Introduction to Wireless / Wi-Fi
SANOG 43 Tutorial

Network Startup Resource Center
www.ws.nsrc.org

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NSRC Network Startup Resource Center

Introductory remarks

After 25 years of Wi-Fi, we are hardly introducing something completely new

Both cellular and satellite connectivity might seem more attractive today (?)
However, on a closer look,

Wi-Fi is still relevant - and even more so than 20 years ago

This talk will try to give a very concise walk through some of the basics,

sacrificing a thorough systematic approach in favor of

Discussion of some of the topics and FAQs that come up repeatedly.

Agenda

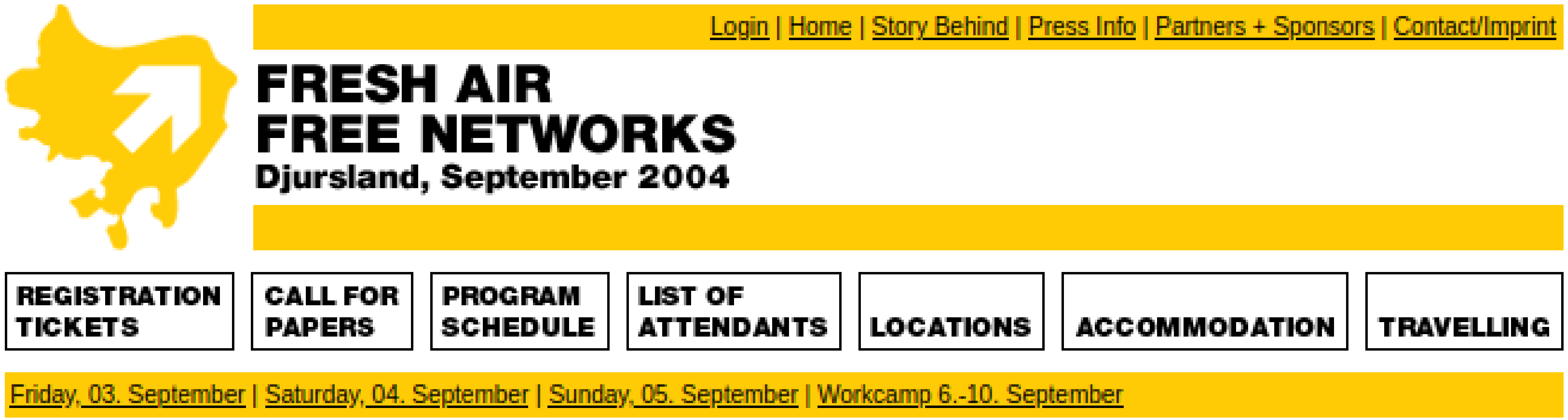
- A bit of my personal Wi-Fi journey
- A little bit of physics: waves, spectrum, propagation
- Wi-Fi standards
- Link Budgets, power, signals
- Antennas
- A wireless cookbook/checklist, step by step
- Some returnings FAQs & discussions

Wi-Fi Journey

- 1998 – Wi-Fi links Denmark-Sweden, “frying seagulls”
  - 20 km, with amplifier
- 2000 – my good friend Tomas Krag helps Wi-Fi ISP in Ghana
  - “this is it! Wi-Fi as infrastructure and community network”
- 2004 – we invite 50 community networkers from 30+ countries to Denmark / Djursland summit
- 2005 – we launch pan-african wireless workshop series
- 2005 – the green book https://wndw.net

2004 Community Summit: Fresh Air Free Networks

- Freifunk Berlin
- consume.net London
- wire.less.dk
- + 35 countries, 50 people
  - Incl Nepal (via video link), India, Africa, South America



Africa Workshop series

- APC, IDRC

Africa Workshop series

- APC, IDRC
  - Tanzania, South Africa, Morocco, Ghana, Kenya, Mozambique

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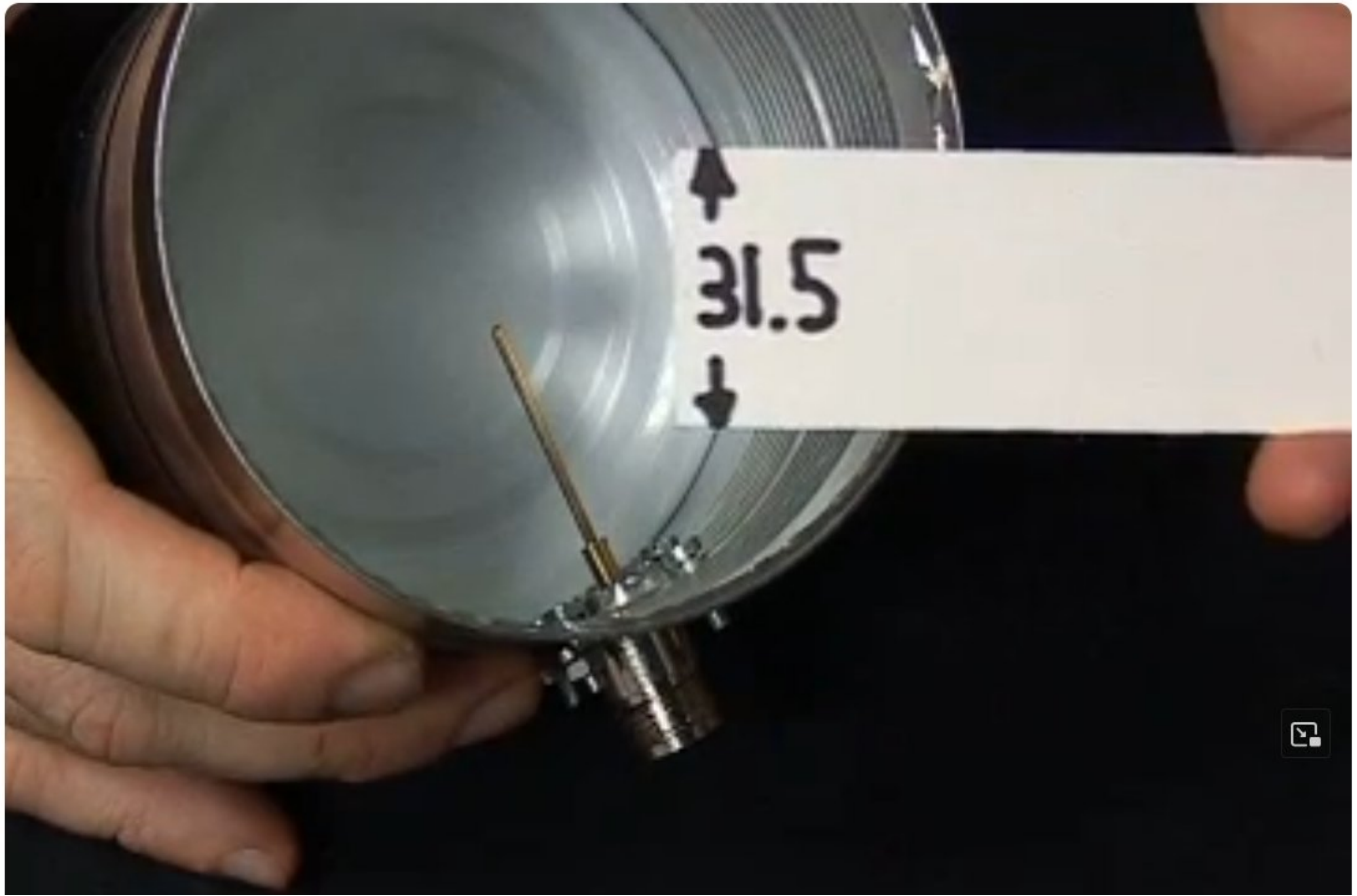
Zanzibar Workshop 2005

- https://www.youtube.com/watch?v=rhzkMIHcS9I

Workshop of Zanzibar

DIY Antennas: Cantenna 2005

- https://www.youtube.com/watch?v=prTKZXoTLgQ



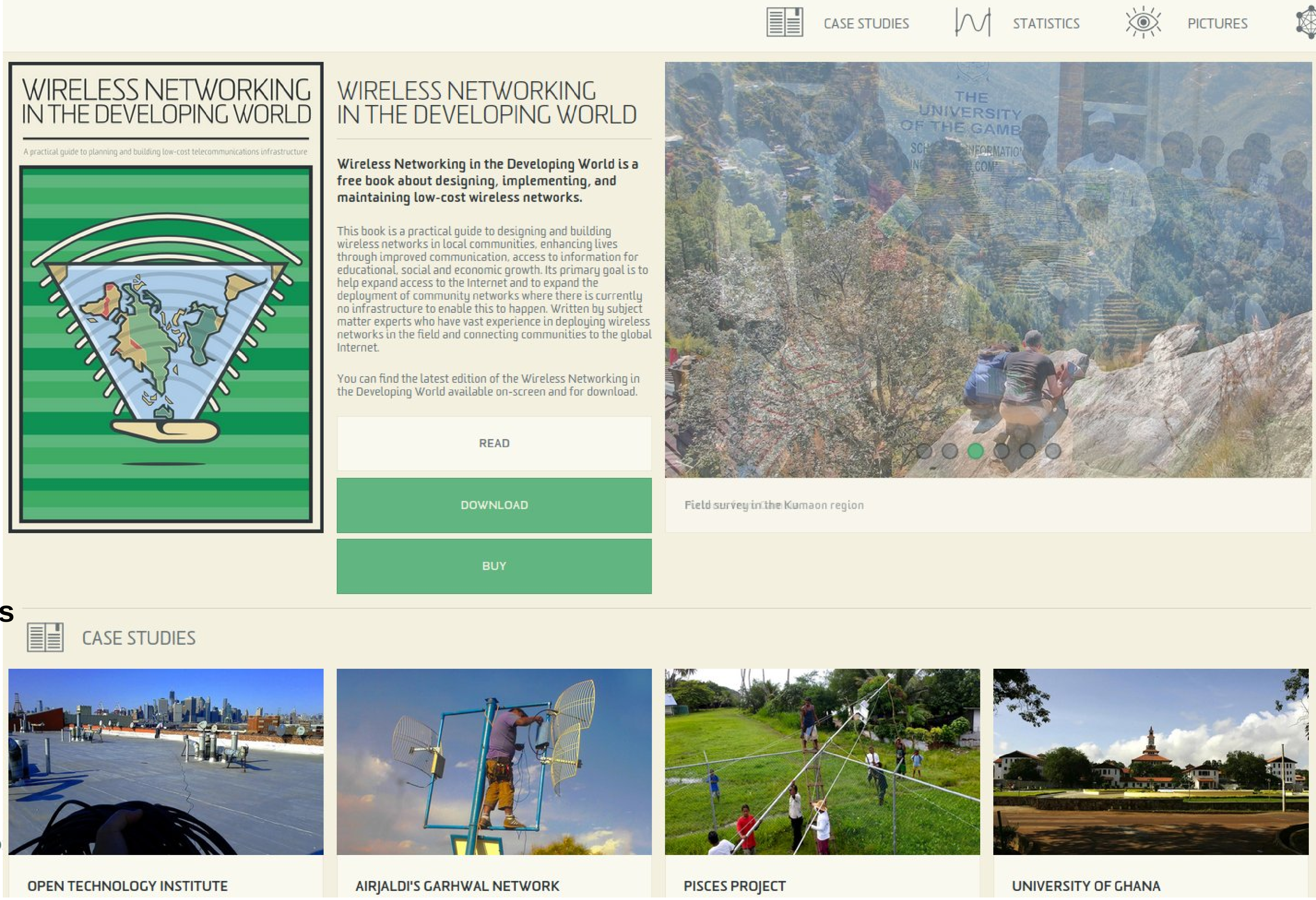
The Green Book

Wireless Networking in the Developing World

https://wndw.net

4 editions
6 languages
3 million downloads

Still valid, still useful!



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Physics

"Wireless" = Electromagnetic waves –
Electromagnetic fields that oscillate and travel in space.

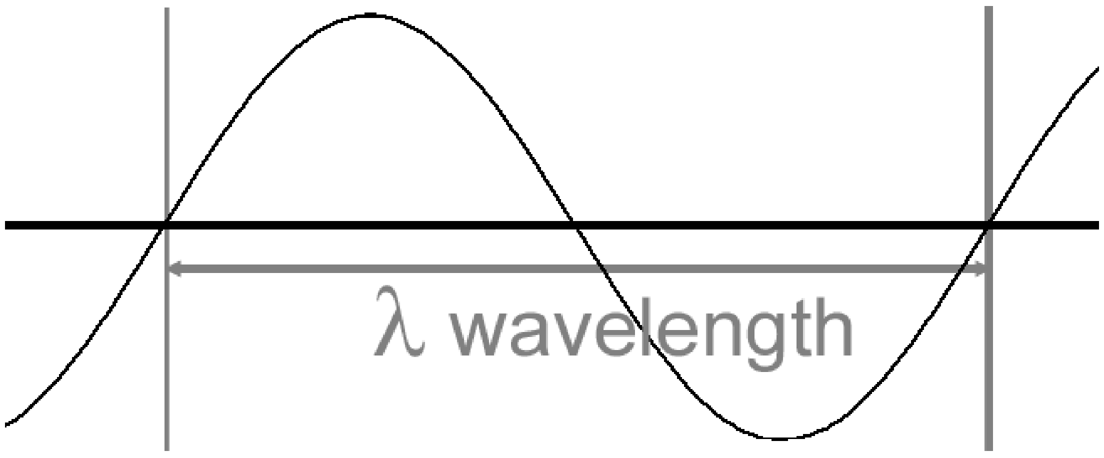
They have a speed, a frequency, a wavelength:

$$c = \lambda * \nu$$

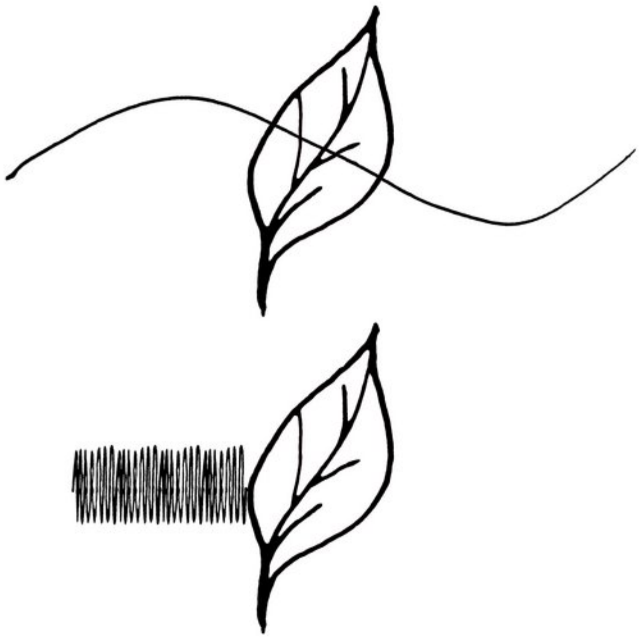
c is the speed of light (in vacuum) 3×10^8 m/s
λ Lambda is the wavelength [m]
ν Nu is the frequency [1/s = Hz] (more often you will find it called **f**)

Wavelength

$c = \lambda * \nu$



All radio behaviour scales with wavelength!



2.4 GHz – 12 cm
5 GHz – 6 cm
868 MHz – 34.5 cm

Electromagnetic waves

Mechanical waves – like sound, waves in water - require a physical medium to transport them.

Electromagnetic waves do not – they are the “dance without a dancer”.

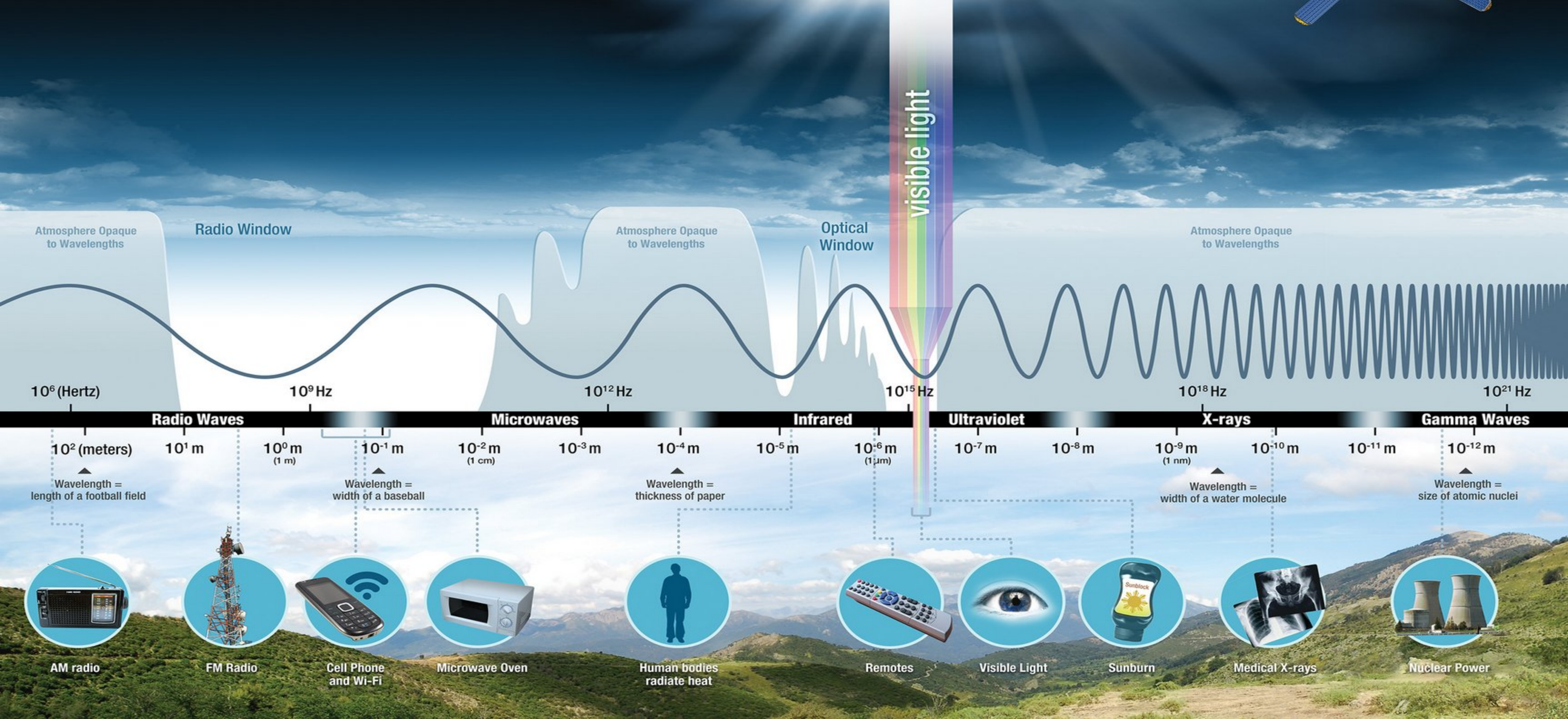
They can travel through vacuum and through physical medium

(but very dependent on what that medium is!)

Examples: Light, Radio, Infrared, X-Ray, Gamma Ray

Electromagnetic spectrum

source: NASA, public domain



Terms – sometimes confusing

• **radio**	30 Hz to 300 GHz
• microwave	300 MHz to 300 GHz
• VHF	30 MHz to 300 MHz
• UHF	300 MHz to 3 GHz
• S-Band	2 GHz to 4 GHz

It's all wireless … and we can call it all **radio.**

Simple rules for wavelength & frequency

Higher frequency – shorter wavelength

More bandwidth available → higher data rate possible → "more data"
Shorter range, less good in going through or around things
Need LOS (Line of sight)

Lower frequency – longer wavelength

Less bandwidth → lower data rate → "less data"
Longer range, better in going through and around things
Better suited for NLOS (non Line of Sight)

Waves

Waves do not move in straight lines.
Any point in a wavefront

is the origin of a new wave (Huygens' principle).

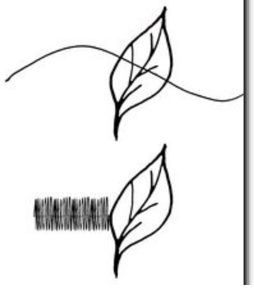
Even light does this – just difficult to see,

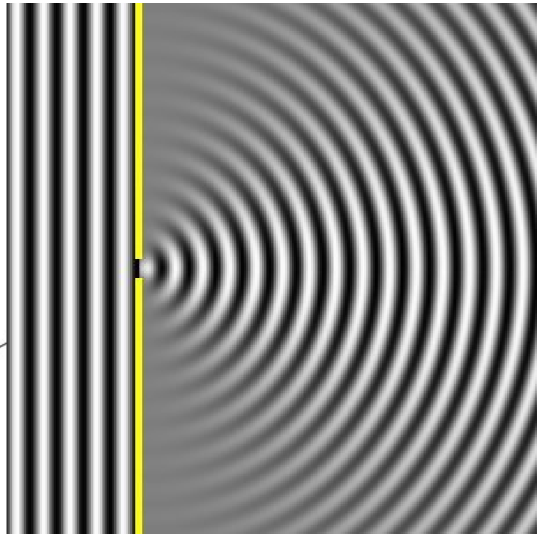
as

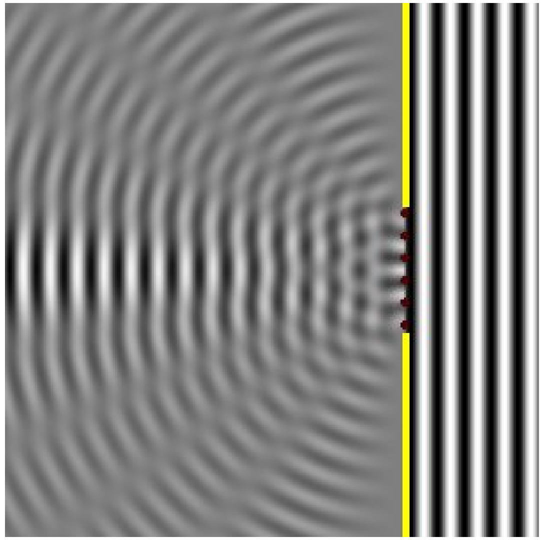
behaviour

scales with

wavelength.







Visualization – think of light

Many ways to visualize wireless -

Imagine it to be a form of light

that is

a little more soft and ‘flexible’ -

Shadows are not so sharp,

Light rays a bit wider,

And it goes through things (a bit)

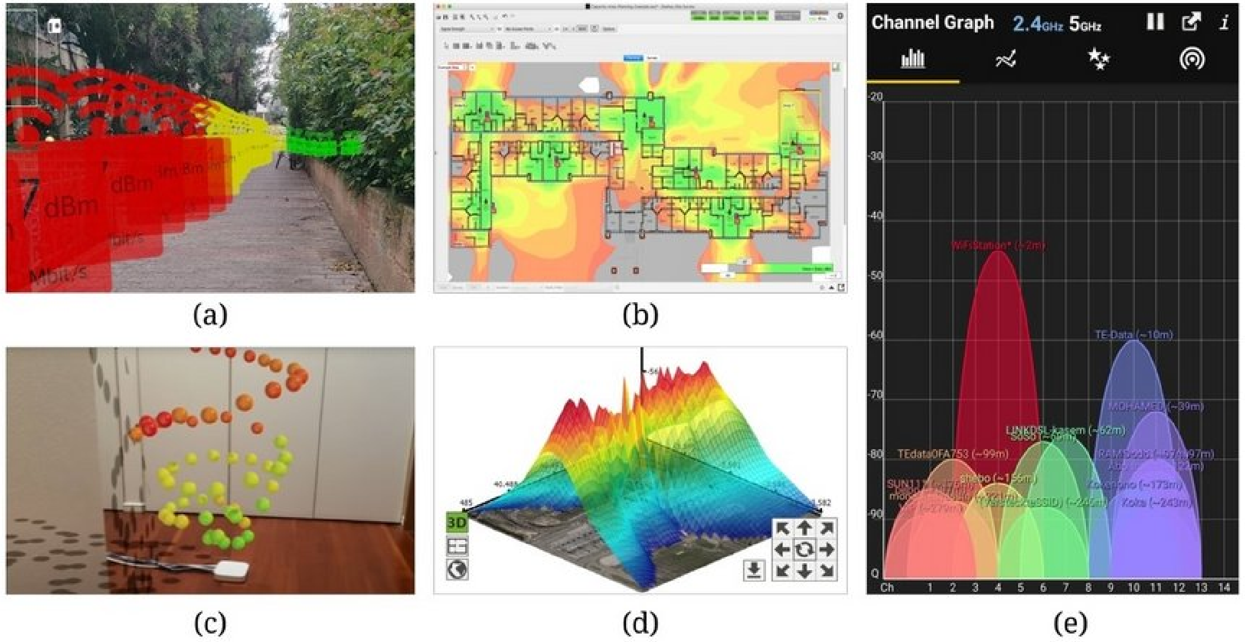


Figure 2: The current state of the art in WiFi visualization tools. Each image represents a commercial application for visualizing WiFi Signal Strength. *a)* WiFi AR [46] is an Android app that uses a color-coded data glyph to represent sample points. *b)* Ekahau Survey [9] is a heatmap-based visualization product for MAC OS. *c)* AR Sensor [19] is a basic glyph visualization that uses colored spheres to represent signal strength. *d)* Acrylic Wi-Fi Heatmaps [40] uses a heatmap that dual encodes height. *e)* WiFi Analyzer [29] is a simple channel graph visualization that uses simplified shapes to bin signals by frequency to make reading the spectrum easier and help visualize channel congestion. None of these visualizations can represent multiple networks while maintaining a sense of the environment.

Radio propagation

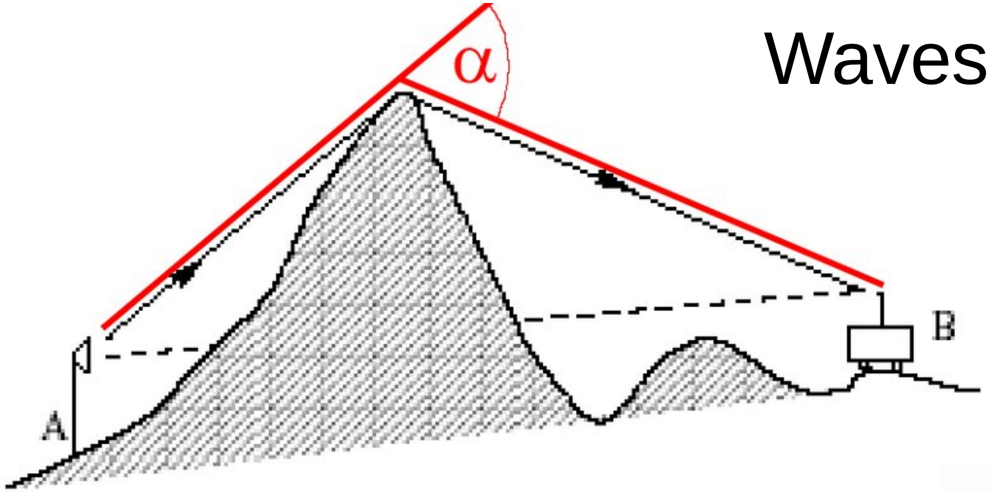
Absorption

Wave gets weaker in material because it interacts with it

Strongest absorption in **metal, water – those are our two main enemies.**
Dry materials (buildings, vegetation) are somewhat transparent.
The question “how much will it absorb?” is impossible to answer – measure!
Watch out for unexpected materials – e.g. discuss windows!

Radio propagation

Diffraction

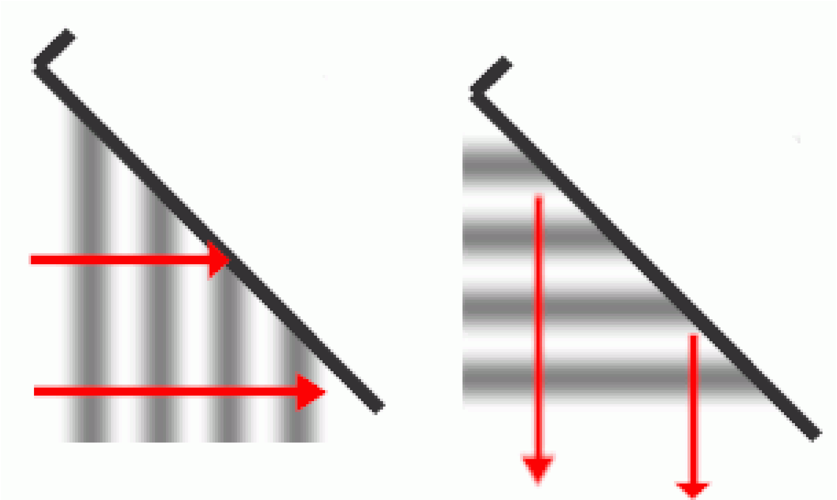


Waves go “around corners”, to some extent

(because of the Huygens’ principle)

Reflection

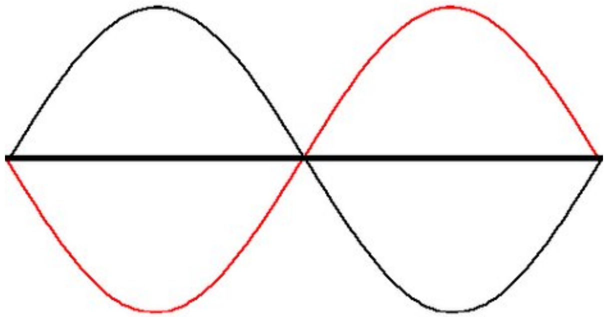
(think what a parabole dish does)



Interference

Many ways of using the term:

Physicist sees this: two waves with same frequency and fixed phase relation



Engineer – probably means

any kind of noise related interaction with “other signals”

Interference, continued

Your average Wi-Fi user probably uses the term Interference for any problem that they can’t assign to anything else :)

90% of all Wi-Fi probs assigned to Interference are really something else.

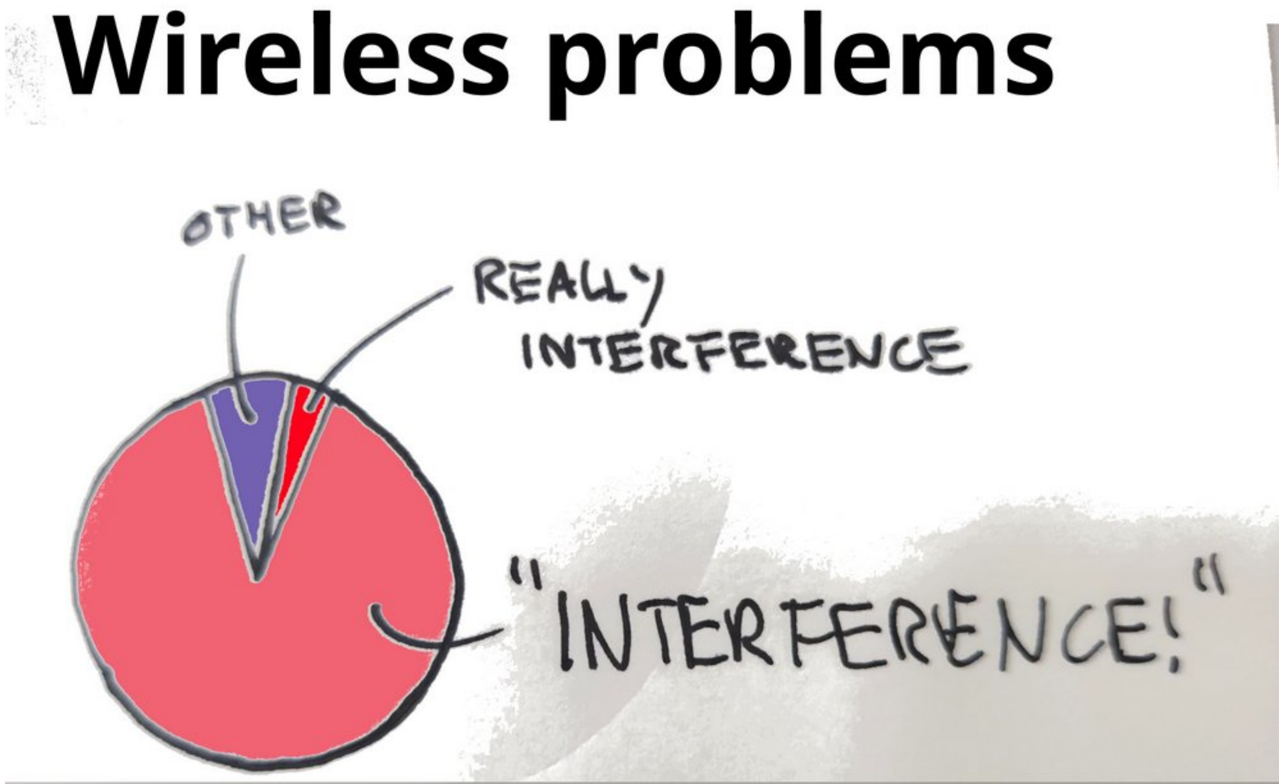
How to tell?

Layer thinking & proper tools –

Layer 1: spectrum analyzers,

Layer 2: Wi-fi scanners

Layer 3+: General TCP/IP tools



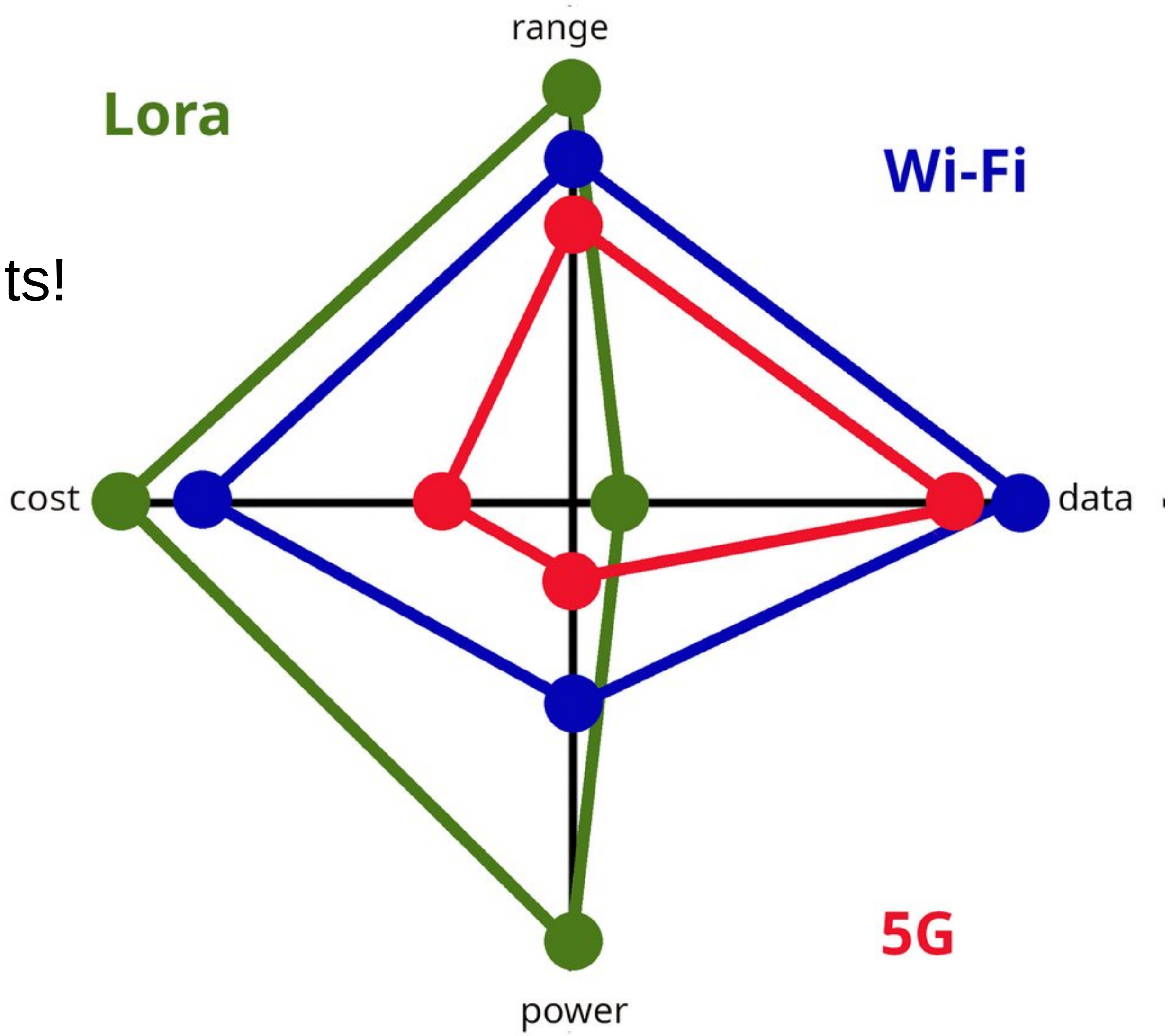
Wireless for communication

- Many options, many frequencies
  - Wi-Fi, mobile/cellular, satellite, ...
- Decision based on requirements such as
  - range
  - power consumption
  - data throughput
  - cost
- For campus and community, choice almost always Wi-Fi
  - One main reason: license-exempt (“free”) ISM frequencies

Wireless for communication

You can't have all!
Trade-offs!

Know your requirements!



Overview 802.11 Standards

IEEE Standard	Generation	Year	Representative Use Cases	Key Features	Peak Rate
802.11b	—	1999	Basic broadband: email, browsing, file sharing (home/small office)	2.4 GHz, DSSS	11 Mbps
802.11a	—	1999	Faster enterprise connections, early media streaming	5 GHz, OFDM	54 Mbps
802.11g	—	2003	Home media, consumer electronics integration	2.4 GHz, OFDM, backward compatible with 802.11b	54 Mbps
802.11n High Throughput (HT)	Wi-Fi 4	2009	HD video, cloud access, multi-device homes	Up to 40 MHz channels, packet aggregation, MIMO (up to 4×4)	600 Mbps
802.11ac Very High Throughput (VHT)	Wi-Fi 5	2013	4K video, online gaming, mobile offload, enterprise WLANs	Up to 160 MHz channels, DL MU-MIMO (up to 4×4), 256-QAM	6.9 Gbps
802.11ax high-efficiency (HE)	Wi-Fi 6/6E	2021	Dense deployments (stadiums, campuses), IoT, teleconferencing	DL/UL OFDMA and MU-MIMO (up to 8×8), 1024-QAM, spatial reuse, TWT, 6 GHz band	9.6 Gbps
802.11be extremely-high throughput (EHT)	Wi-Fi 7	2024	8K video, real-time collaboration, cloud gaming, AR/VR, IIoT pilot	Up to 320 MHz channels, 4096-QAM, MLO, multi-RU, enhanced QoS	23 Gbps
802.11bn ultra-high reliability (UHR)	Wi-Fi 8	2028+	Robotic surgery prep, industrial automation, holography, ultra-reliable closed control loops	ELR PPDU, distributed-RU, LDPC enhancements, unequal modulation, seamless roaming, dynamic power save, NPCA, DSO, MAPC	TBD

Source: Geraci, Giovanni, et al. "Wi-Fi: Twenty-Five Years and Counting." arXiv preprint arXiv:2507.09613(2025).

Feature	Wi-Fi 4	Wi-Fi 5	Wi-Fi 6	Wi-Fi 7	Wi-Fi 8
Maximum Channel Bandwidth (MHz)	40	160	160	320	320
Frequency Bands (GHz)	2.4 and 5	5	2.4, 5 and 6	2.4, 5 and 6	2.4, 5 and 6
Max PHY rate	150Mbps * 4 600Mbps	433Mbps * 8 ~4.3Gbps	1200Mbps * 8 ~9.6Gbps	2880Mbps*8 ~23Gbps1	2880Mbps * 8 ~23Gbps
Modulation	64 QAM	256 QAM	1024 QAM	4096 QAM	4096 QAM
Spatial Streams	4	4	8	8	8
MU-MIMO		DL only	UL & DL	UL & DL	UL & DL
Target Wait Time			Individual, broadcast	Restricted	Coordinated
OFDMA (# RU per STA)			Yes (single)	Yes (multiple)	Yes (multiple)
Multi-Link Operation				Yes	Yes
Multi-AP Coordination					Yes
DSO/NPCA					Yes
dRU					Yes
IEEE Standard	11n	11ac	11ax	11be	11bn

Which Wi-Fi standard to choose?

Most important: keep your **brain** switched on!

For 99% of our use cases, we don’t need the latest and fanciest.

Consider **traffic sources, destinations, bottlenecks**.

Why offer 1 Gbps each to 1000 users, when your ISP link is 10 Mbps?

Wi-Fi 6 and up might be relevant for niche use cases – it is **not** for campus!

If you have a campus (or company or organization) to cover,

many moderate or even basic level APs probably serve you better than a few cutting edge ones.

For most use cases, Wi-Fi 5 (802.11ac) is more than enough.

How far can Wi-Fi go? The Link Budget

Often misunderstood -
Wi-Fi can go 100 km and more, if done right (p2p links).

Link budgets, much like household budgets,
calculate how much we have, and what is left at the end.

Calculated in dB -

the **Decibel (dB)** is a handy unit for calculating

Natural processes are easier to calculate in dB

Say, every tree takes half of the signal:

1 Watt 0.5 Watt 0.25 Watt 0.125 Watt

30 dBm 27 dBm 24 dBm 21 dBm

or relative,

0 -3 -6 -9 dB

Decibel (dB)

Definition: 10 * Log_{10} (P_1/ P_0)

3 dB = 2x power,
10 dB = 10x power = order of magnitude

dBm = relative to 1 mW, dBi = relative to ideal isotropic antenna

dBm is decibels relative to 1 milliwatt: 1 mW = 0 dBm, 100 mW = 20 dBm, 1 W = 30 dBm

Transmitter power TX and Receive sensitivity RX typically given in dBm

Losses in dB, e.g. in cables, in free space

dBi is decibels relative to a perfect antenna - The “i” stands for isotropic. Examples:

An omni antenna with 6 dBi gain. A parabolic dish with 29dBi gain

Link budget

- adding up gains and losses
- two kinds of contributions
  - what we can not change: path loss
  - what we can change: antennas, cables, RX, TX

Link budget

- **Effective transmit power:**

  transmit power [dBm]
  - (cable + connector) loss [dB]

  + amplifier gain [dB]
  + antenna gain [dBi]

- **Propagation loss [dB]:**

  Free space loss [dB]

- **Other losses**
  (terrain, vegetation, buildings, ...)

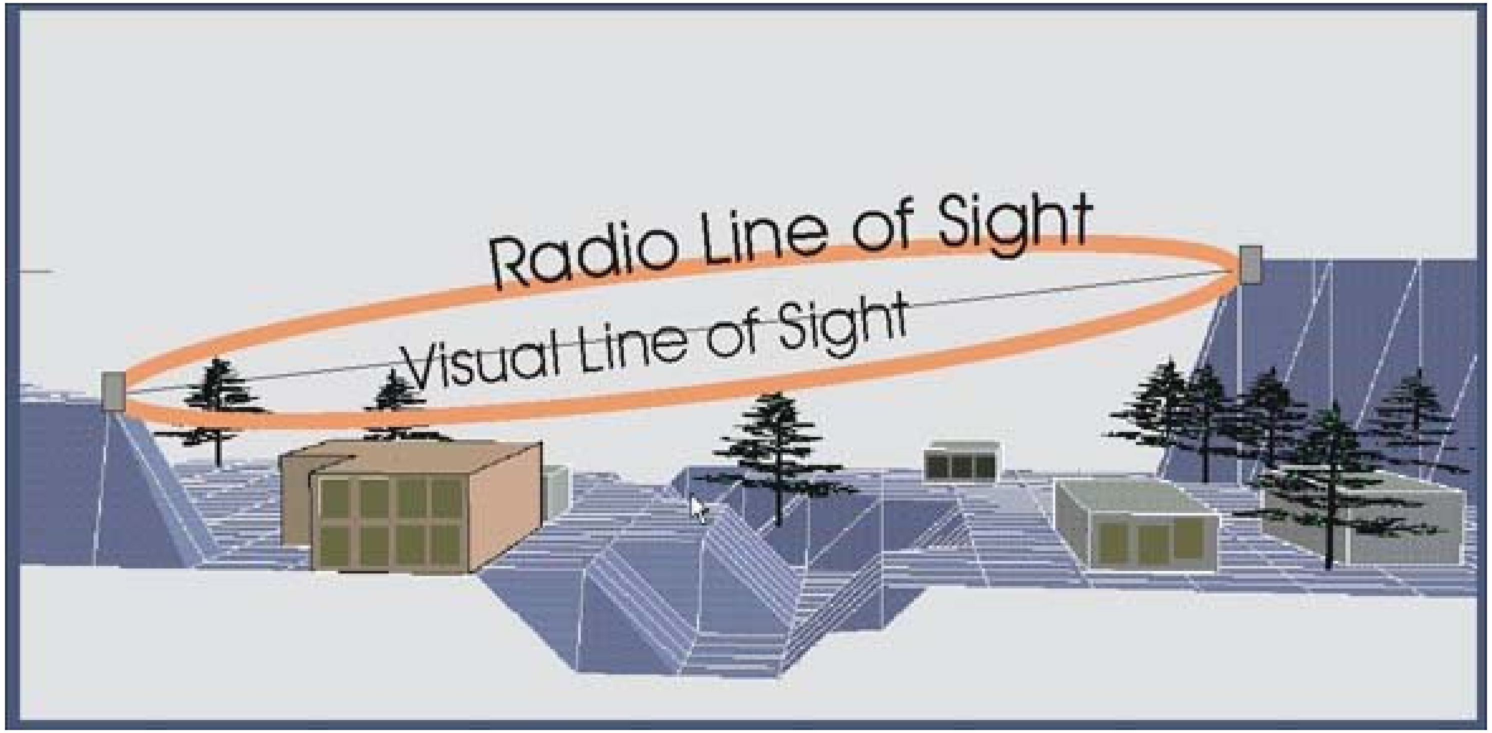
- **Effective receiving sensibility:**

  antenna gain[dBi]
  + amplifier gain [dB]
  - cable loss [dB]

  - receiver sensitivity [dBm]

Line-of-sight (LOS)

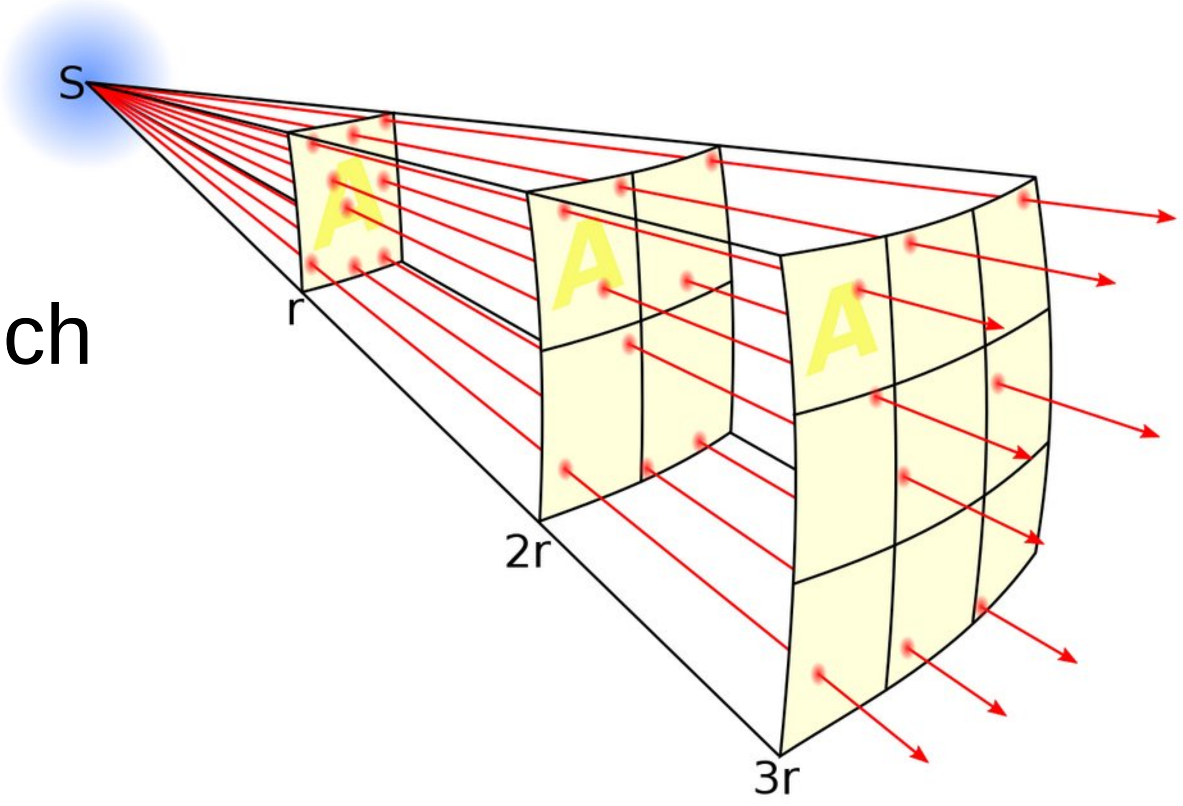
- the higher the frequency, the more we need free line of sight



Path loss / Free space loss

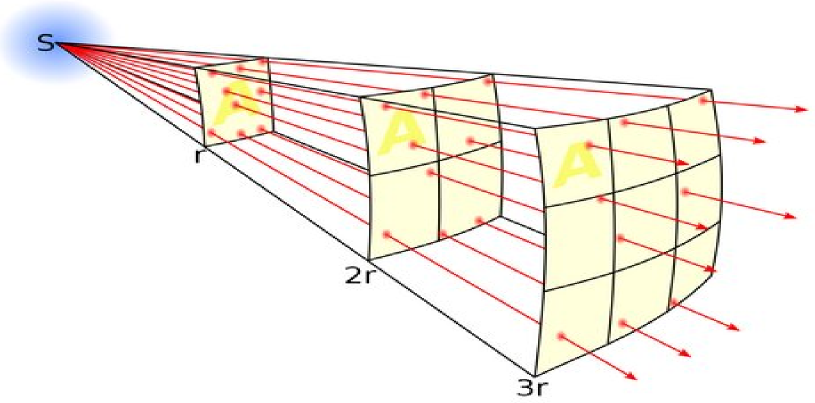
Due to geometry -
it has nothing to do with obstacles, rain, fog, or such

$$\text{FSPL} = \left(\frac{4\pi d f}{c}\right)^2$$



source: By Borb, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=3816716

Path loss / Free space loss



in dB, with f in GHz and d in km:

$$\mathrm{FSPL(dB)} = 20\log_{10}(d) + 20\log_{10}(f) + 92.45$$

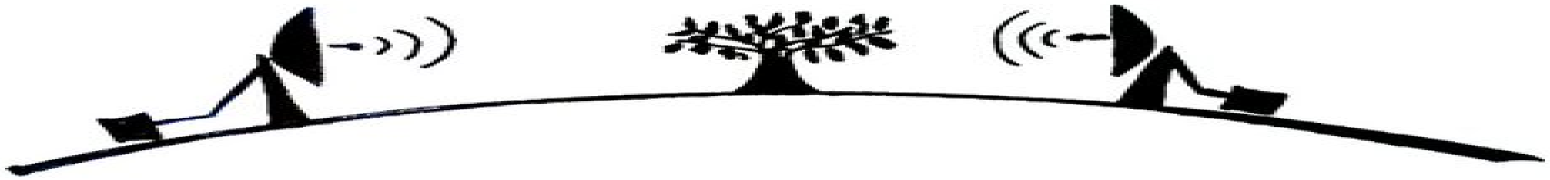
for 2.4 GHz, memorize: 1 km = - 100 dB

and then 20 dB for every order of magnitude:

100 m	- 80 dB
1 km	-100 dB
10 km	-120 dB
100 km	-140 dB

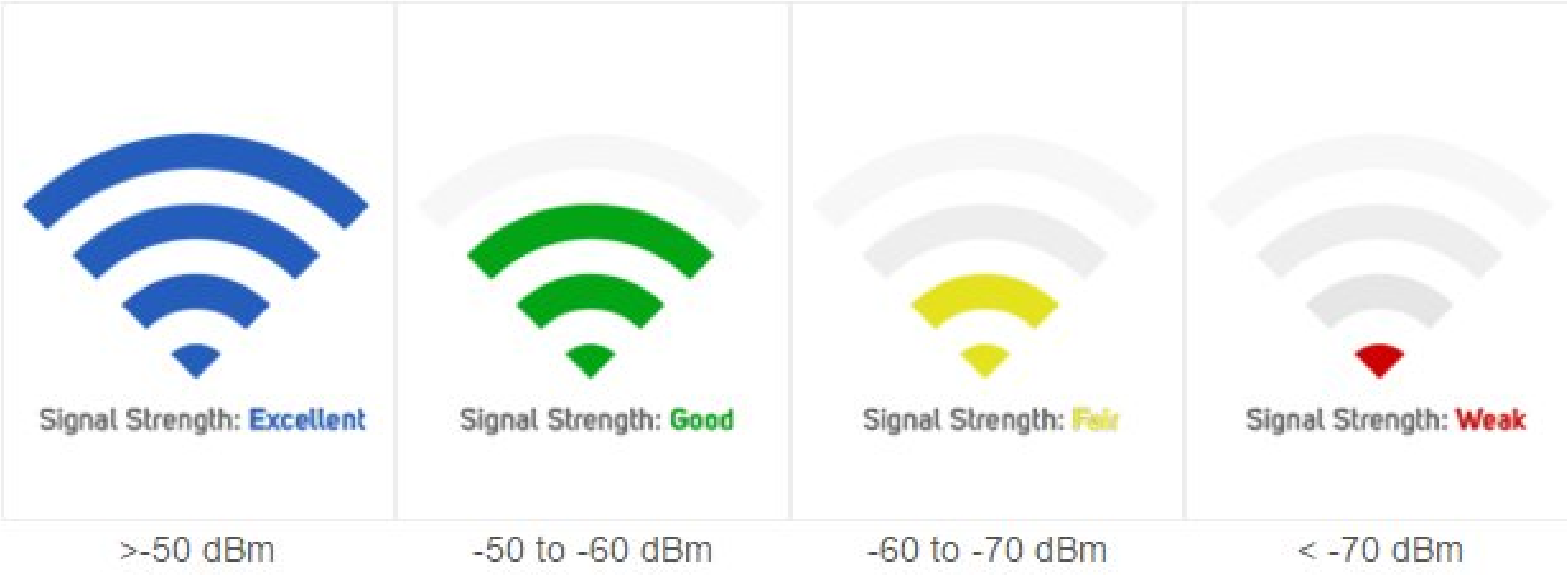
Now the parts we can change

- Output power (TX): limited by regulations, often 20 dBm
- Receive sensitivity: depends on quality of radio
    - Professional AP: -98 dBm
    - Home AP: -95 dBm
    - Mobile phone: -85 dBm
- Antennas



How much is needed?

- For the end user (laptop, phone),
  typically -75 dBm is the minimum we need to have



Link Budget / examples

Hotspot to Mobile Phone

```
TX                          + 020 dBm
Cable + Connectors          - 001 dB
Antenna TX                  + 005 dBi (medium omni antenna)
FSL (1 km at 2.4 Ghz)       - 100 dB
Antenna RX                  + 002 dBi (phone or laptop)
Cable + Connectors          - 001 dB
-----------------------------------------------------------------------
Result                      - 075 dBm

Receive Sensitivity         - 085 dBm (average phone)
-----------------------------------------------------------------------

TOTAL                       + 010 dB Link Margin Just about OK!
```

Link Budget / examples

Backhaul point-to-point link, 100 km

```
TX                          + 020 dBm
Cable + Connectors          - 001 dB    (good cabling)
Antenna TX                  + 025 dBi   (strong directional antenna)
FSL (100 km at 2.4 Ghz)     - 140 dB
Antenna RX                  + 025 dBi   (strong directional antenna)
Cable + Connectors          - 001 dB
----------------------------------------------------------------------
Result                      - 072 dBm

Receive Sensitivity         - 090 dBm ()
----------------------------------------------------------------------
TOTAL                       + 018 dB Link Margin This works!    (is it legal?)
```

Importance of the Antenna

The antenna is a passive element bringing the signal from the wire to air and back again.

It does not amplify overall, but it can strongly focus the signal to where we need it.

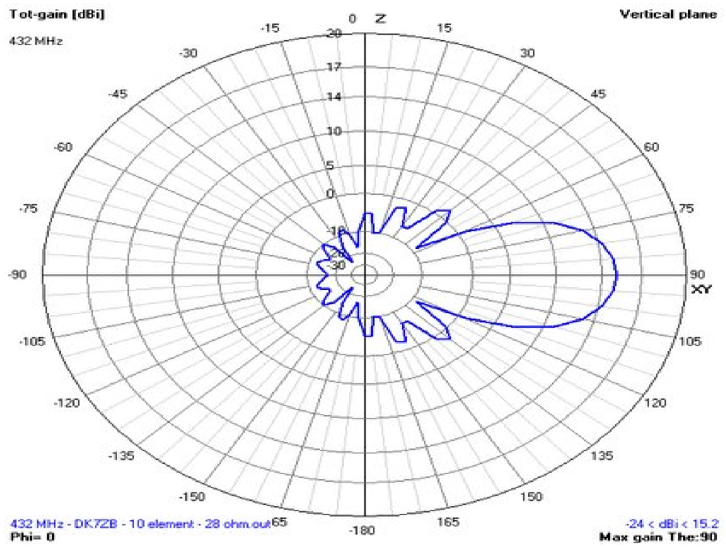
It is the most important part we can win those dBs with!

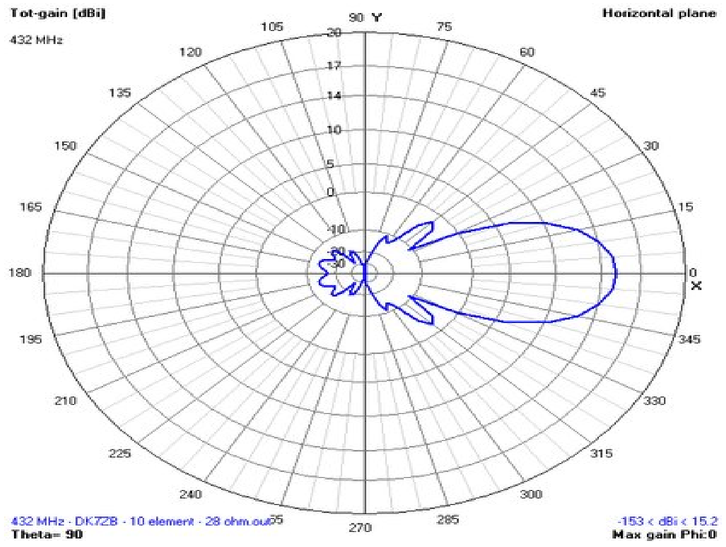
General Antenna Properties

- Directivity
  - Gain, shown by radiation patterns
    - Beam-width, lobes, side-lobes, nulls
    - Front to back ratios
- Polarization
- Center Frequency
- Bandwidth (How far ⬆️ & ⬇️ below center Frequency?)
- Physical Size
- Impedance & Return Loss

Radiation Patterns

- Distribution of power radiated from or received by the antenna
- Shown as a function of direction angles from the antenna
- Patterns usually use a polar projection
- Directional antennas have differing Vertical & Horizontal gain
- Good source: https://www.cisco.com/c/en/us/products/collateral/wireless/aironet-antennas-accessories/prod_white_paper0900aecd806a1a3e.html





Antenna – three types we see often

Omnidirectional – for all around coverage

Patch / Panel & **Sector**
– some directionality,
e.g. for covering square or building

Grids, parabolas, dishes –
strongly directional for point to point links

And many are almost too small to see

Phones & gadgets:

miniaturized print antennas

NSRC
Network Startup Resource Center

Wireless cookbook/checklist

Solid wired network - Good IP architecture - Reliable Core Services (Routing, DHCP, DNS, ...)

Choosing hardware - What is important?

Good SSID decisions (use eduroam!)

Physical deployment - Good choice of places, cell sizes, ranges … Site Survey is essential!
Good wiring - Reliable power

Wireless management/controller - Use frequencies, channels, speeds wisely

Wireless monitoring – a mix of general NMM tools and specific wireless ones

Wireless authentication - Do 802.1x and eduroam - Captive portal an alternative for some networks

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Wired backbone

Good IP architecture -

Wireless subnets, per location / building

APs are infrastructure, belong on management subnet
(*“switches without ports”* – and they probably connect most of your clients)

Reliable Core Services (Routing, DHCP, DNS, ...)

Wireless cookbook/checklist

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Hardware / gear options

- Your requirements
  - Point to point links
  - Access networks
- Your Budget
  - Access Points range from $10 to several $1000s
- It is all about trade-offs:
  - life expectancy, robustness
  - standards, speeds
  - management (!)

Gear options – price ranges

- TP-Link — Home user / cheap ($20/unit)
- D-Link
- Netgear
- Linksys
- Asus
- Belkin
-
- Ubiquiti
-
- Extreme / Aerohive
- Ruckus
- Cambium — Enterprise / expensive ($1000/unit)
- Cisco
- HPE / Aruba — + annual license costs for device and controller

Task: $20 and one day to connect 100 people ...

- Find a $20 wireless access point, some wire, and spend the day building an antenna and soldering it on
- This solution will work, to some extent – it does not always have to be the newest standard.
  - 200-300 people can read mail and browse a littl
  - I could give a Zoom talk over 802.11b/g/n
- This solution will have many limits:
  - no management at all
    - this is ok for one, but what if I need more?

Choosing the right compromise

- If the range is $10 … $1000s, is there a recommendation?
  - Yes
- At the NSRC, we think that there is quite some good options in the midfield
  - Access: Routers in the range of $100
  - Point-to-point links also in the $100s
- In particular, Ubiquiti products strike a good balance
  - no affiliation!
  - local availability, service and skills are always important criteria - your choice might be different!

Ubiquiti products

- Access: Unifi – managed access network with free controller software
- Point-to-point and point-to-multipoint links:
  - AirMax: budget level
  - AirFiber: performance level
  - LTU (proprietary, non-802.11 standard, 5GHz)

Note: for backhaul links, compliance with 802.11 might not be important - for user access it is!

Wireless cookbook/checklist

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Good SSID decisions (use eduroam!)

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SSID planning

Two approaches: one SSID across campus or different ones?

Clear recommendation. One SSID (and preferably **eduroam**)

Remember: Your IP design likely has different subnets in different locations.
But you can have one SSID regardless!

(Historical comment: There are implications on **Roaming** -

Clients do not renew their DHCP lease as long as they are on one SSID.
This used ot be an issue, however from circa 2015, Wi-Fi clients got smarter - they check connectivity state, and renew if they find themselves unconnected.)
Roaming is not your most important worry!

Wireless cookbook/checklist

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Deployment and placing of APs

Think light!

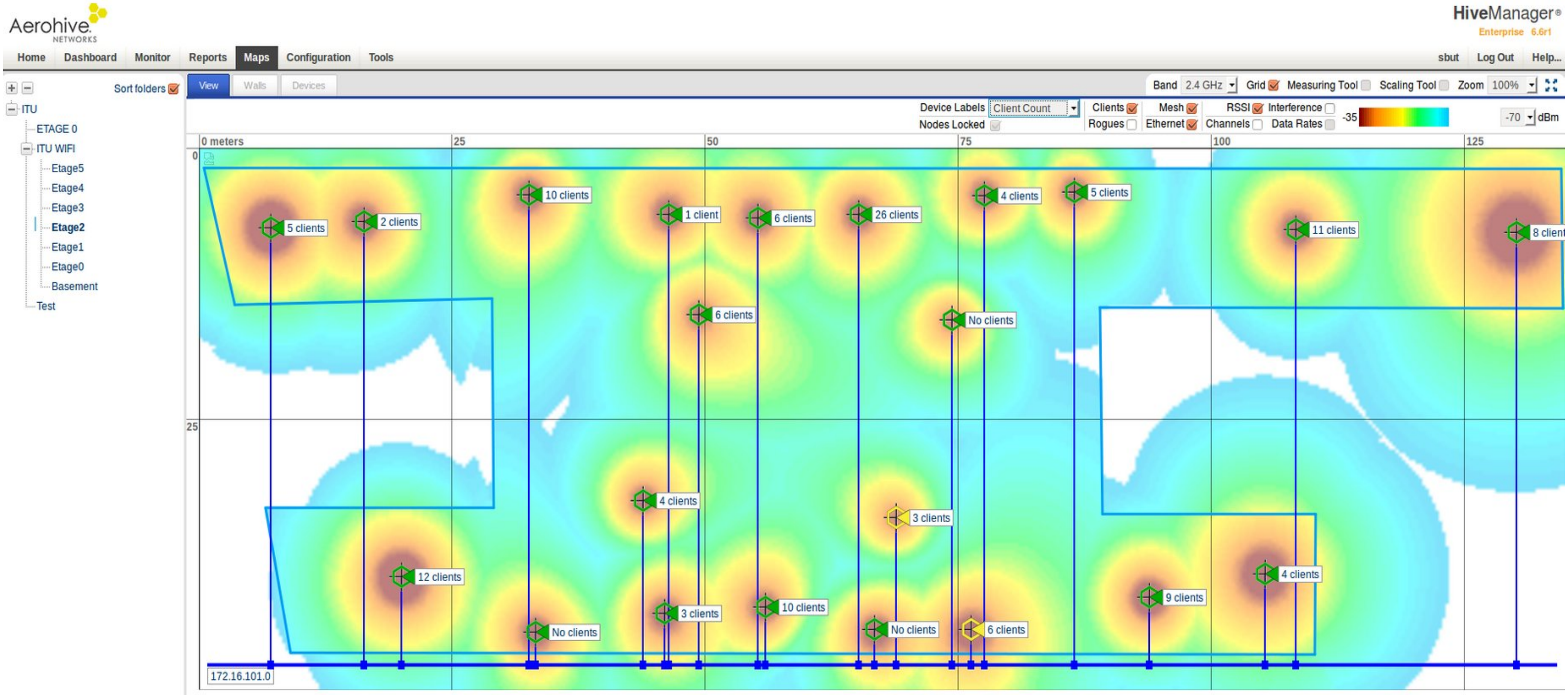
Remember antenna patterns!

One key question: how to cover large number of offices/rooms?

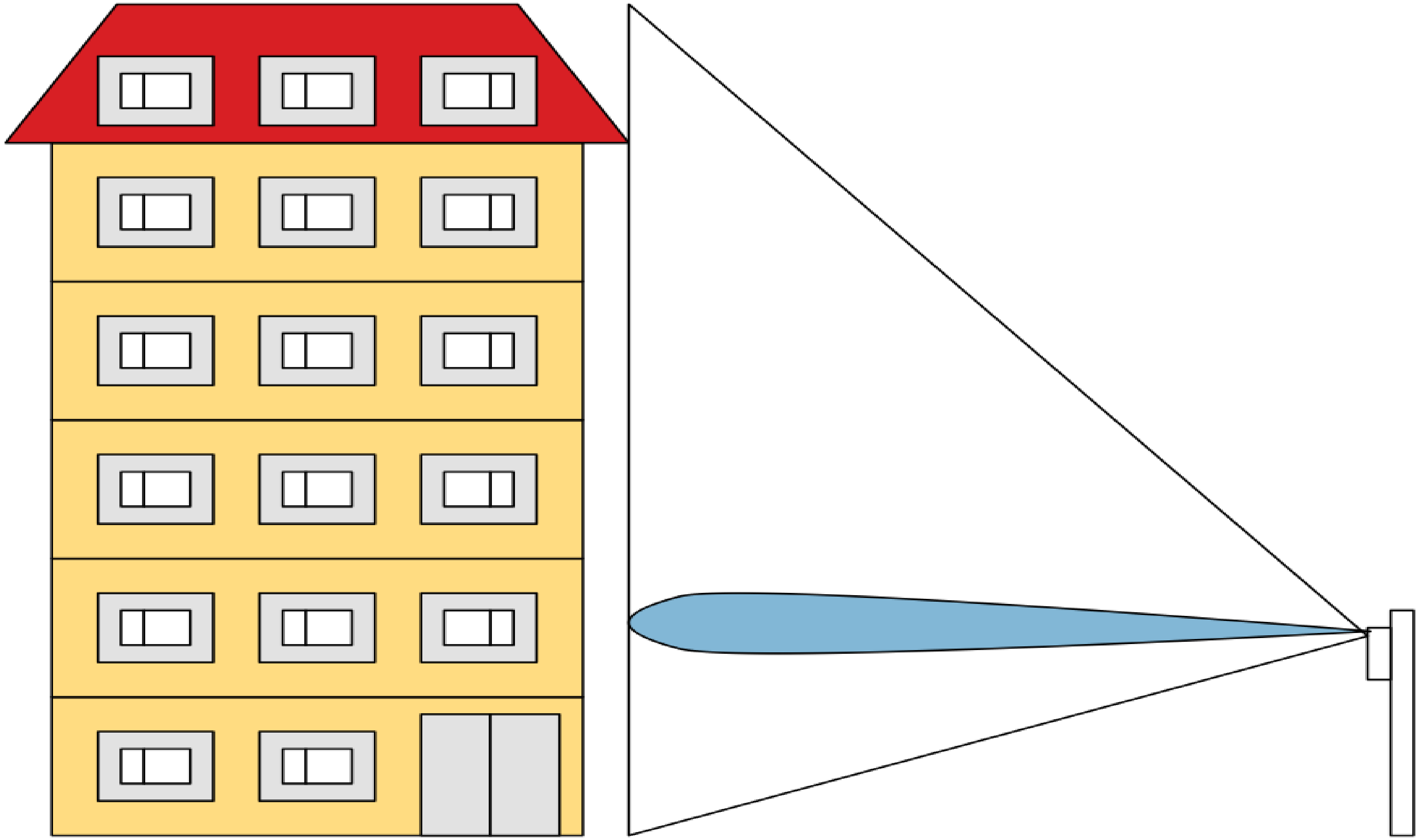
Preferred: one (or more) AP per room, if you have the budget.
Small cells, low power.

If you can not (budget!) ,
sometimes coming from outside is better than coming from the corridor.
Always measure resulting signal levels! -75 dBm is not enough, -50 dBm is.

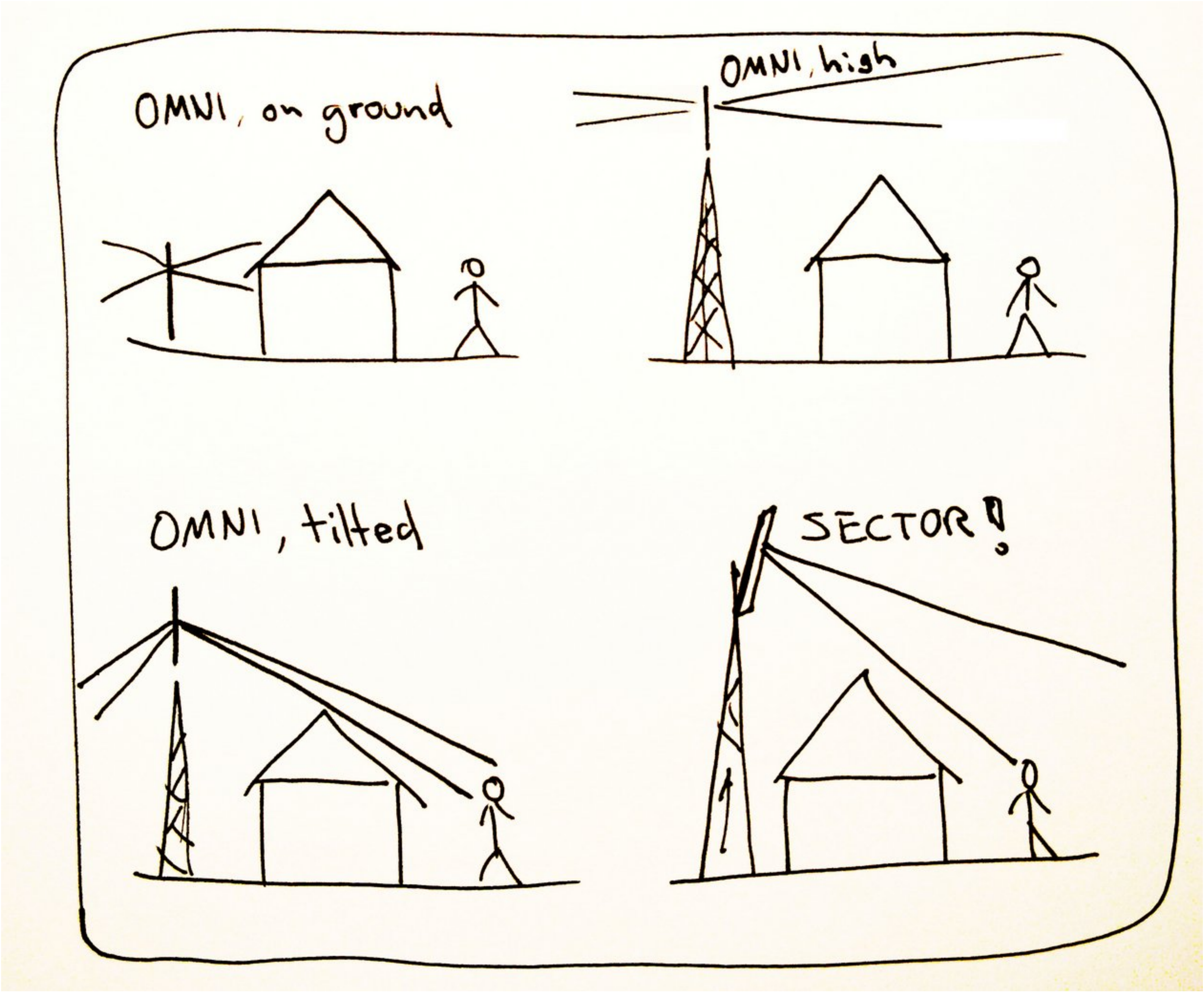
Target: One AP per room, low power



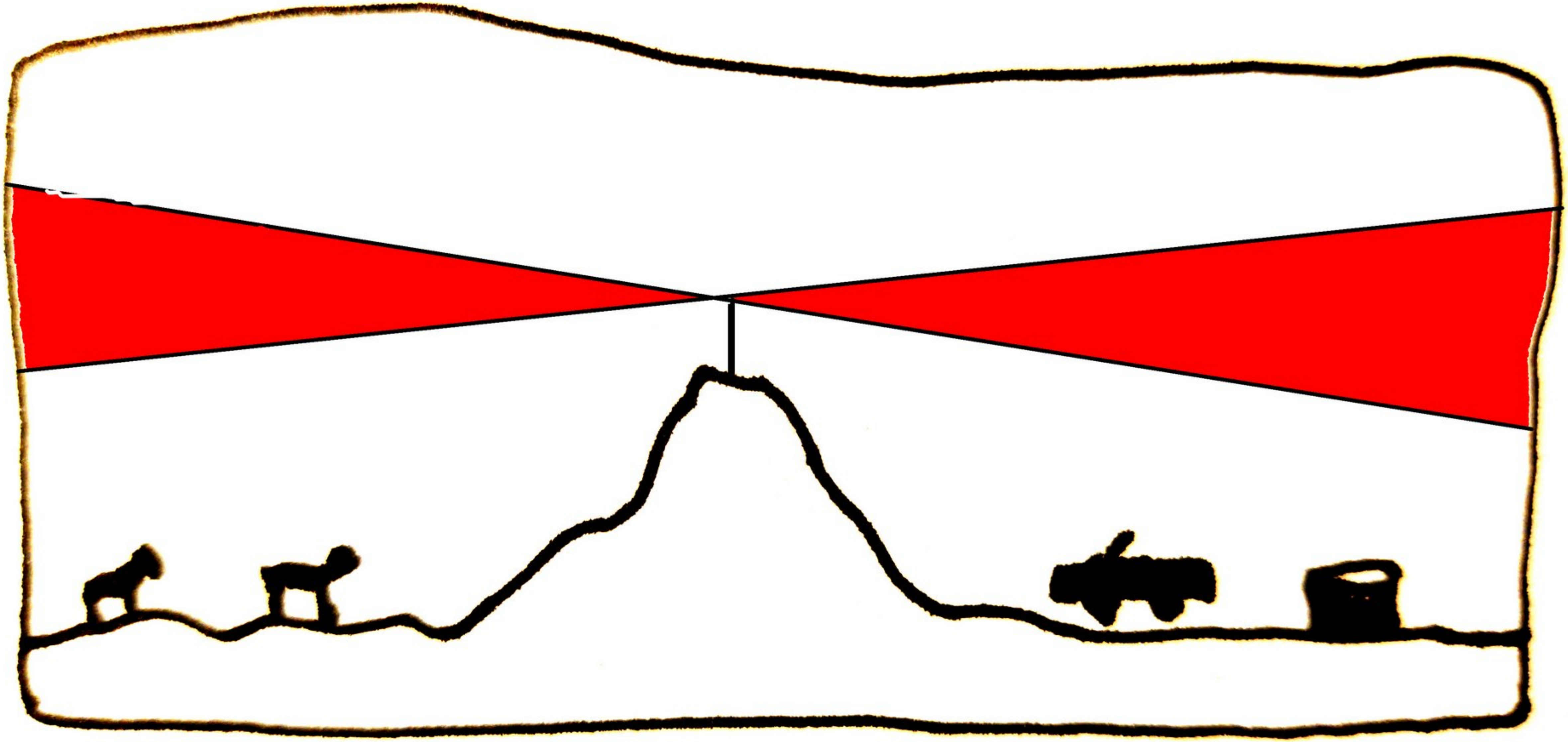
Perhaps from outside - & too strong is not good!



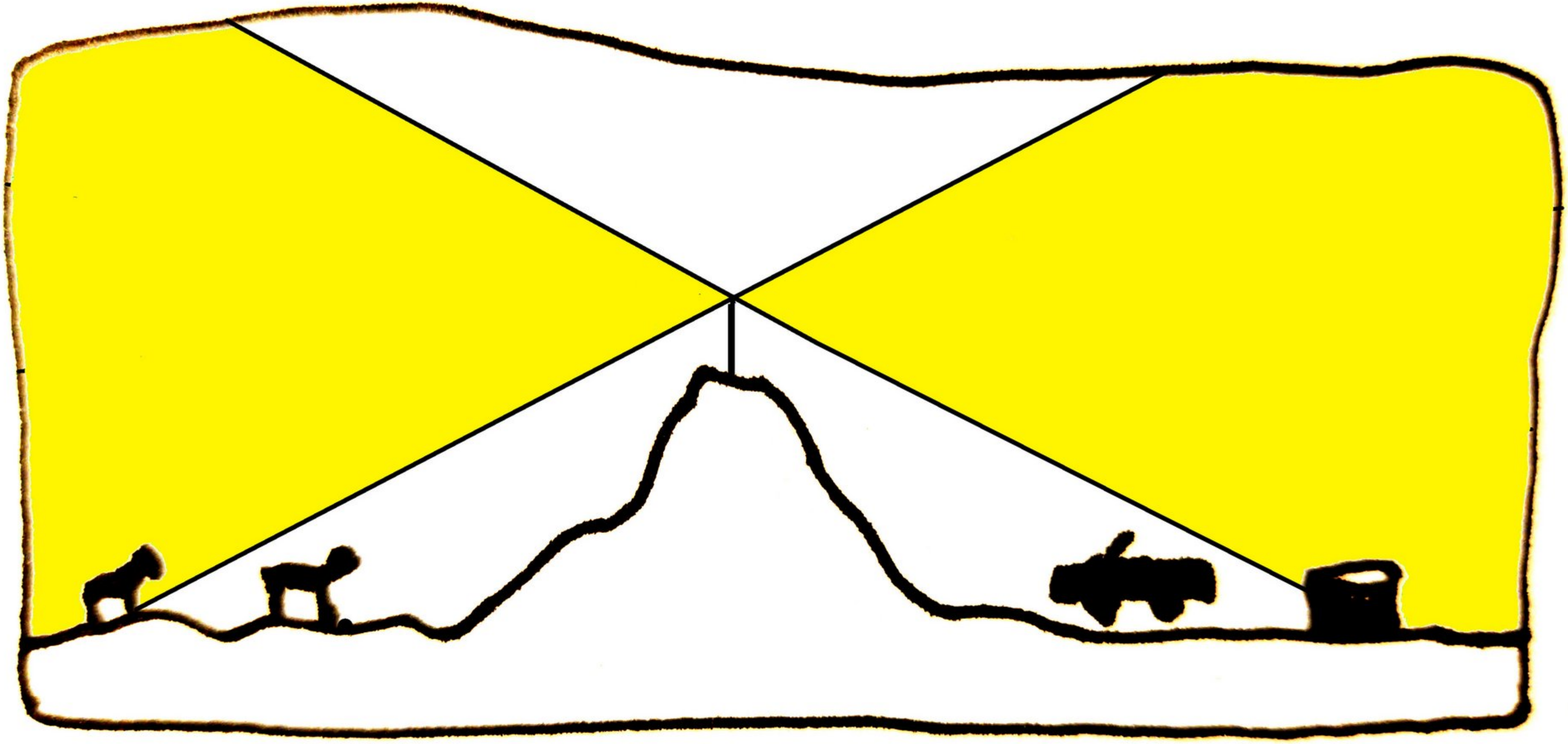
Optimization



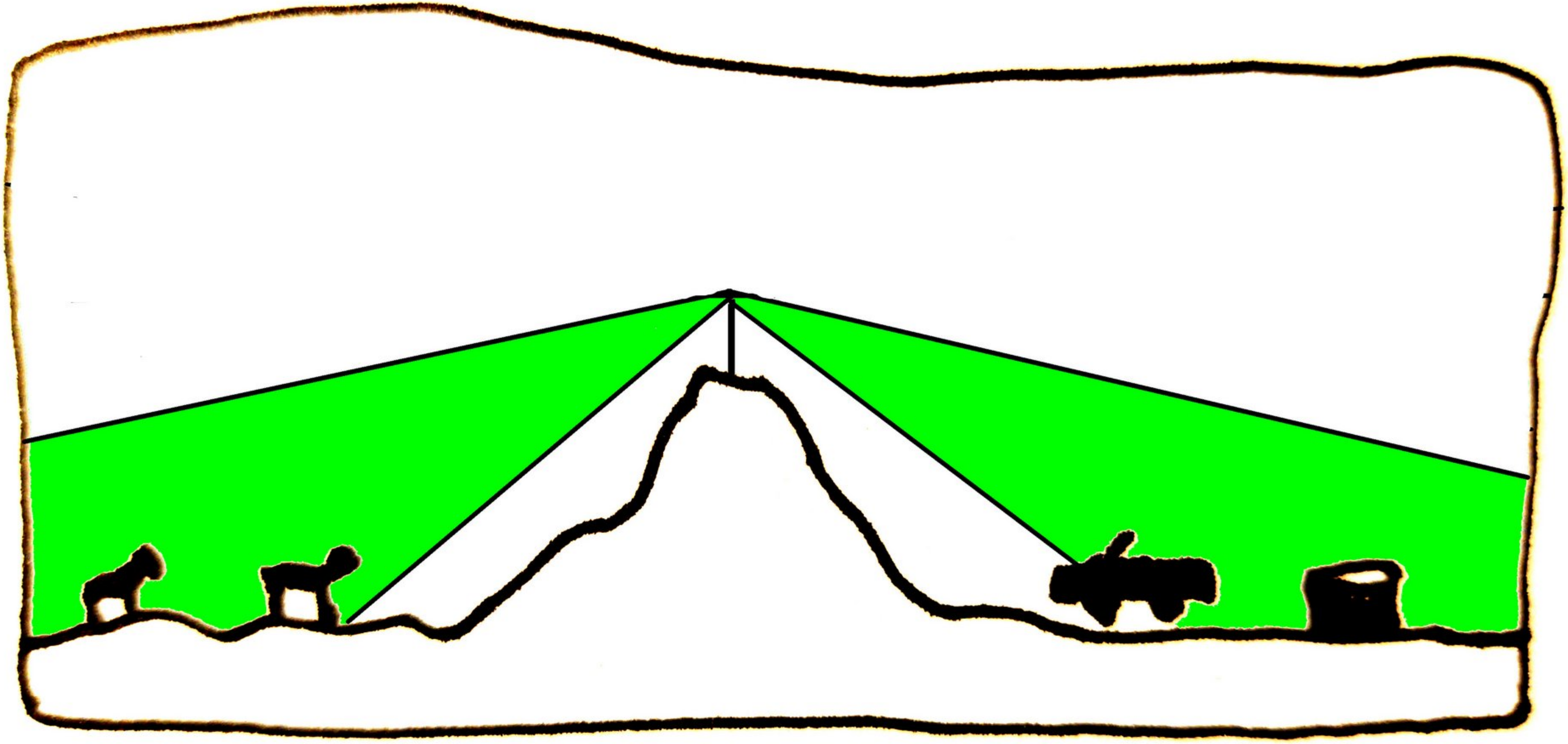
Strong is not always good!



This is better – a weaker omni antenna!



This is even better – an omni with beam-tilt!



Wireless cookbook/checklist

Solid wired network - Good IP architecture - Reliable Core Services (Routing, DHCP, DNS, ...)

Choosing hardware - What is important?

Good SSID decisions (use eduroam!)

Physical deployment - Good choice of places, cell sizes, ranges … Site Survey is essential!
Good wiring - Reliable power

Wireless management/controller - Use frequencies, channels, speeds wisely

Wireless monitoring – a mix of general NMM tools and specific wireless ones

Wireless authentication - Do 802.1x and eduroam - Captive portal an alternative for some networks

Wireless management – frequencies and channels

Modern managed Wi-Fi systems take care of some of the channel optimization.

But check manually -

Also for what your neighbours are doing (!).

The wireless management system takes other roles too:

SSID management

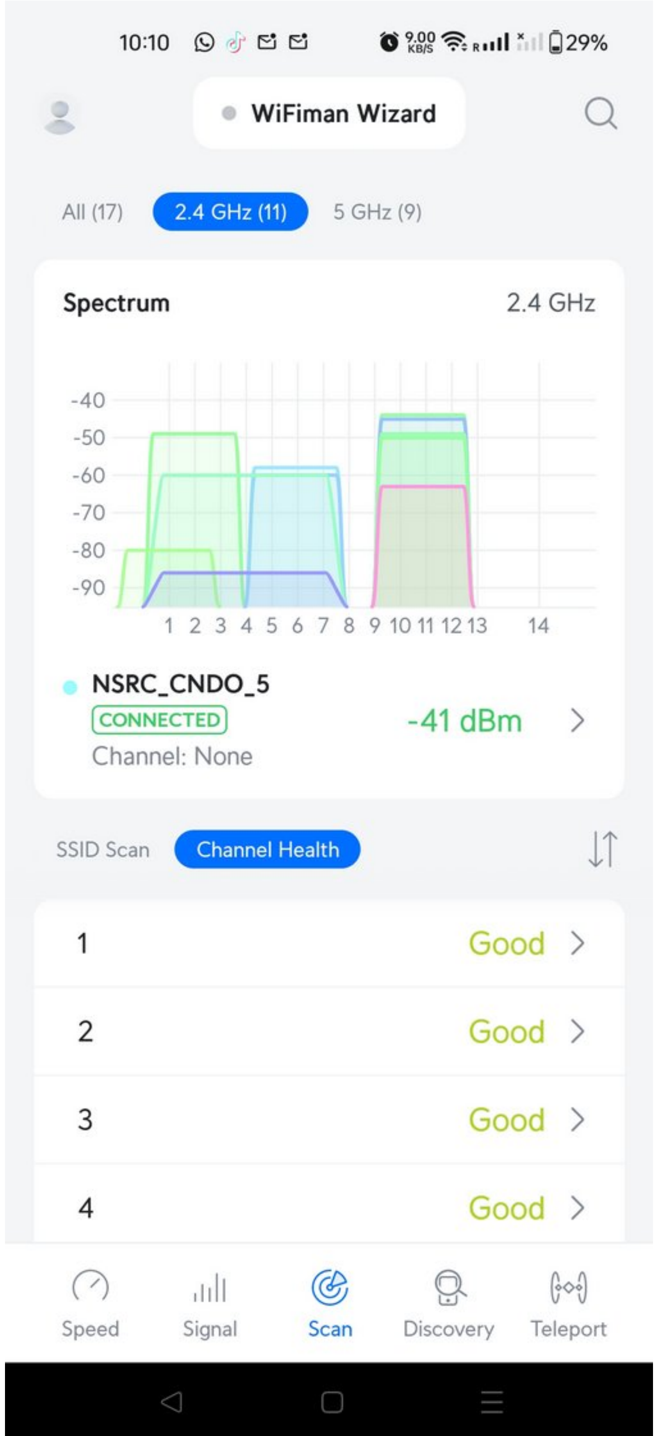
Location management

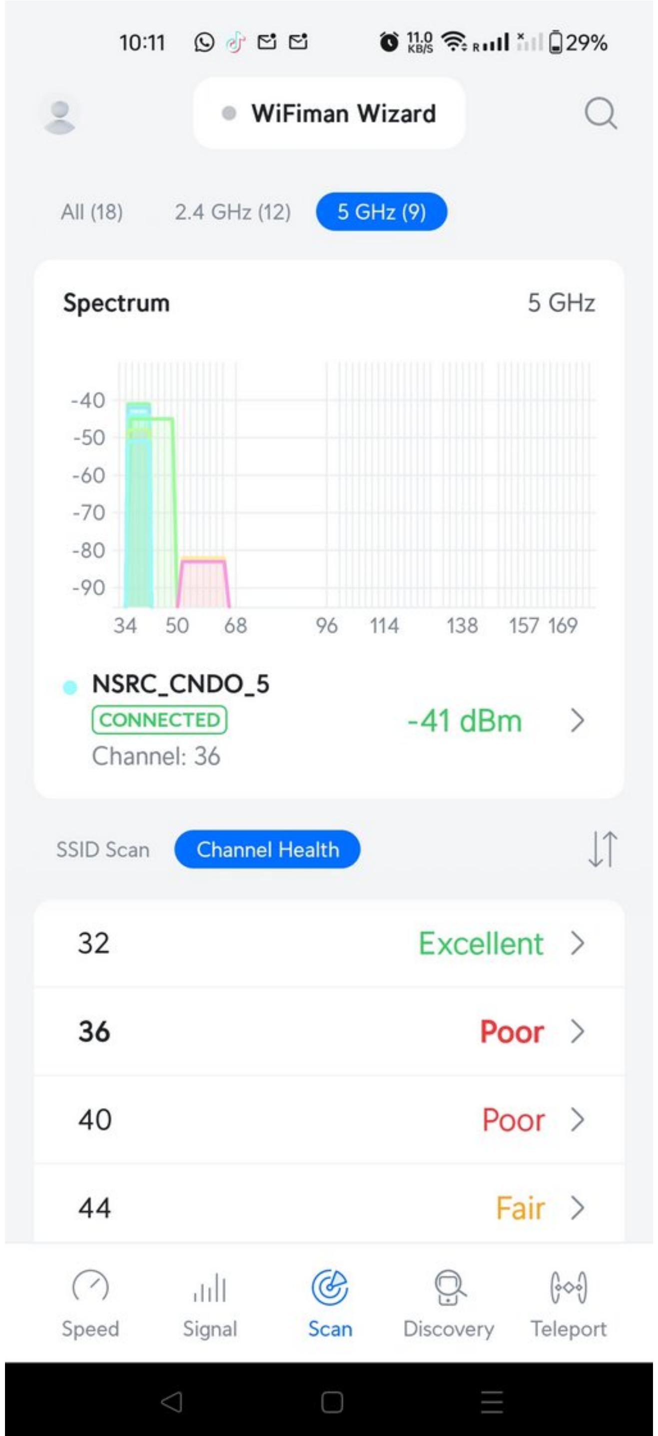
Device management – firmware upgrades
User management

Bandwidth steering

Authentication (interfacing)

Security (to some degree)

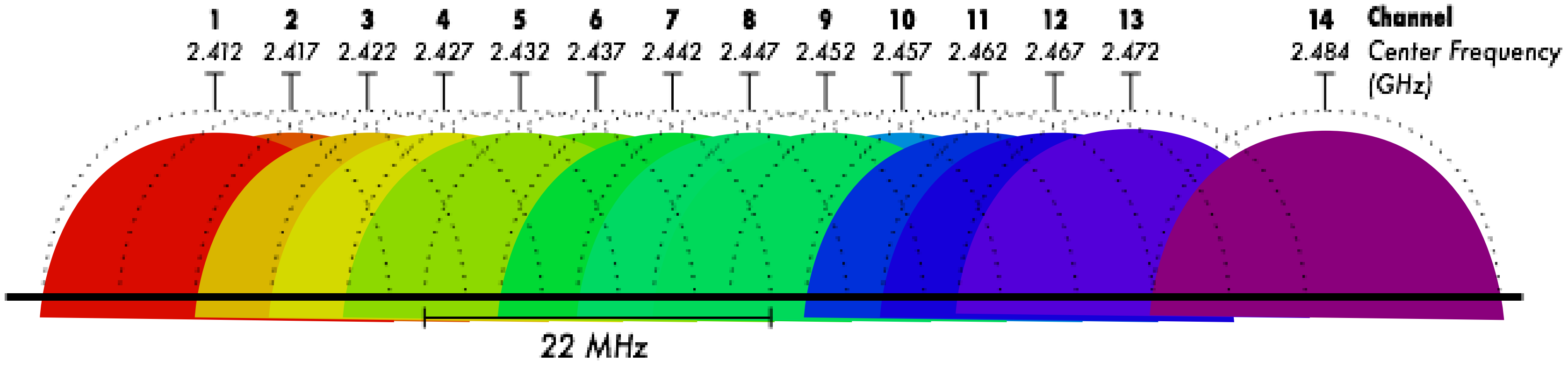




UNIVERSITY OF OREGON

NSRC
Network Startup Resource Center

802.11 Wi-Fi Channels

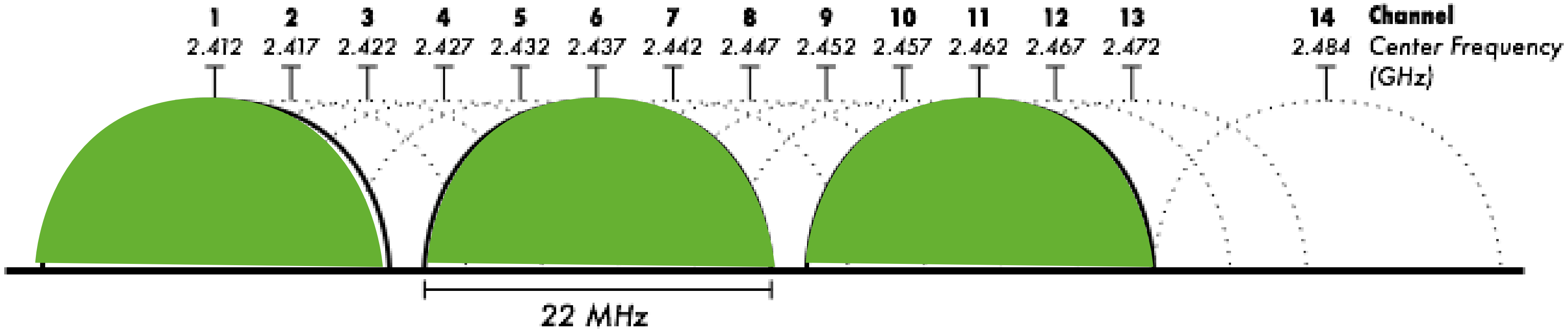


- Frequency bands are divided into channels
- 2.4 GHz has 14 overlapping channels of 22 MHz each
- 5 GHz has 25 non-overlapping channels of 20 MHz each
  - Country dependent
  - https://en.wikipedia.org/wiki/List_of_WLAN_channels

802.11 5GHz Channels

- 5 GHz has 25 non-overlapping channels:
  - U-NII-1: 5170-5250 has 4 of 20 MHz each
    - 36 ,40, 44, 48
  - U-NII-2A: 5250-5330 has 4 of 20 MHz each
    - 52, 56, 60, 64
  - U-NII-2C: 5490-5730 has 12 of 20 MHz each
    - 100, 104, 108, 112, 116, 120, 124, 128, 132, 136, 140, 144
  - U-NII-3: 5735-5835 has 5 of 20 MHz each
    - 149, 153, 157, 161, 165
- Wider channels allow bigger bandwidths

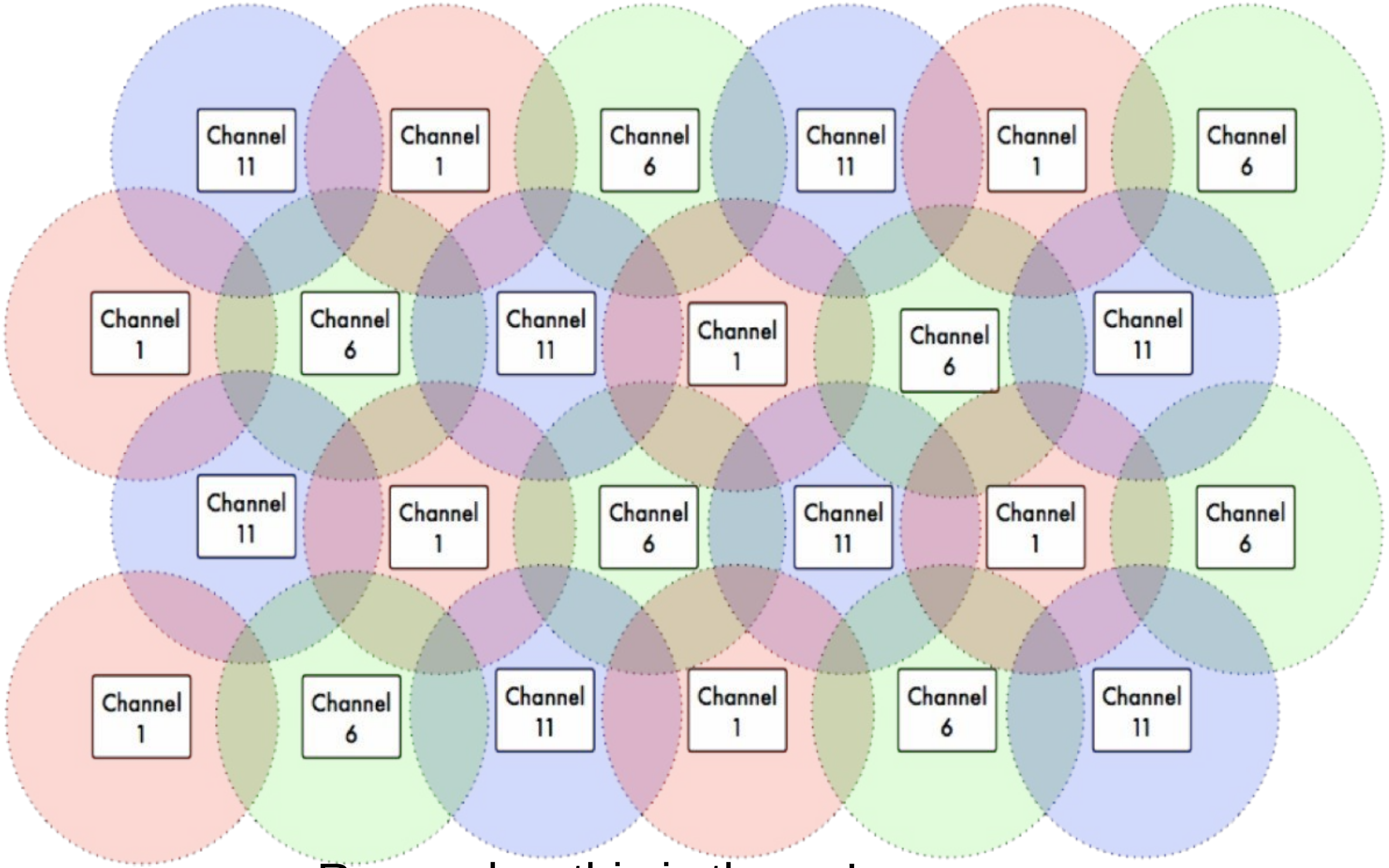
Non-Overlapping Channels 1, 6, 11, 14



- Check for channels in your country
- 1, 6, 11 is a possible plan

  1, 5, 9, 13 is another (and sometimes preferred!)

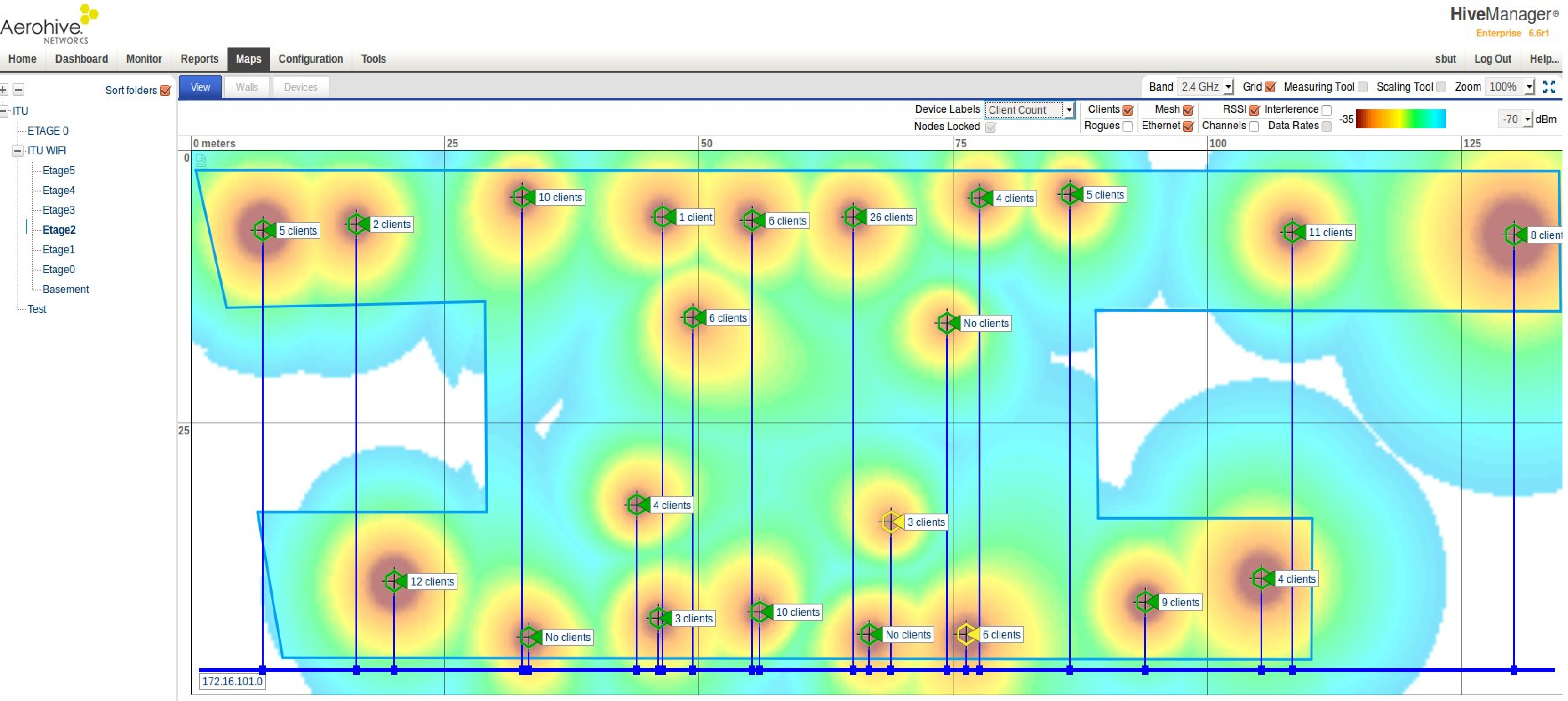
Three Channel Coverage Design



Remember this is theory!

Reality does not look this nice.

Wireless controllers manage channels



Wireless controllers manage channels

Let’s look at the controller behind our workshop Wi-Fi

Wireless cookbook/checklist

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Wireless tools for management and troubleshooting

Layer 1:

Spectrum analyzers – lab grade are expensive!
RFExplorer is affordable alternative.
SDR (Software defined radio) dongles

Layer 2:

Wi-Fi analyzers: Mobile apps:
Ubiquiti WiFiman, Aruba tools, Net Analyzer

kismet

Layer 3:

General tools as introduced in other units.

wireshark, kismet, TCP/IP tools

Some returning FAQs & discussions, things we could do

Power

- link budgets
- why more isn't always good
- why amplifiers are generally a bad idea

Placement of APs

Numbers of users on an AP

Layer thinking in Troubleshooting

Unifi install and demo

Authentication & eduroam

Summary

- Know Layer 1! waves, spectrum, propagation
- Wi-Fi standards
- Understand and do Link Budgets –
  understand power, signals
- Understand Antennas
- Follow a cookbook/checklist, step by step
- Discuss!