center wire to the other.

# 5 Measurements

## 5.1 Values of Interest

For our measurements, we were mainly interested in the gain (ratio of power per surface area radiated by our antenna along the direction of maximum radiation compared to the power radiated by a dipole antenna for the same surface area [dBd]) and directivity (relative dependence of the radiated power on the radiation direction). More elaborate explanations of gain and directivity can be found in [4].

## 5.2 Expected Gain

The JavaScript application mentioned in Section 3 suggested a gain of approximately 11.8 dBd.

## 5.3 Practical Results

### 5.3.1 First Test

As a first test, we connected our antenna to a laptop at ETH and observed the signal strength reported by the wireless card. Comparing the signal strength to the signal strengths of internal antenna showed no gain at all, even though we were able to see some additional Access Points (APs). We assume, that the antenna actually did have some directivity and gain, but the gain was likely lost again, due to bad impedance matching and/or connector losses. This might result in a signal strength similar to the internal antenna, but the Signal to Noise Ratio (SNR) would still be better, as we receive noise and interference only from one direction.

It should also be noted, that the signal strengths reported by the card are likely to be inaccurate, and the interference from other access points, clients and reflections further worsens the quality of our results.

## 5.4 Analysis with a Vector Network Analyzer

The analysis of the antenna with copper wire elements with a Vector Network Analyzer (VNA) showed an impedance of about $31 - i15\Omega$ and an Standing Wave Ratio (SWR) of about 2, which is quite bad. Michael pointed us towards the problem, that the feed line is asymmetric, whereas the driving element (dipole) is symmetric. By using a balun and adjusting the length of the dipole, we managed to increase the impedance to about $44 - i22\Omega$, which results in an SWR of about 1.7. While this is still quite bad, we were able to improve the impedance of the antenna with aluminium elements to about y. As this was our best result, we continued our measurements with this antenna.

## 5.5 Analysis of the Gain

To measure the gain of the tuned antenna, we attached our antenna to a signal generator (which was tuned to 2.43 GHz, as the VNA showed the best SWR, about 1.1, at this frequency), and pointed it towards a dipole antenna connected to a Spectrum Analyzer (SA) located in a distance of 4m (as the wavelength is about 12cm, this is well within the far-field region). The spectrum analyzer showed a received signal strength of about $-47$ dBm $\ldots -45$ dBm. Using the same setup with a off-the-shelf commercial dipole on both ends yielded a received signal strength of about $-70$ dBm $\ldots -65$ dBm. From this, we conclude, that our antenna has a gain of about 20 dBd, which is quite surprising, as it is well above the predictions of the JavaScript application.

It was also interesting to note, that a mismatch in the polarization leads to a considerable drop in the received signal strength ($> 10$ dB).

## 5.6 Radiation Pattern

To determine the radiation pattern (in the plane perpendicular to the element direction), we placed the antenna at a distance of 4 meters to a dipole, sent a 2.43 GHz signal from a signal generator through the Yagi, and measured the received signal strengths with a spectrum analyzer. The results are given in Table 2.

| Angle | 0 | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 |
|---|---|---|---|---|---|---|---|---|---|
| Signal strength [dBm] | -45 | -46 | -49 | -56 | -61 | -63 | -65 | -70 | -78 |

| Angle | 90 | 100 | 110 | 120 | 130 | 140 | 150 | 160 | 170 |
|---|---|---|---|---|---|---|---|---|---|
| Signal strength [dBm] | -61 | -60 | -76 | -72 | -74 | -65 | -63 | -61 | -63 |

| Angle | 180 | 190 | 200 | 210 | 220 | 230 | 240 | 250 | 260 |
|---|---|---|---|---|---|---|---|---|---|
| Signal strength [dBm] | -73 | -68 | -69 | -85 | -75 | -67 | -67 | -66 | -68 |

| Angle | 270 | 280 | 290 | 300 | 310 | 320 | 330 | 340 | 350 |
|---|---|---|---|---|---|---|---|---|---|
| Signal strength [dBm] | -62 | -59 | -66 | -62 | -62 | -58 | -50 | -48 | -47 |

Table 2: Measured angle dependent signal strengths.

As the reference dipole yielded a signal strength of approximately $-70\,\mathrm{dBm}$, this results in the radiation pattern shown in Figure 3. Although the measurements were done indoors, and there were many possible reflectors nearby, the main lobe can be nicely seen at an angle of 0 degrees.

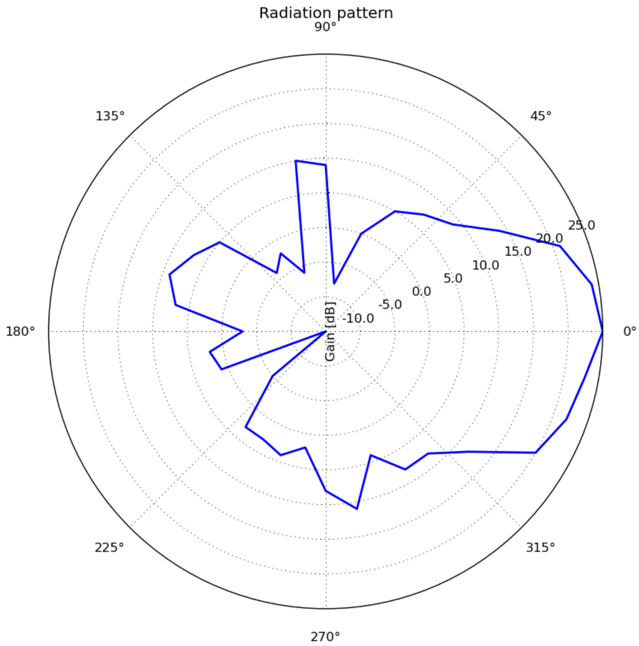



Figure 3: Radiation pattern of our Yagi antenna.

## 5.7 Practical Results with a WiFi Card

Once our antenna was tuned and working, we again attached it to a wireless card and a laptop. Directed towards Zurich for about an hour, with Kismet continually running, we discovered more than 500 networks.

One access point, which stuck out, was named "UtoKulm". This is the name of a hotel on Zurich's Üetliberg. As the direction, in which we discovered this access point was appropriate, and the corresponding signal strength was about 30 dB smaller than the signal strength of the strongest access points, we assume that this access point actually belongs to the Uto Kulm hotel, which, according to Google Earth, is located at a distance from the ETH of about 5.5 km air line(!). We find this particularly amazing, as there was an access point directly behind our antenna, on the wall across the room, which generated interference from a distance of approximately 5m.

As Kismet dumps the collected data also in CSV format, we can easily extract some interesting statistics, e.g.:

- Number of access points per channel:

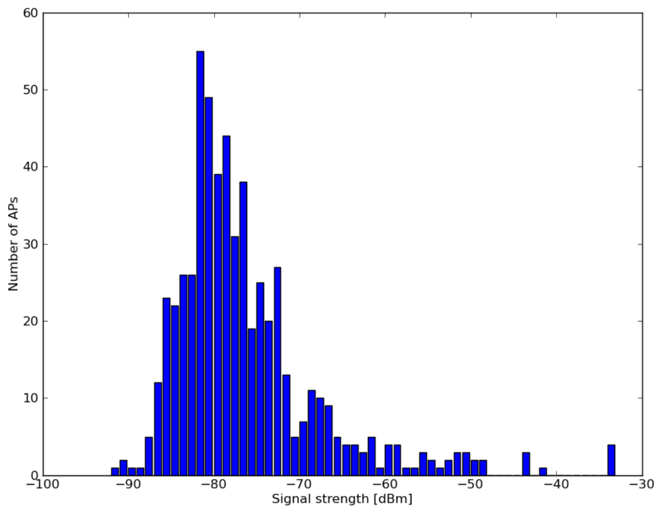
| Chan. | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| APs | 29 | 158 | 1 | 14 | 6 | 6 | 209 | 9 | 6 | 8 | 5 | 122 | 3 | 3 |

  (It should be noted, that the card was locked to channel 6 for a considerable amount of time.)

- Number of unencrypted, encrypted (WEP) and encrypted (WPA) access points:

| Unencrypted | WEP only | WPA | Total |
|---|---|---|---|
| 171 | 129 | 279 | 579 |

- Number of APs found for a given signal strength:



# 6 Conclusions

Although the Yagi-Uda antenna looks rather simple, building a working antenna proved to be quite a demanding task. We found good element spacings only via experimentation, and with the professional equipment at the CTL. Without this, we might not have been able to get our antenna to work. Once we found good spacings, we however had a lot of fun with our antenna, and we got a good gain and directivity.

# A Acronyms

**AP** Access Point

**NBS** National Bureau of Standards

**SA** Spectrum Analyzer

**SNR** Signal to Noise Ratio

**SWR** Standing Wave Ratio

**VNA** Vector Network Analyzer

**WEP** Wired Equivalent Privacy

**WPA** WiFi Protected Access

# References


[1] 802.11b channel-to-frequency mappings. Available at http://www.qsl.net/n9zia/dsss-channels.html.

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