IOT Online Course

Fundamentals of IoT

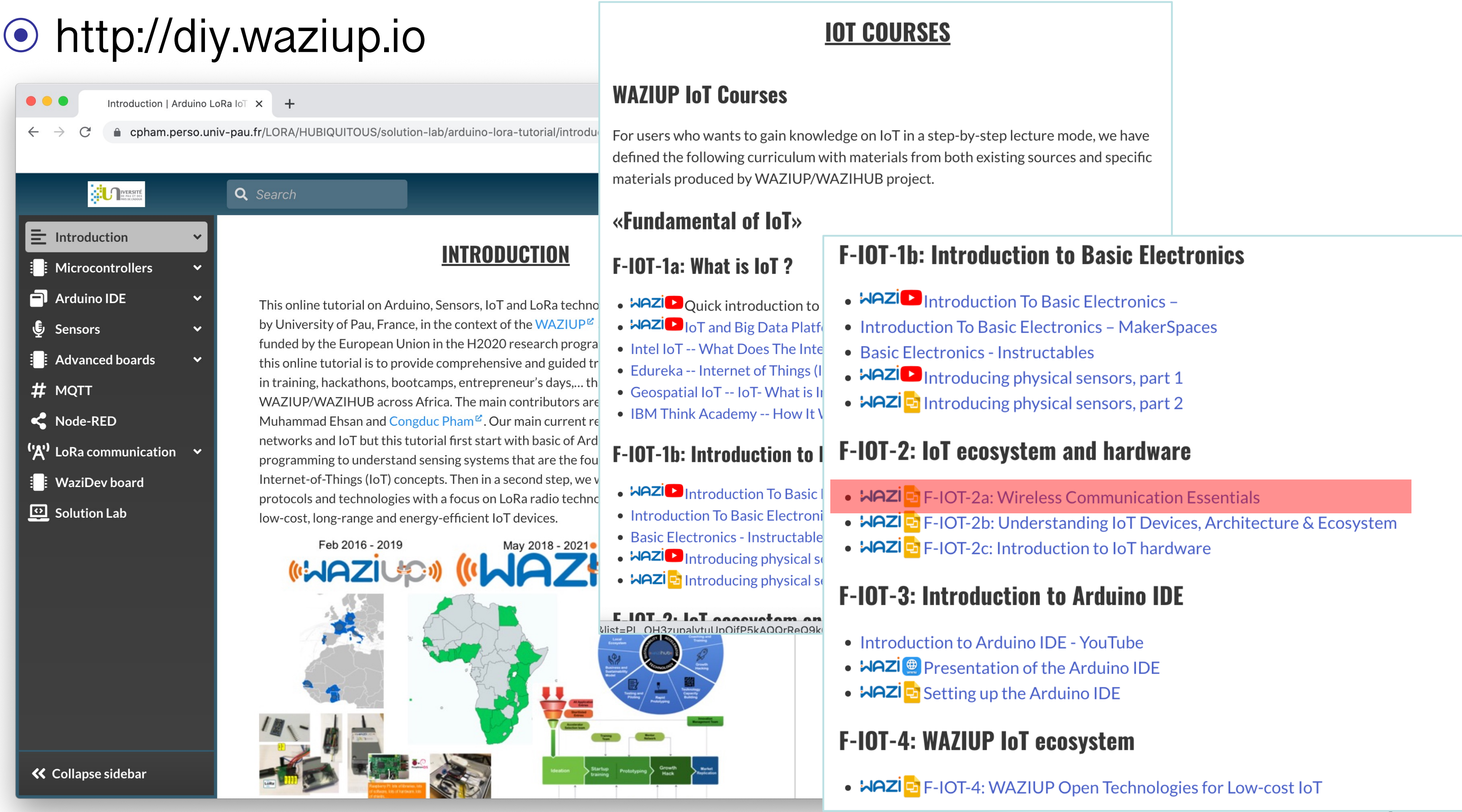
F-IOT-2a: Wireless Communication Essentials

Prof. Congduc Pham
http://www.univ-pau.fr/~cpham
Université de Pau, France

IoT – from idea to reality

IoT Online Course

- http://diy.waziup.io



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Wireless networks: WiFi

802.11ac
HOW DID WE GET HERE?

1973
Ethernet developed at Xerox's Palo Alto Research Center (PARC)

1977
Ethernet patented by Xerox

xerox

1997
802.11 Standard

The 802.11 standard is created. Products using the 2.4 GHz band have a maximum data rate of 2 Mbps

2.40 GHz — Max Data Rate: 2 Mbps

1999
802.11a Standard

The 802.11b and 802.11a standards are created. 802.11b drives the implementation of widespread use of WLAN technology. It is considered the first generation of wireless local area network technology. Products use 2.4 GHz and have a maximum data rate of 11 Mbps. 802.11a is considered the second generation. Products use the 5 GHz band and have a maximum data rate of 54 Mbps.

5.0 GHz — Max Data Rate: 54 Mbps

2003
802.11g Standard

The 802.11g standard is considered third generation; this standard permits products to use the 2.4 GHz band and match the 54 Mbps throughput of 5 GHz devices.

2.40 GHz — Max Data Rate: 54 Mbps

>> Throughput of 5 GHz devices

2005
802.11e Standard

The 802.11e standard is created. It is intended to take 11b and 11a to the next level with quality of service (QoS) features capable of prioritizing data, talk and video transmissions. Networks using 11e operate at radio frequencies of up to 5.850 GHz. It is most suitable for networks with multimedia capabilities.

5.85 GHz

2007
802.11n Standard (I)

The 802.11n standard is considered the fourth generation. Products are created for 2.4 GHz and 5 GHz bands and both have a maximum data rate of 450 Mbps.

5.0 GHz — Max Data Rate: 450 Mbps

2009
802.11 Standard (II)

The second wave of 802.11n is created and products operating in both the 2.4 GHz and 5 GHz bands now support a maximum data rate of 600 Mbps.

5.0 GHz — Max Data Rate: 600 Mbps

2011
The 802.11v, 802.11k and 802.11u standards are created. 11k is designed to improve the way wireless traffic is distributed through a network by determining which access points (APs) have available capacity. 11u allows users to know what wireless services a network offers before they are connected to it. It is most beneficial in crowded areas with multiple wireless services.

2013
802.11ac Standard (I)

The 802.11ac standard, so-called gigabit Wi-Fi, is ratified. In the first wave, Wi-Fi certified products have a maximum data rate of 1.3 Gbps and operate only in the 5 GHz band. Among other technological enhancements, this standard allows APs to send multiple streams to one client at a time. It is considered the fifth generation.

5.0 GHz — Max Data Rate: 1.3 Gbps

2014
802.11ac Standard (II)

Second-wave 802.11ac products hit the market. These products also use the 5 GHz band, but at a speed of 6.93 Gbps. It expands AP capabilities through the support of multiple input, multiple output (MIMO) technology, which enables APs to send multiple streams to multiple clients instead of just one at a time. The second wave also employs wider 160 MHz channels that can be used to give high-throughput applications their own exclusive pathways, thus further improving performance.

5.0 GHz — Max Data Rate: 6.93 Gbps

TechTarget

For up-to-date news, analysis and advice on networking, visit SearchNetworking.com.

Information by: Sonia Groff/TechTarget
Design by: Brian Linnehan/TechTarget

Wireless networks: 2G/3G/4G/5G/...

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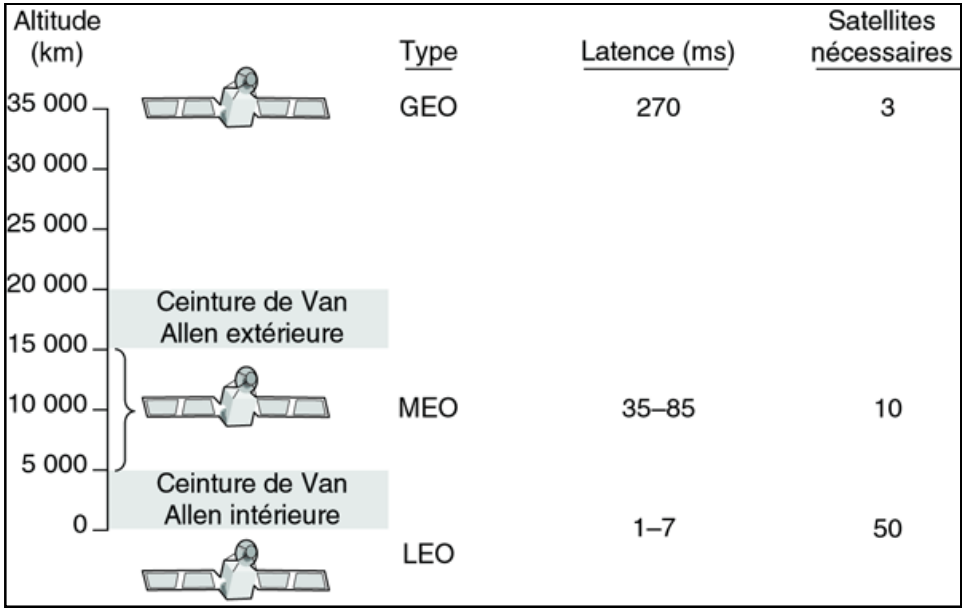
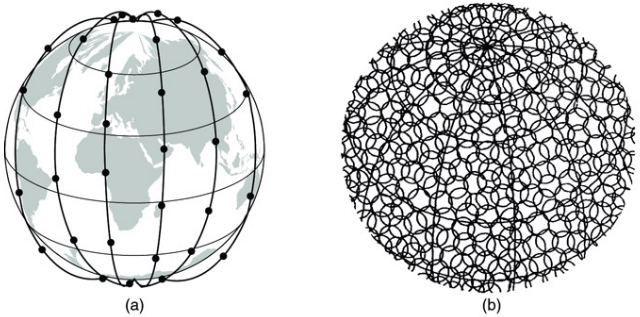
Wireless networks: Bluetooth

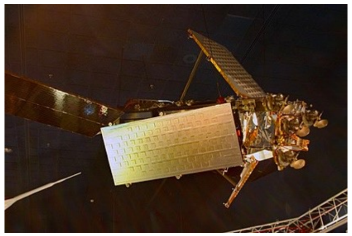
Wireless networks: Satellites

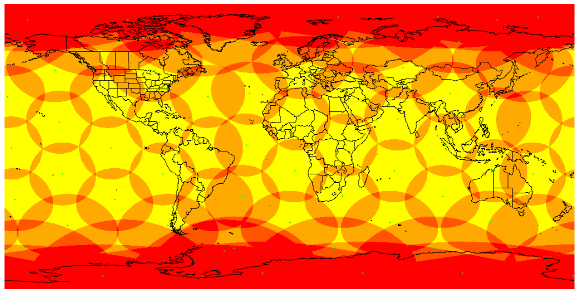




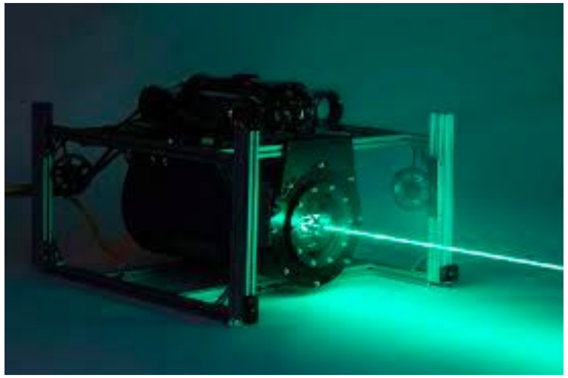
Iridium, 66 satellites

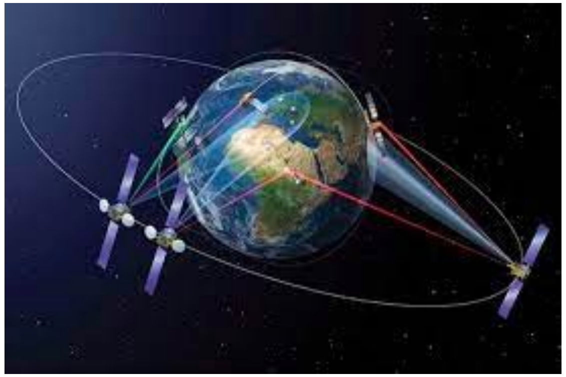
Initially 77

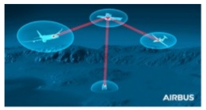




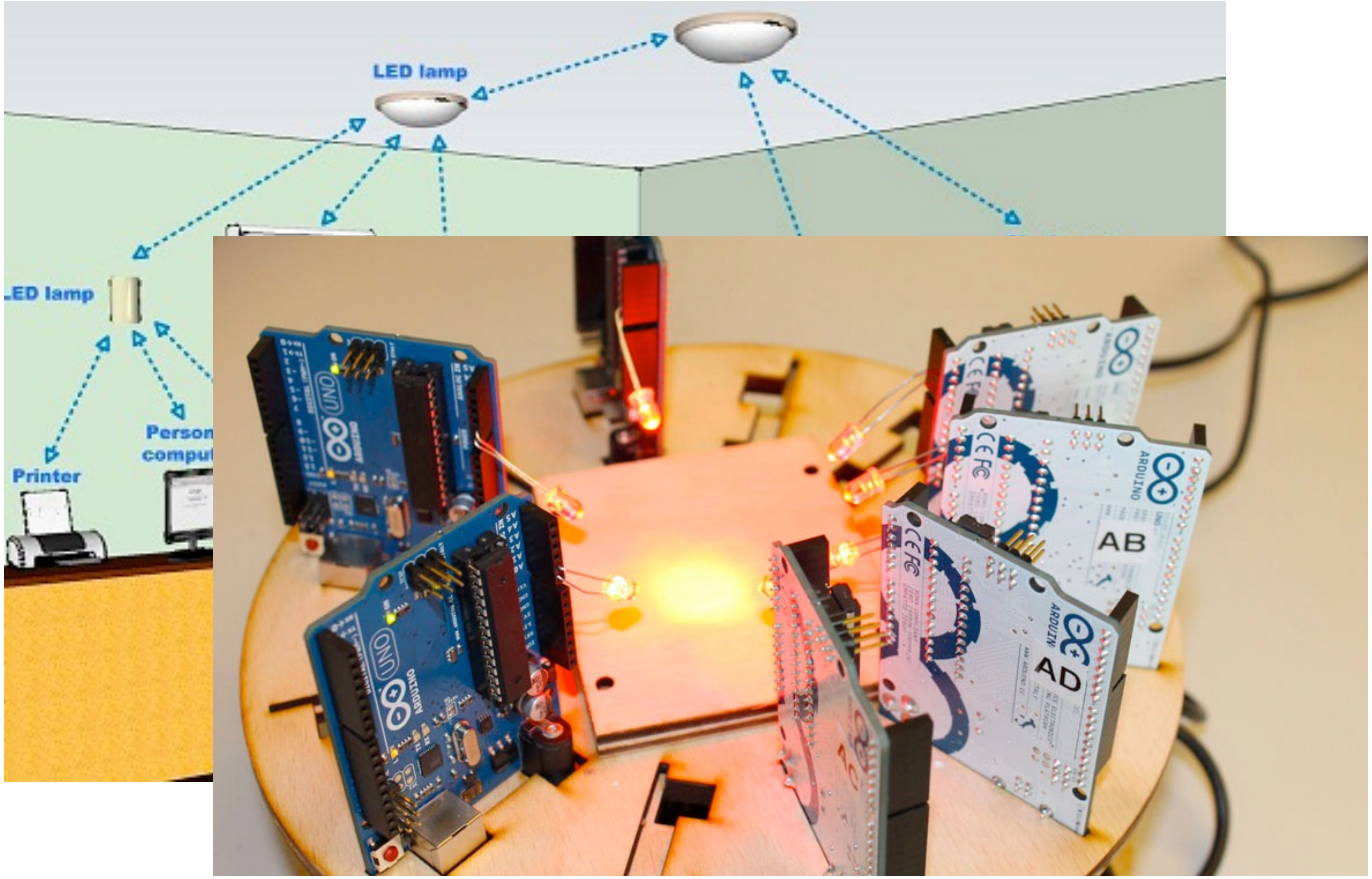
Wireless networks: Laser/Optical





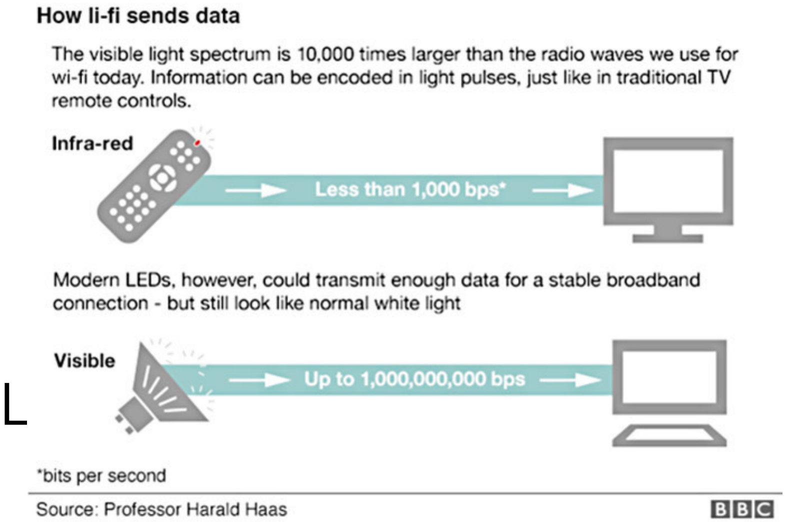


Wireless networks: Visible Light



Visible Light Communications, con't

- High throughput is "easy"
- Bi-directionality is still an issue
- VR is a perfect application for VL



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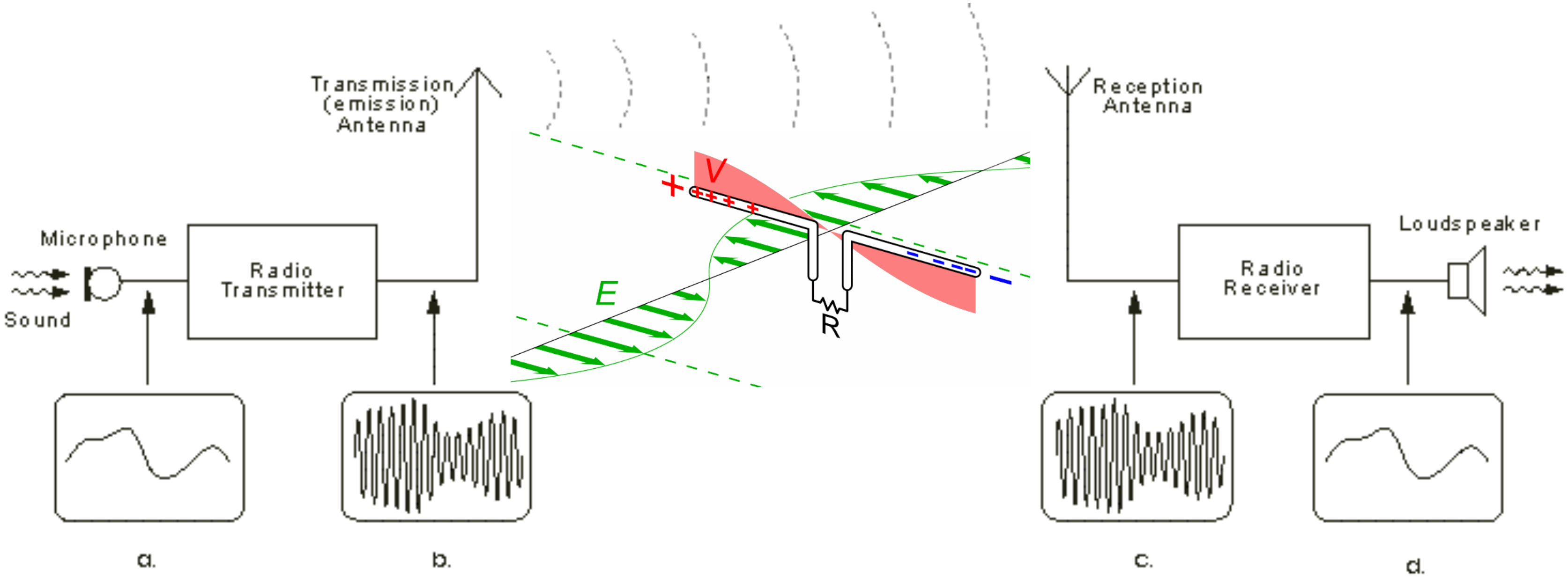
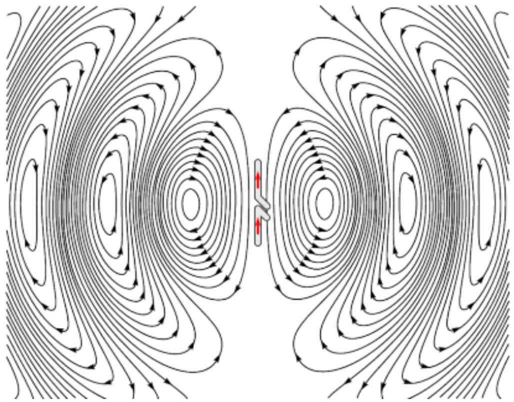
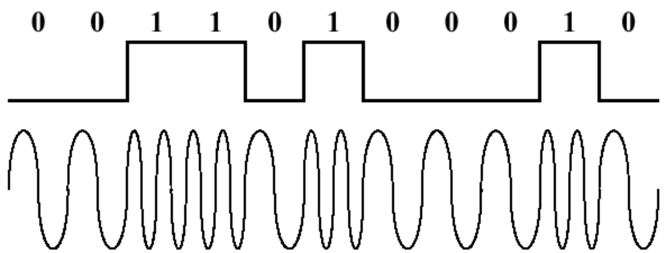
Wireless radio transmission basics



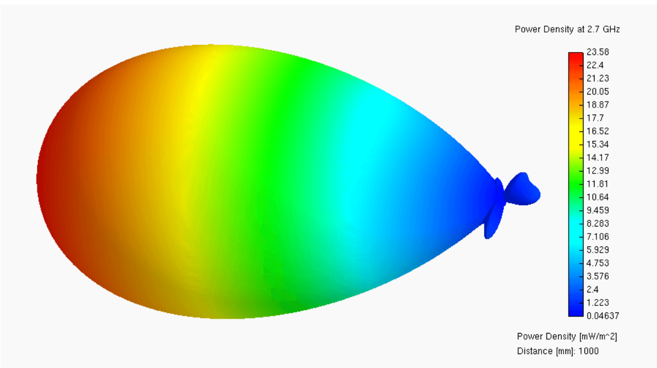


datal modulation



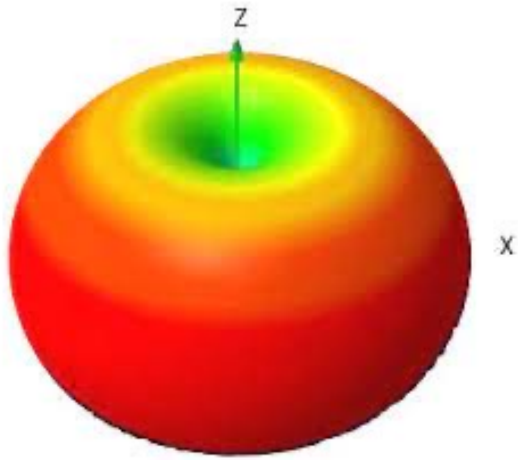
(b) Frequency-shift keying

Antenna types

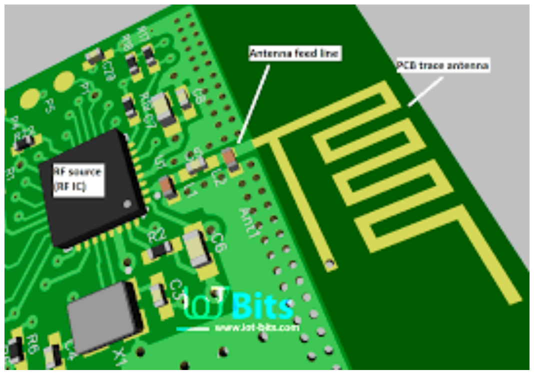


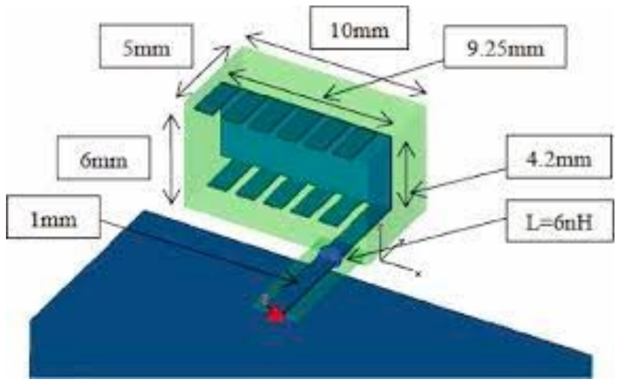
Directional antenna

Omni-directional antennas



PCB, patch, ceramic,...





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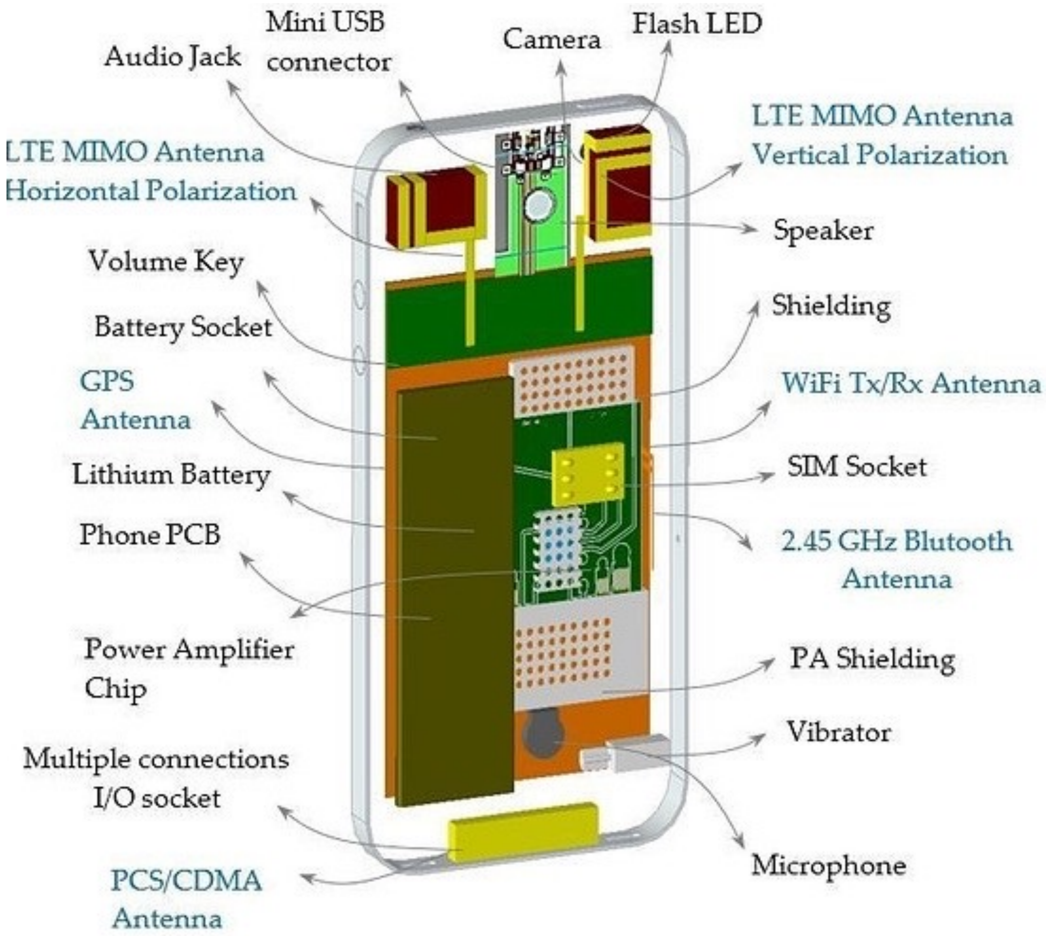
Antennas in a smartphones!



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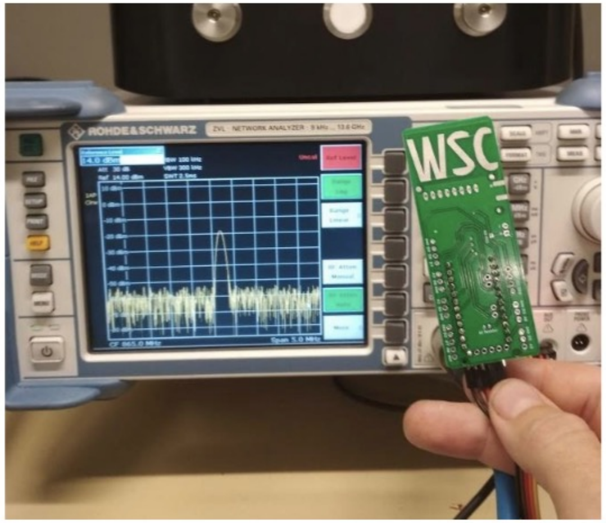
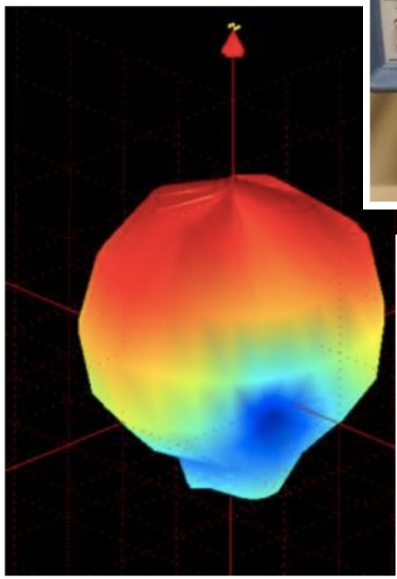
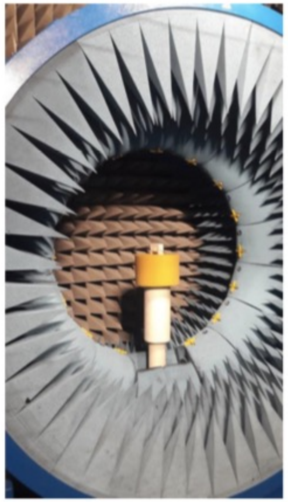
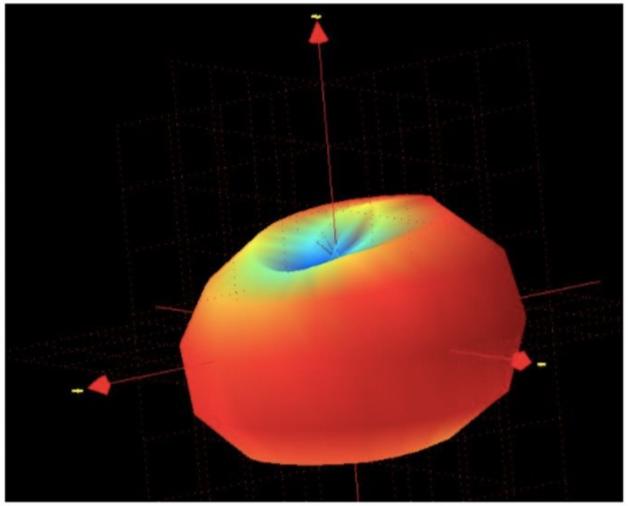
Testing antennas

- Source: F. Ferrero, University of Nice



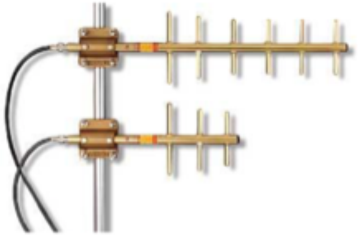


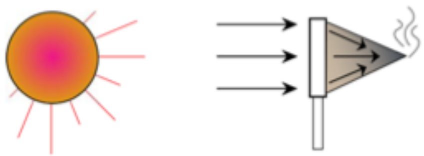




Antenna gain (1)

- Antenna gain
  - Directional antennas FOCUS energy: they DO NOT ADD energy





- Antenna Gain
  - Omni-directional antennas FOCUS energy: they DO NOT ADD energy

RF Essentials from Digi

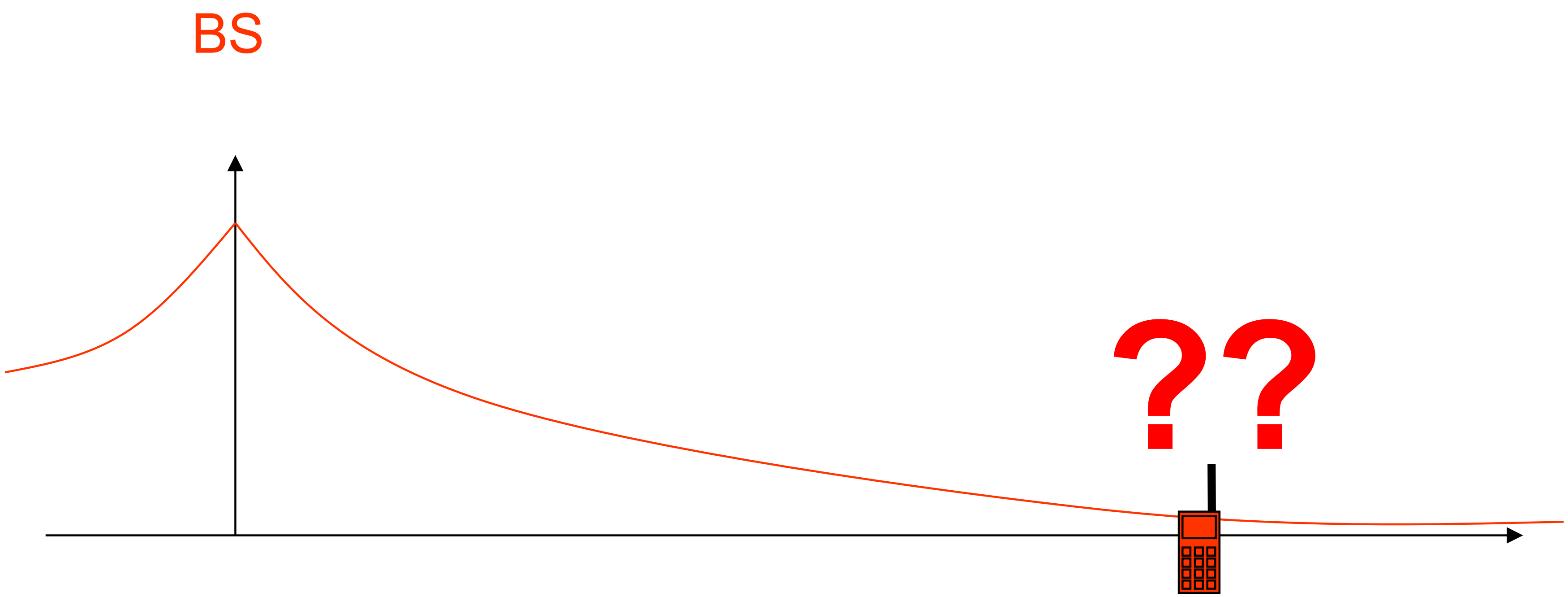
Antenna gain (2)

- Antenna gain and its effective surface

$$G = \frac{4\pi A_e}{\lambda^2} = \frac{4\pi f A_e}{c^2}$$

- with
  - G = gain
  - A_e= effective surface
  - f = signal frequency
  - c = light speed in space 3.10^8 m/s
  - λ= wave length of the signal=c/f

1st challenge: signal attenuation



Attenuation limits the range!

- Attenuation depends mainly on distance

$$\boxed{P_r = P_e d^{-\alpha}}$$

- with :
  - P_e = transmitted power
  - P_r = received power
  - d = distance between antennas
  - α from 2 to 4

Attenuation in practice

- For an ideal antenna (theoretic)

$$\boxed{\frac{P_e}{P_r} = \frac{(4\pi d)^2}{\lambda^2} = \frac{(4\pi f d)^2}{c^2}}$$

- P_e = transmitted power
- P_r = received power
- P_e / P_r is high when P_r is small → high attenuation
- d = distance between antennas
- c = light speed in space 3.10^8 m/s
- λ= wave length of the signal=c/f
- Higher frequencies f means higher attenuation!

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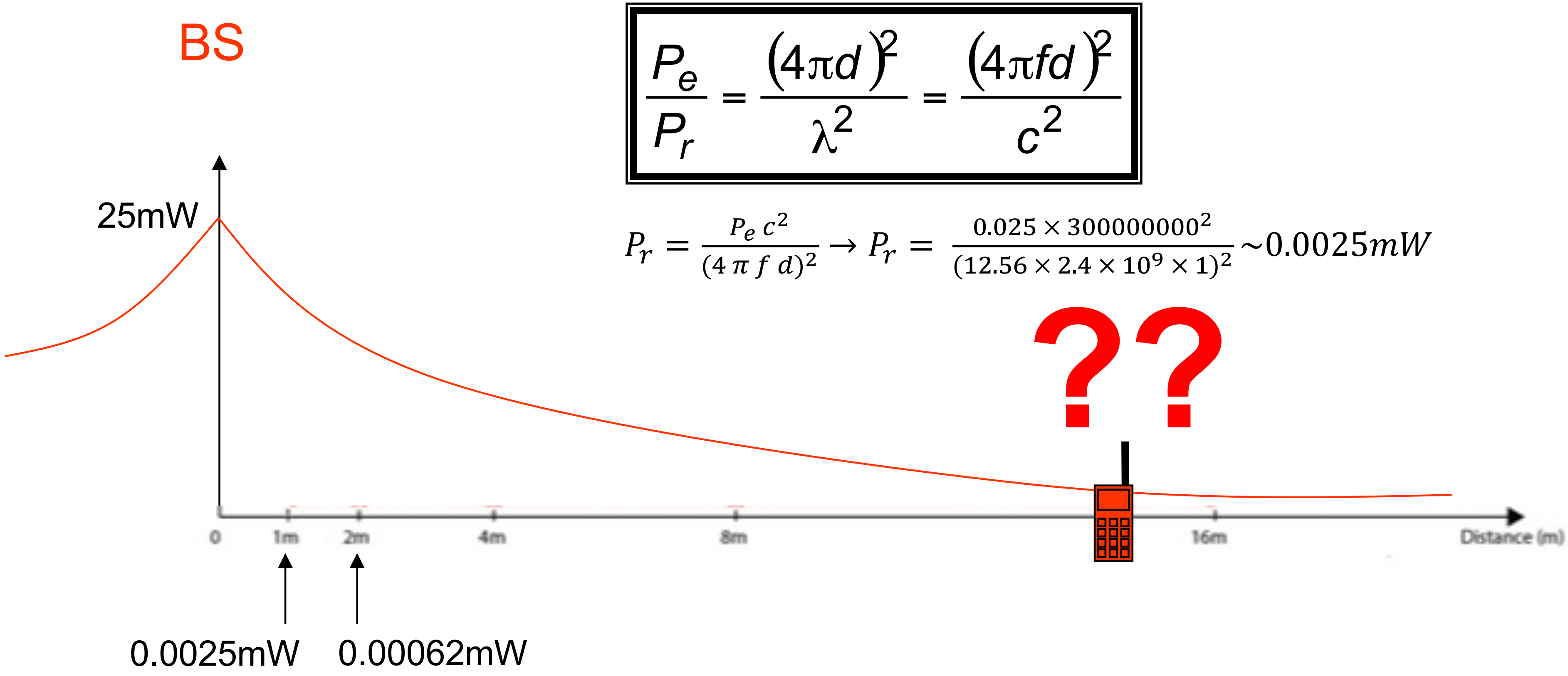
Attenuation, value in watts

- Free Space Path Loss model

$$\boxed{\frac{P_e}{P_r} = \frac{(4\pi d)^2}{\lambda^2} = \frac{(4\pi f d)^2}{c^2}}$$

$$P_r = \frac{P_e\, c^2}{(4\,\pi\, f\, d)^2} \rightarrow P_r = \frac{0.025 \times 300000000^2}{(12.56 \times 2.4 \times 10^9 \times 1)^2} \sim 0.0025mW$$



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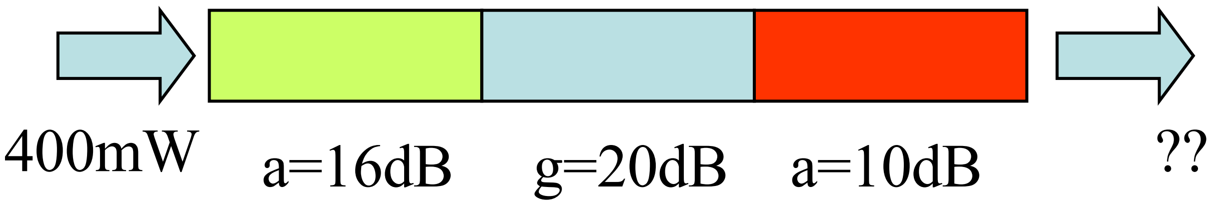
Attenuation in decibel (dB)

- Decibel uses logarithmic scale as attenuation values can be very large
- Attenuation in dB: $10\log10(P_e/P_r)$, P_e and P_r in watts
  - So $P_e/P_r = 10^{dB/10}$
  - Difference of 3dB≈half (divided by 2) as $P_e/P_r = 10^{3/10} = 10^{0.3} = 1.99526\ldots$
- ➡Gain = $10\log10(P_r/P_e)$
- We can add various sections with attenuation or gain



-16dB + 20dB - 10dB = -6dB, so it is an attenuation

$P_e/P_r = 10^{6/10} = 10^{0.6} = 3.98$ ➡ $P_r = P_e/3.98 \approx 100\text{mW}$

dB, dBm, …

- Total net output power of transmitter
- Typically measured in dBm or mW

- **mW:** milliwatts are a measurement of power (1000 mW = 1 Watt).
- **dB:** decibel is a unit for expressing the ratio of two amounts of signal power equal to 10 times the common logarithm of this ratio. So, a power measurement in dB has to be relative to something.
- **dBm:** dB(mW) is power relative to 1 milliwatt (mW to dBm = $10\text{Log}_{10}(\text{mW}/1000) + 30$).

  $P(\text{dBm}) = 10 \cdot \log 10(P(\text{mW}) / 1\text{mW})$
- **dBi:** dB(isotropic) is the forward gain of an antenna compared to the hypothetical isotropic antenna, which uniformly distributes energy in all directions.

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dBm to mW conversion

P(dBm)=10.log$_{10}$(P(mW)/1mW)

$$P(mW) = 10^{\frac{P(dBm)}{10}}$$

Ex:

$$P(mW) = 10^{\frac{14dBm}{10}} = 10^{1.4} = 25.118mW$$

dBm	Watts
0	1.0 mW
1	1.3 mW
2	1.6 mW
3	2.0 mW
4	2.5 mW
5	3.2 mW
6	4 mW
7	5 mW
8	6 mW
9	8 mW
10	10 mW
11	13 mW
12	16 mW
13	20 mW
14	25 mW
15	32 mW

dBm	Watts
16	40 mW
17	50 mW
18	63 mW
19	79 mW
20	100 mW
21	126 mW
22	158 mW
23	200 mW
24	250 mW
25	316 mW
26	398 mW
27	500 mW
28	630 mW
29	800 mW
30	1.0 W
31	1.3 W

dBm	Watts
32	1.6 W
33	2.0 W
34	2.5 W
35	3.2 W
36	4.0 W
37	5.0 W
38	6.3 W
39	8.0 W
40	10 W
41	13 W
42	16 W
43	20 W
44	25 W
45	32 W
46	40 W
47	50 W

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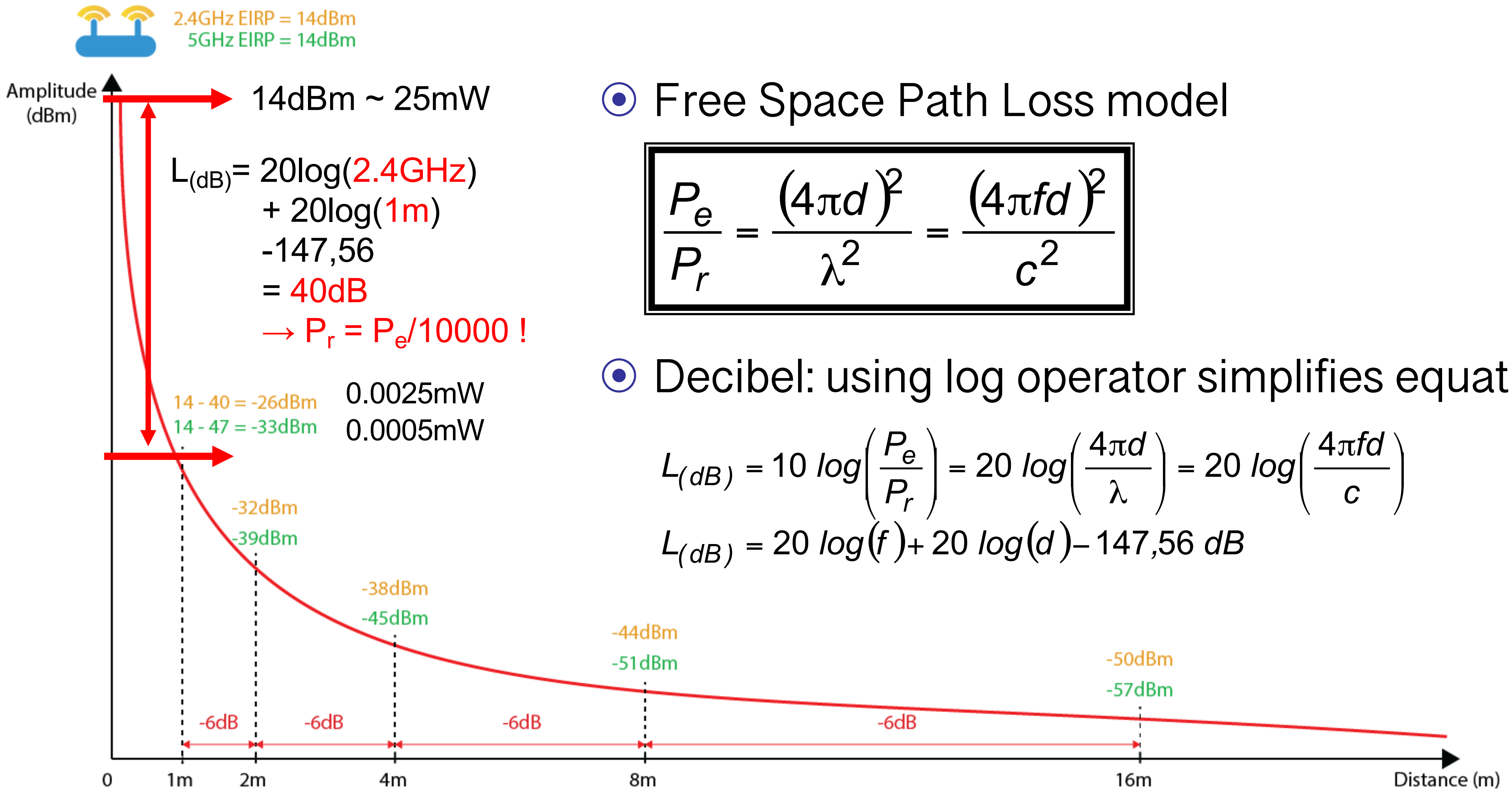
Attenuation, using dBm & dB



$$10^{\frac{-26dBm}{10}} = 10^{-2.6} = 0.0025118mW$$

$$10^{\frac{-32dBm}{10}} = 10^{-3.2} = 0.00063mW$$

- Free Space Path Loss model

$$\boxed{\frac{P_e}{P_r} = \frac{(4\pi d)^2}{\lambda^2} = \frac{(4\pi f d)^2}{c^2}}$$

- Decibel: using log operator simplifies equation

$$L_{(dB)} = 10\ log\left(\frac{P_e}{P_r}\right) = 20\ log\left(\frac{4\pi d}{\lambda}\right) = 20\ log\left(\frac{4\pi f d}{c}\right)$$

$$L_{(dB)} = 20\ log(f) + 20\ log(d) - 147{,}56\ dB$$

Additional advantage of log scale: very large and very small values can be plotted on the same graph

Impact of signal frequency

- Free Space Path Loss model

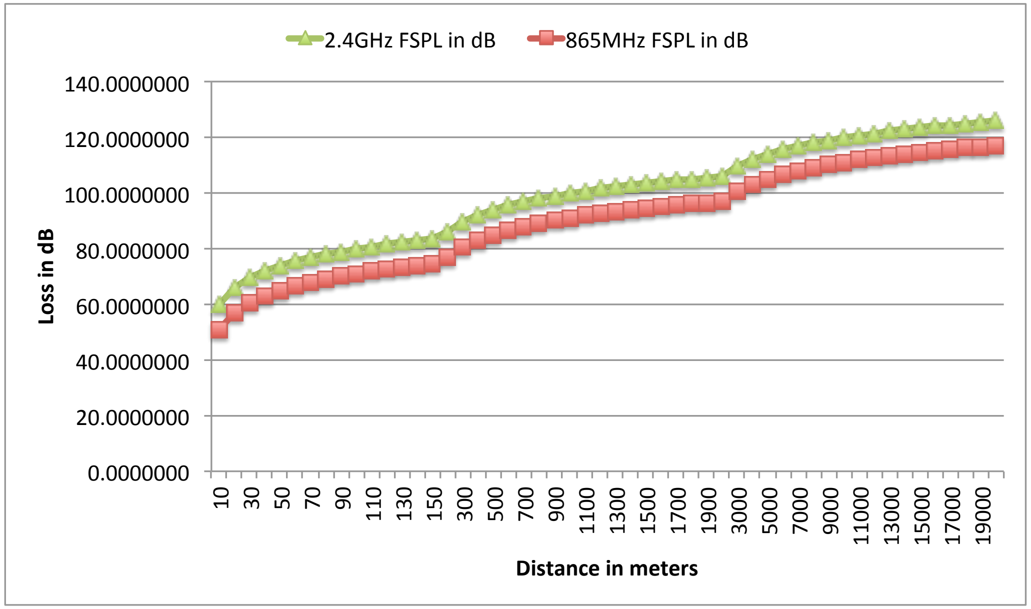
$$\mathrm{FSPL} = \left(\frac{4\pi d}{\lambda}\right)^2 = \left(\frac{4\pi df}{c}\right)^2$$

$$FSPL = \frac{P_t}{P_r} G_t G_r$$

FSPL assume Gt=Gr=1

$$L_{(dB)} = 10\log\left(\frac{P_t}{P_r}\right) = 20\log\left(\frac{4\pi d}{\lambda}\right) = 20\log\left(\frac{4\pi fd}{c}\right)$$

$$L_{(dB)} = 20\log(f) + 20\log(d) - 147{,}55\ dB$$

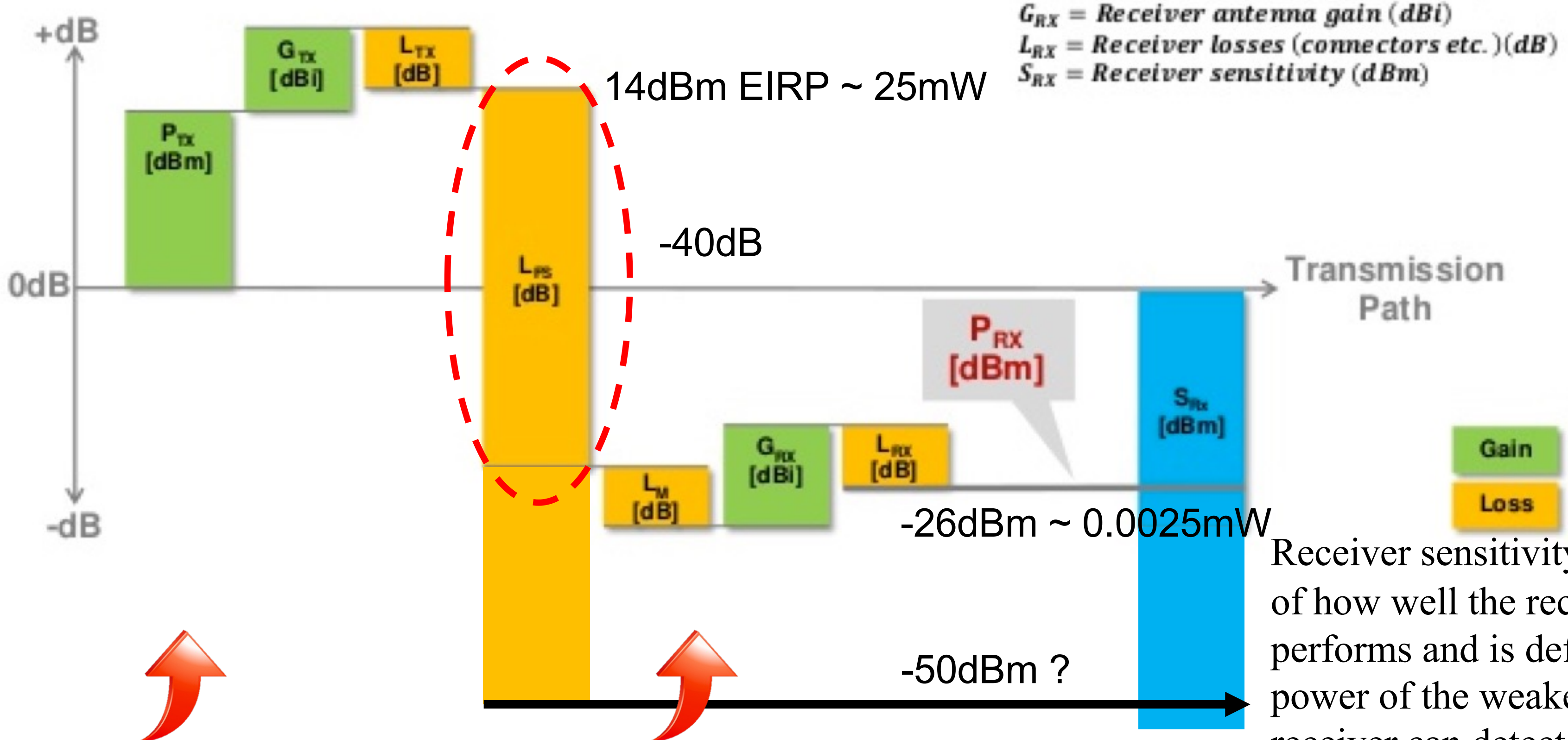


Link budget in wireless system

$$P_{RX} = P_{TX} + G_{TX} - L_{TX} - L_{FS} - L_M + G_{RX} - L_{RX}$$

P_{RX} = Received power (dBm)
P_{TX} = Sender output power (dBm)
G_{TX} = Sender antenna gain (dBi)
L_{TX} = Sender losses (connectors etc.)(dB)
L_{FS} = Free space loss (dB)
L_M = Misc. losses (multipath etc.)(dB)
G_{RX} = Receiver antenna gain (dBi)
L_{RX} = Receiver losses (connectors etc.)(dB)
S_{RX} = Receiver sensitivity (dBm)

Adapted from Peter R. Egli, INDIGOO.COM



Receiver sensitivity is a measure of how well the receiver performs and is defined as the power of the weakest signal the receiver can detect

$$L_{(dB)} = 20\log(f) + 20\log(d) - 147{,}56\ dB$$

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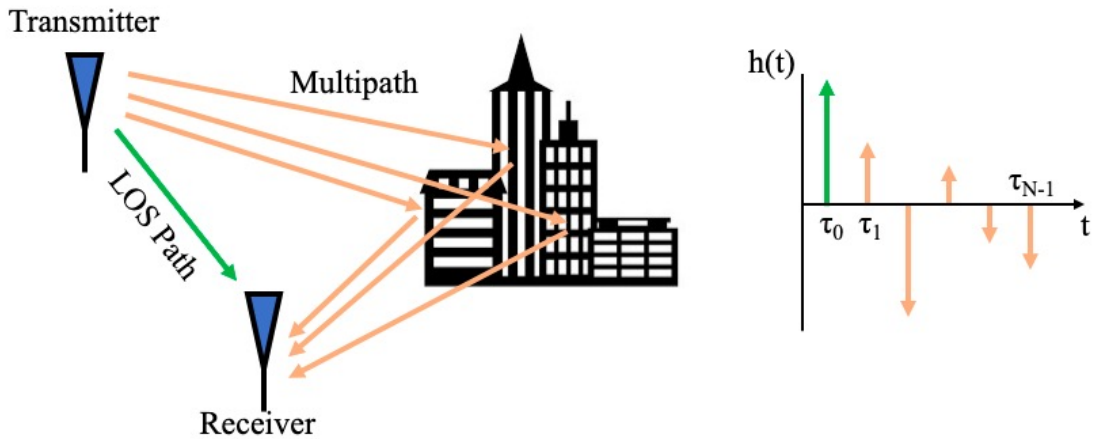
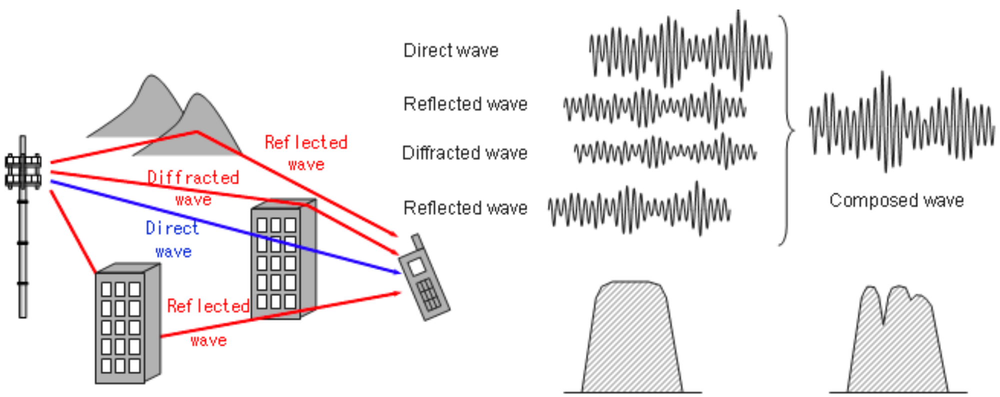
Receiver's sensitivity

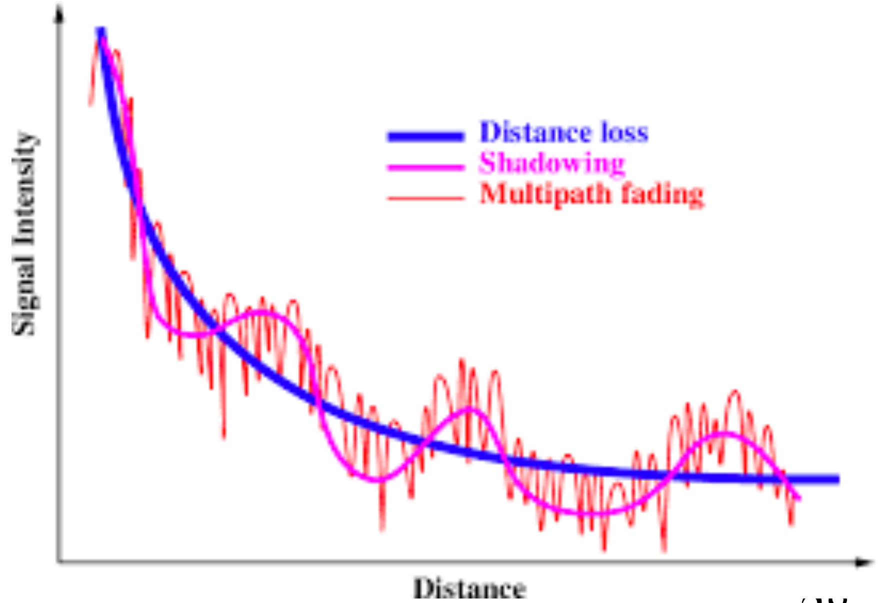
- Receiver's sensitivity is a measure of how well the receiver performs and is defined as the power of the weakest signal the receiver can detect
- How low can you go?

Shadow fading & Multi-path fading

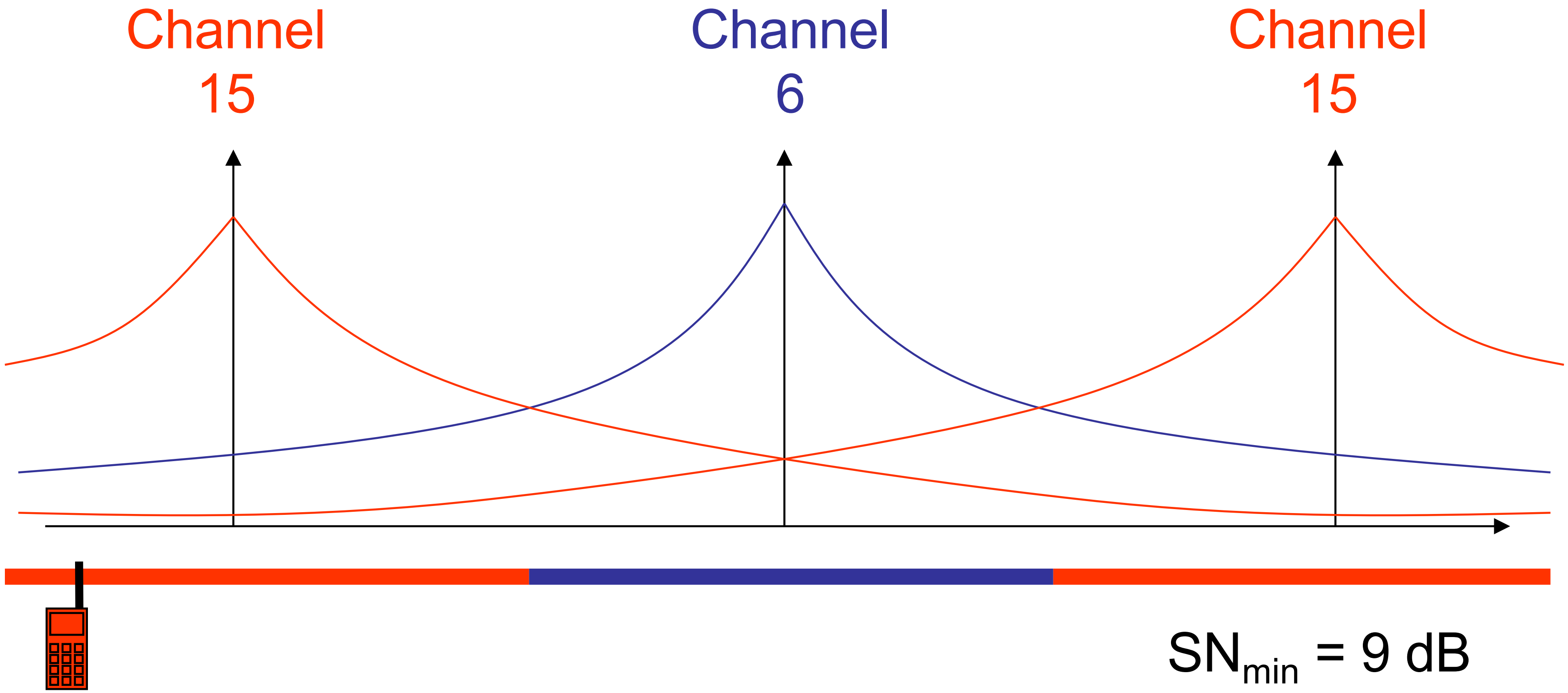
- Things are getting even worse!
- Shadow fading by obstacles
- Multi-path fading
- …







Frequency re-use

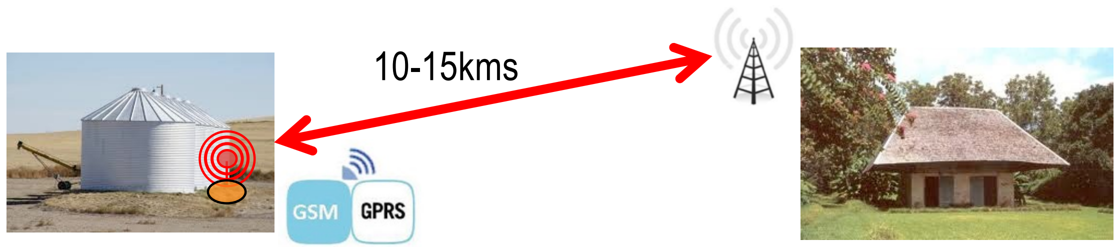


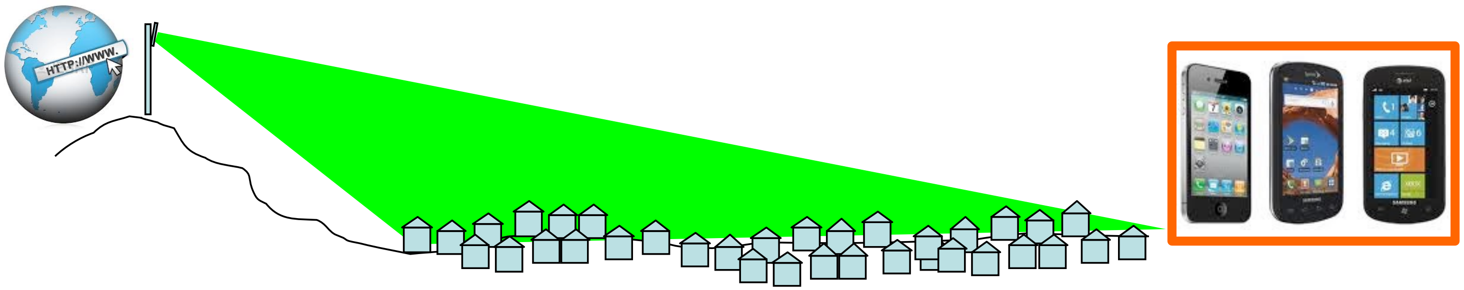
SN_{min} = 9 dB

$S/N=10^{9/10}=7.94$

2nd challenge: energy cost

Moisture/
Temperature of
storage areas



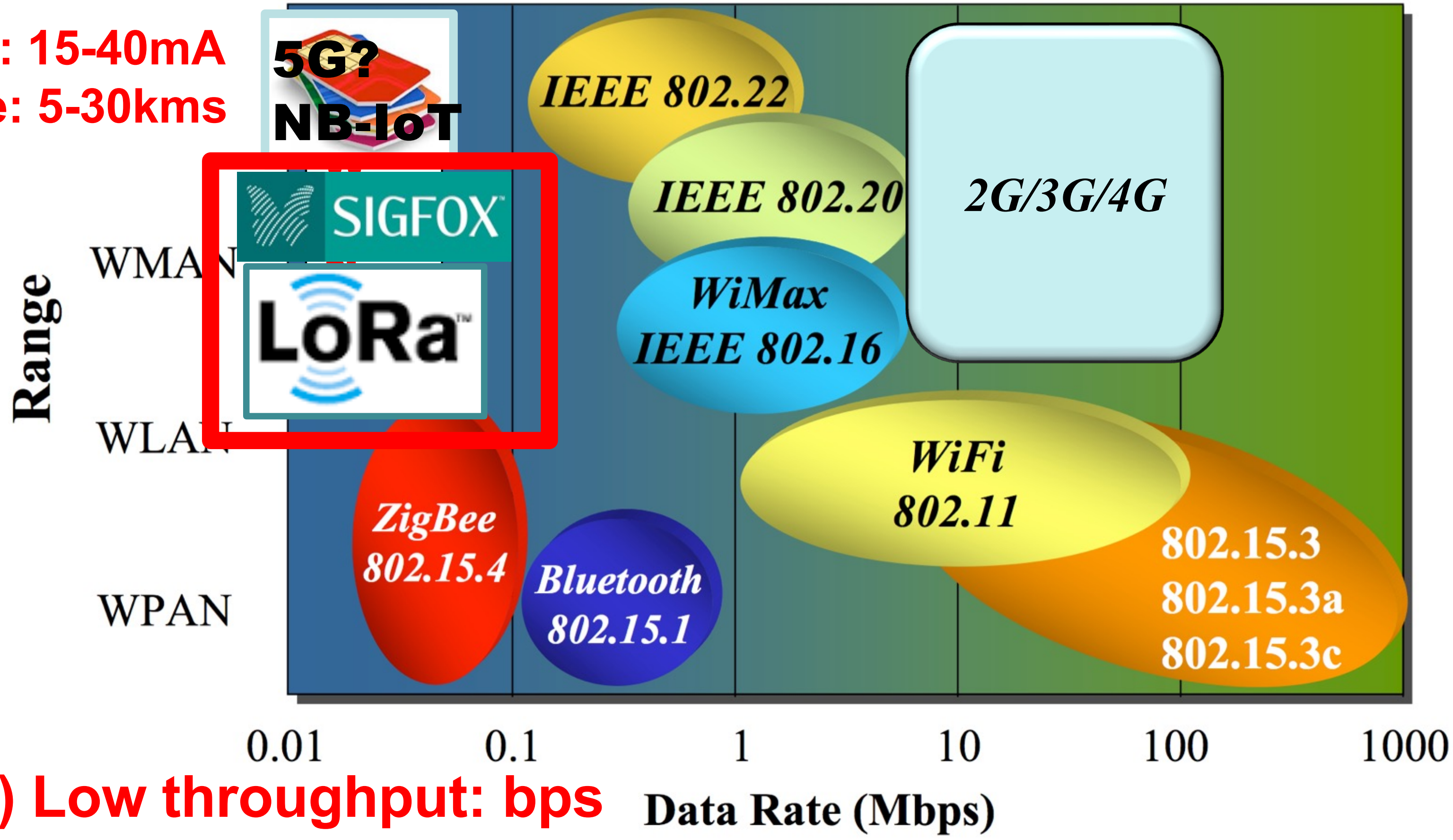


Technology	2G	3G	LAN
Range (I=Indoor, O=Outdoor)	N/A	N/A	O: 300m I: 30m
Tx current consumption	200-500mA	500-1000mA	100-300mA
Standby current	2.3mA	3.5mA	NC

Low-power, long-range radios for IoT systems: LPWAN networks

LPWAN
Low-power: 15-40mA
Long-range: 5-30kms

Energy-Range dilemma



Energy

(Very) Low throughput: bps

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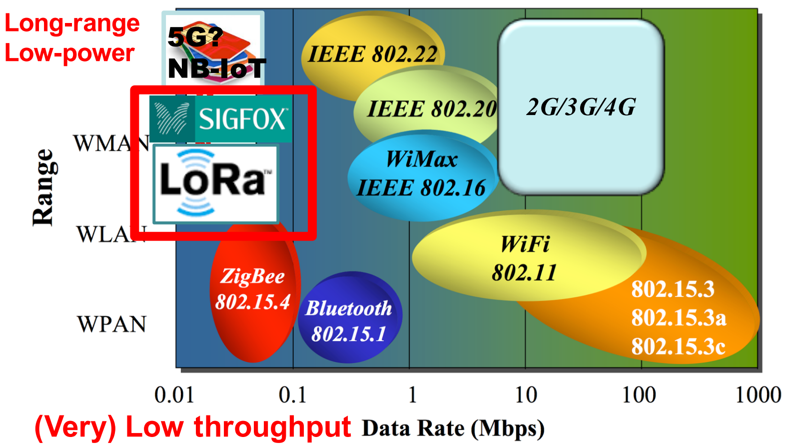
Energy consumption comparaison

Energy-Range dilemma



Energy

2G	3G	LAN	ZigBee	Lo Power WAN
N/A	N/A	O: 300m I: 30m	O: 90m I: 30m	Same as 2G/3G
200-500mA	500-1000mA	100-300mA	18mA	18mA-40mA
2.3mA	3.5mA	NC	0.003mA	0.001mA

2500mA

TX power: 500mA. Mean consumption: (8sx500+3592sx0.005)/3600=1.11mA

2500/1.11=2252h = 93 days = 3 months ☹

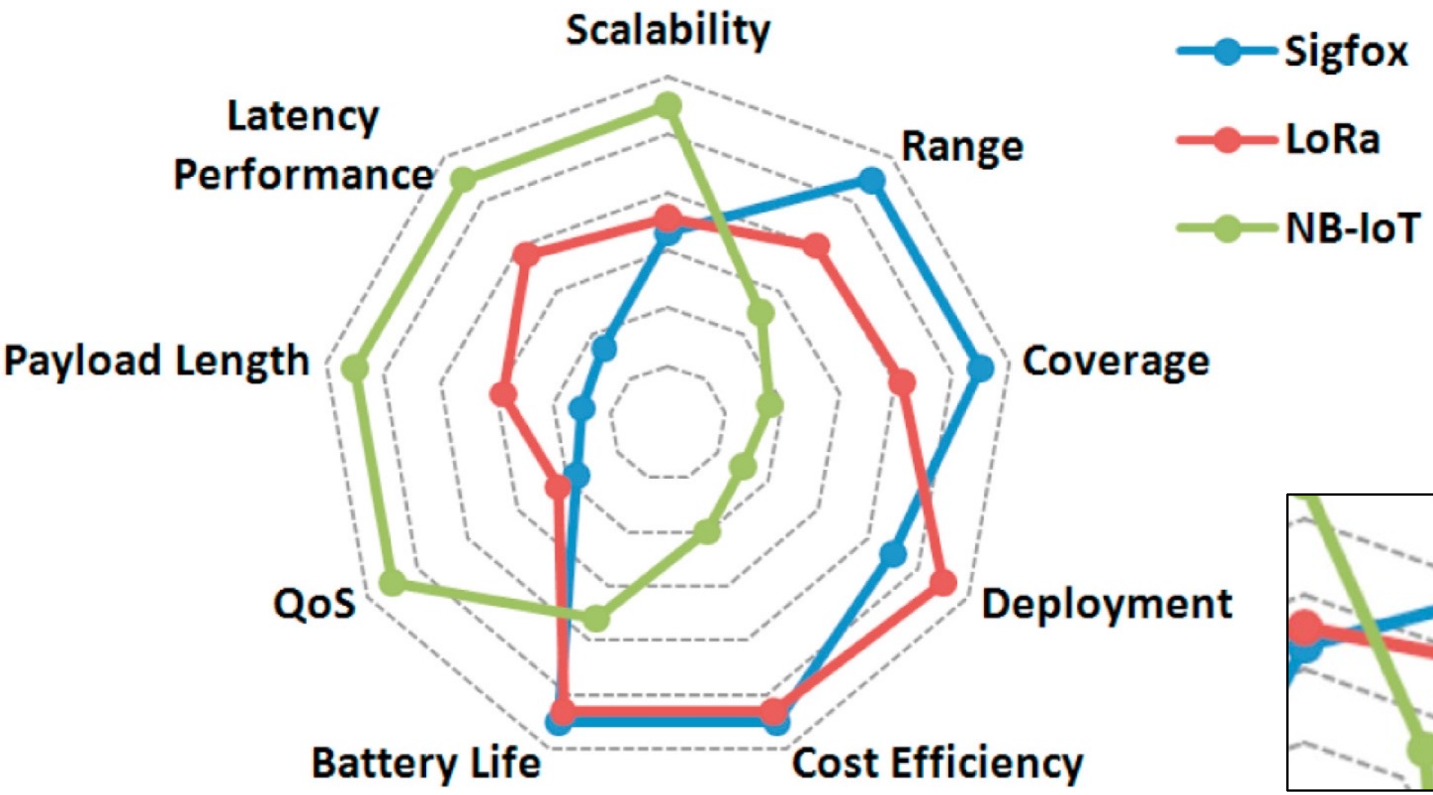
In most cellular networks, the device is still maintaining communication with BS even if it is inactive

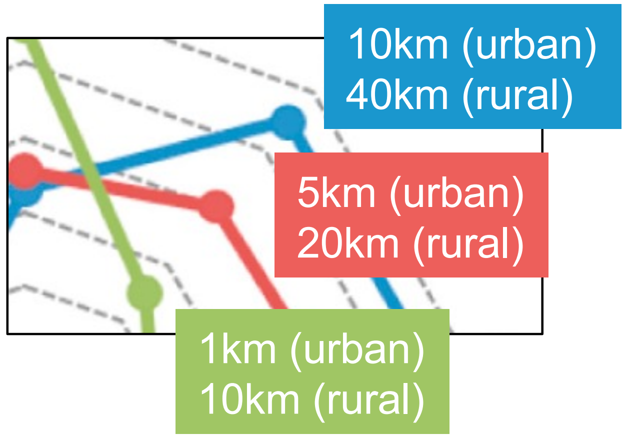
TX power: 40mA. Mean consumption: (2sx40+3598sx0.005)/3600=0.027mA

2500/0.027=92592h = 3858 days = 10 y. ☺

LPWAN does not need to maintain connection if not in used

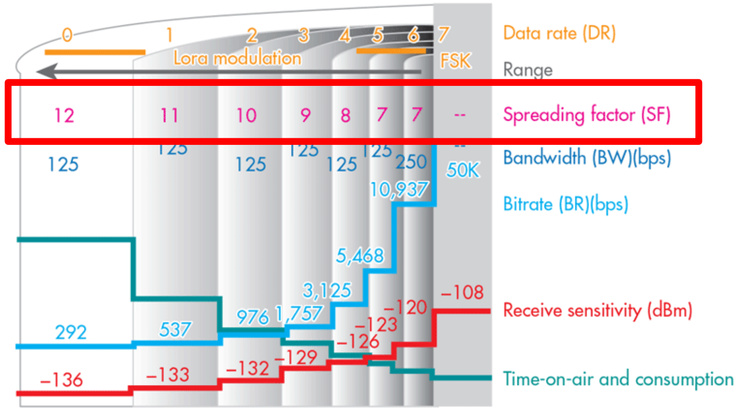
Expected range?





How can we increase range?

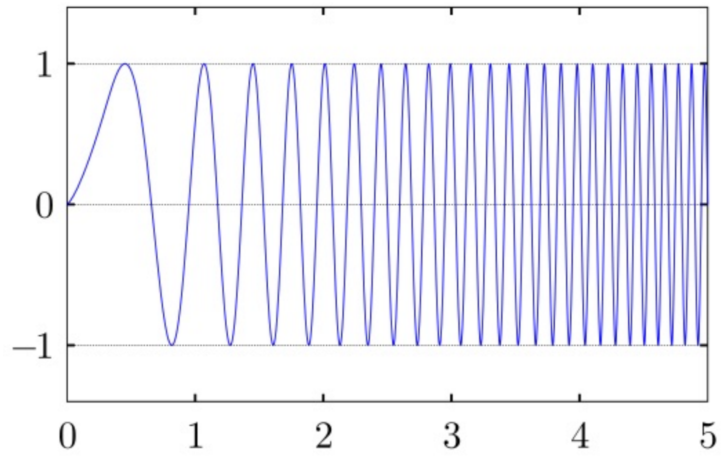
- Increase TX power and/or improve RX sensitivity
- Generally, RX sensitivity (~robustness) can be increased when transmitting (much) slower (like speaking slower!)
- LoRa uses spread spectrum approach to increase RX sensitivity
  - Spreading Factor defines how many chips will be used to code a symbol. More chip/symbol=longer transmission time ➟ more robustness
- **The price to pay for LPWAN**
  - LoRa has very low throughput: 200bps-37500bps (0.2-37.5kbps)



- WiFi 802.11n: 450 000 000 bps (450Mbps)
- WiFi 802.11g: 54 000 000 bps (54Mbps)
- Bluetooth3&4: 25 000 000 bps (25Mbps)
- Bluetooth BLE: 2 000 000 bps (2Mbps)
- 3G/4G : 20Mbps-200Mbps
- LoRa : 200bps-37500bps (0.0002-0.0375Mbps)
- 3G/LoRa ratio: 20,000,000bps/200bps=100000!

Chirp Spread Spectrum in LoRa

- Compressed High Intensity Radar Pulse (CHIRP) is a signal which frequency either increases or decreases in time, in a deterministic way



- Can be very low power, but then low data rate!
- Very high interference immunity
  - Thus adapted to very large distances
  - Better resistance to frequency shift (e.g. Doppler shift, low-cost oscillator)

LoRa spreading factor in image

- Higher spreading factor means lower data rate but increased receiver sensitivity

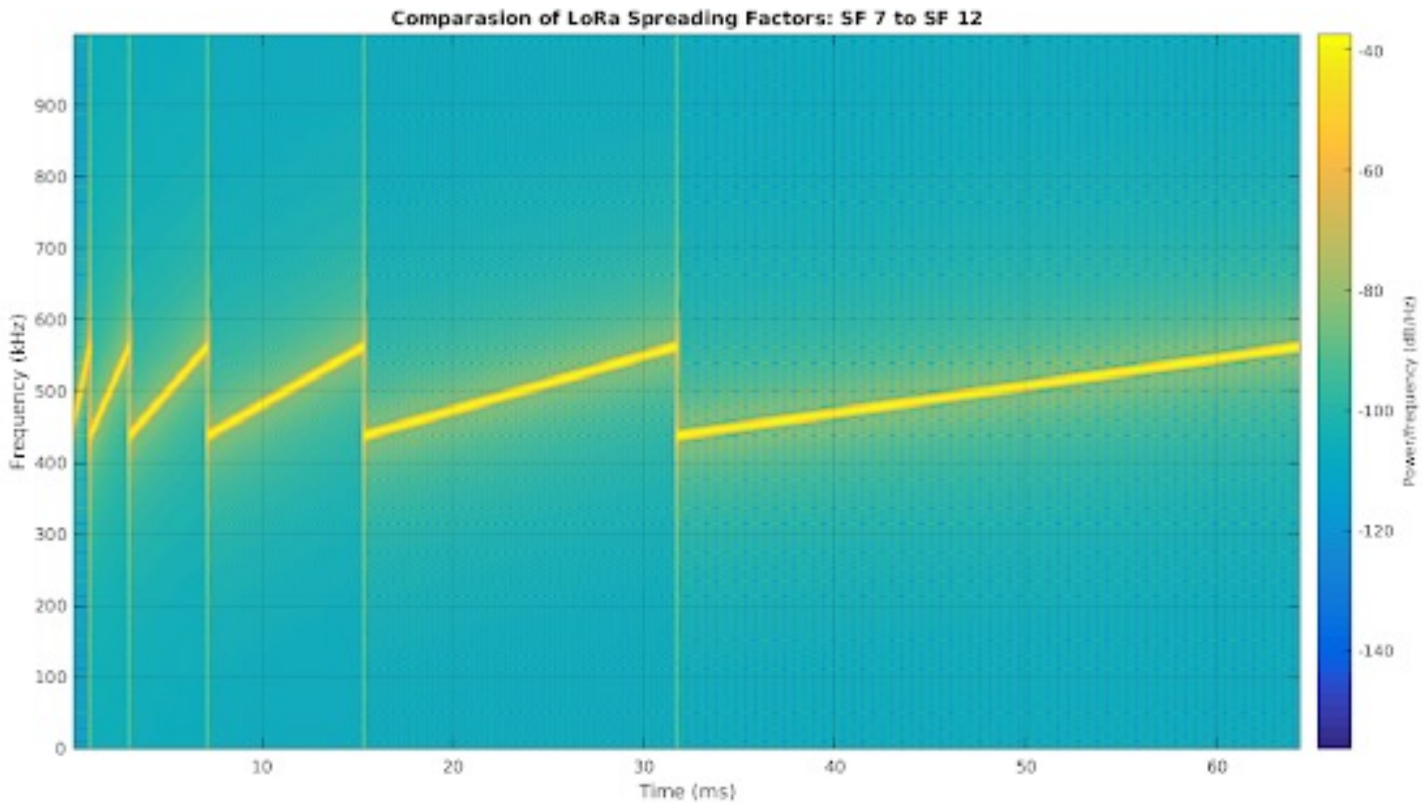
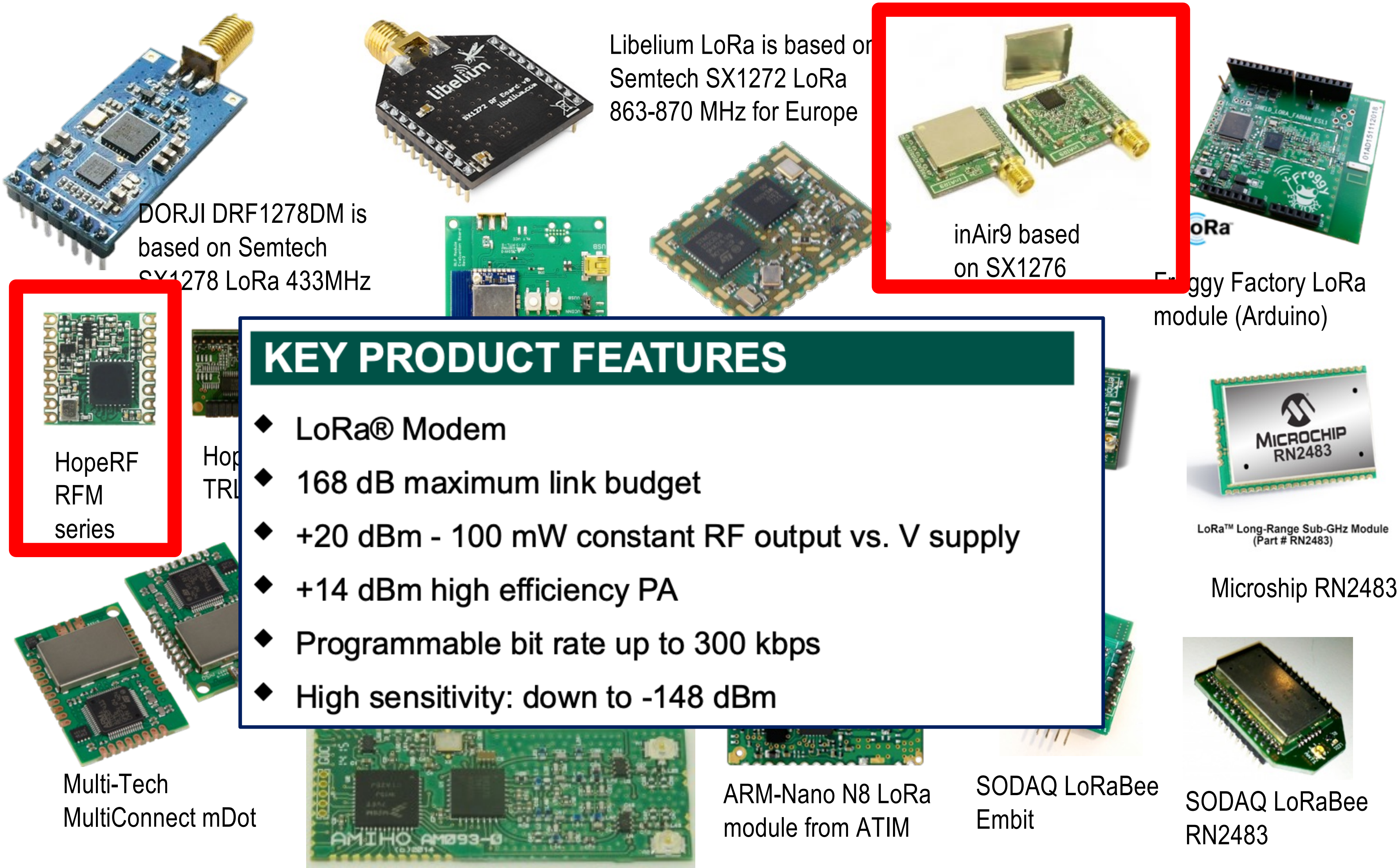


Figure from "All About LoRa and LoRaWAN", https://www.sghoslya.com

LoRa modules with Semtech's SX127x

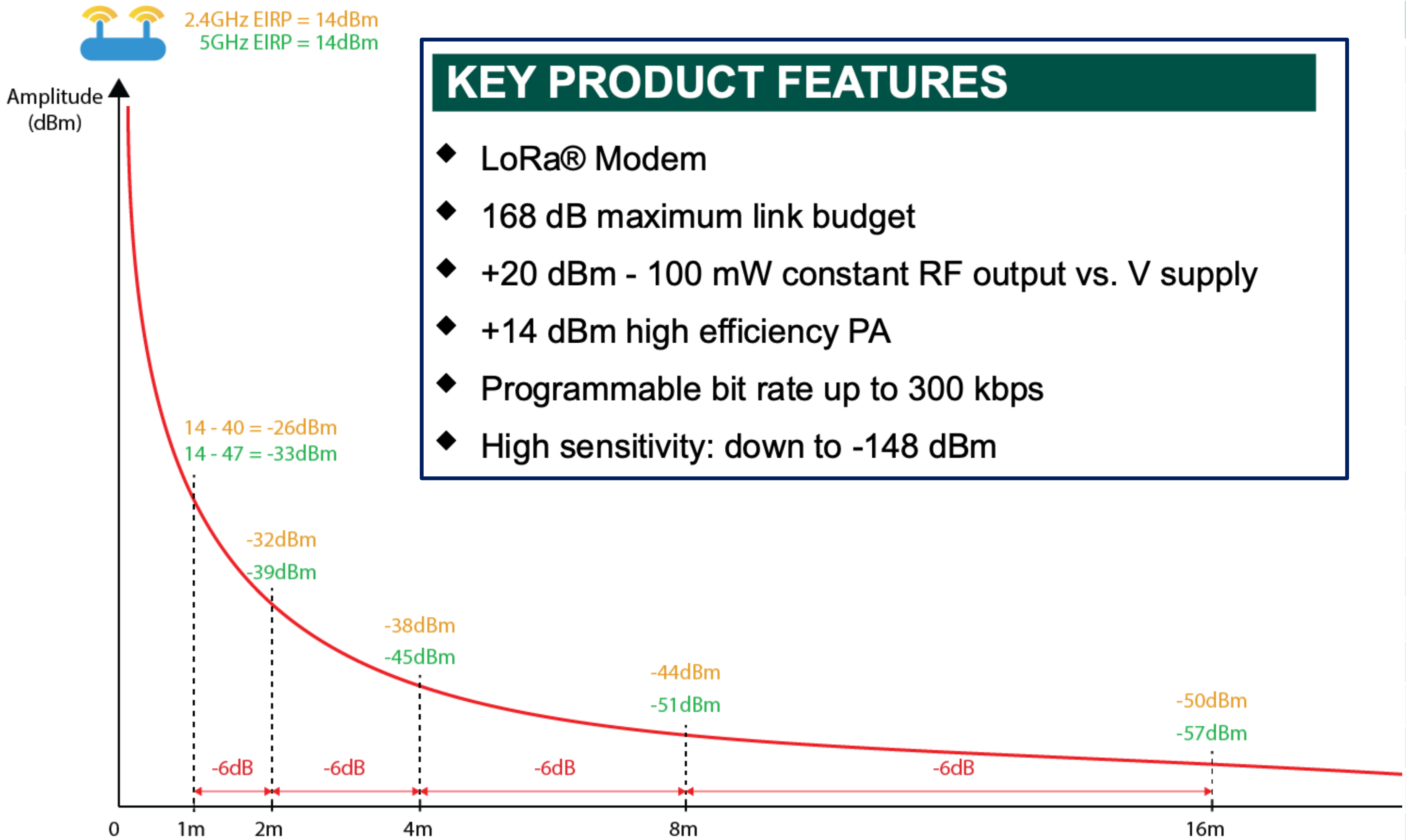


KEY PRODUCT FEATURES

- LoRa® Modem
- 168 dB maximum link budget
- +20 dBm - 100 mW constant RF output vs. V supply
- +14 dBm high efficiency PA
- Programmable bit rate up to 300 kbps
- High sensitivity: down to -148 dBm

Prof. Congduc Pham
http://www.univ-pau.fr/~cpham

What distance for -148dBm?



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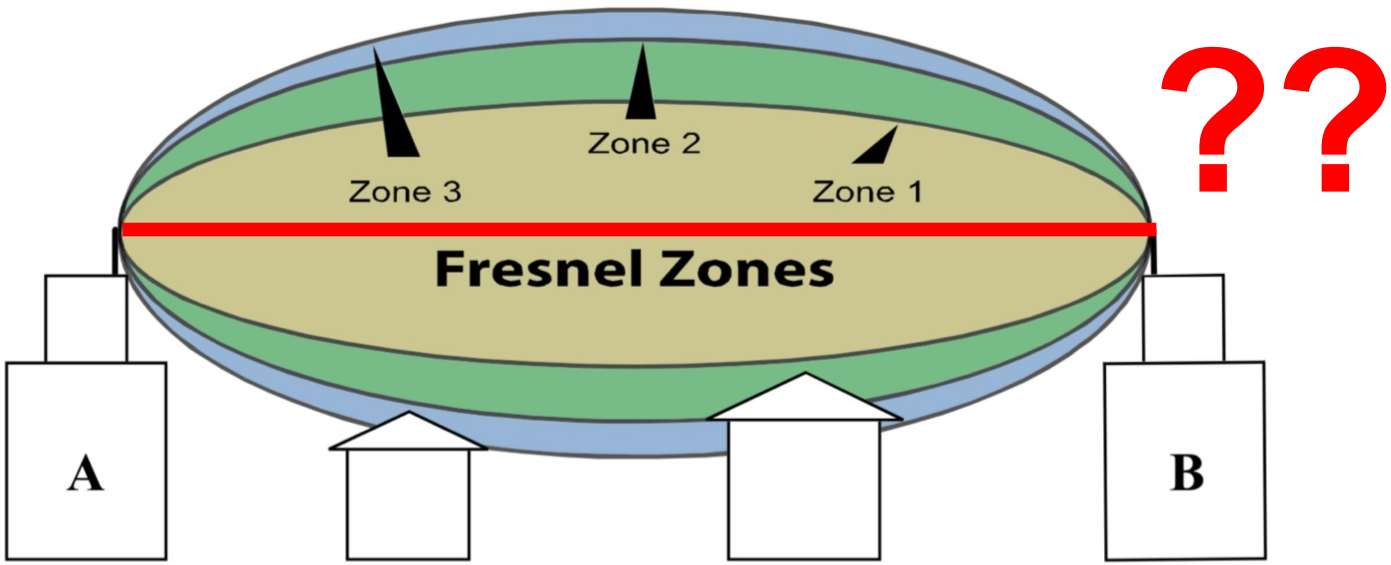
-26	1
-32	2
-38	4
-44	8
-50	16
-56	32
-62	64
-68	128
-74	256
-80	512
-86	1024
-92	2048
-98	4096
-104	8192
-110	16384
-116	32768
-122	65536
-128	131072
-134	262144
-140	524288
-146	1048576
-152	2097152

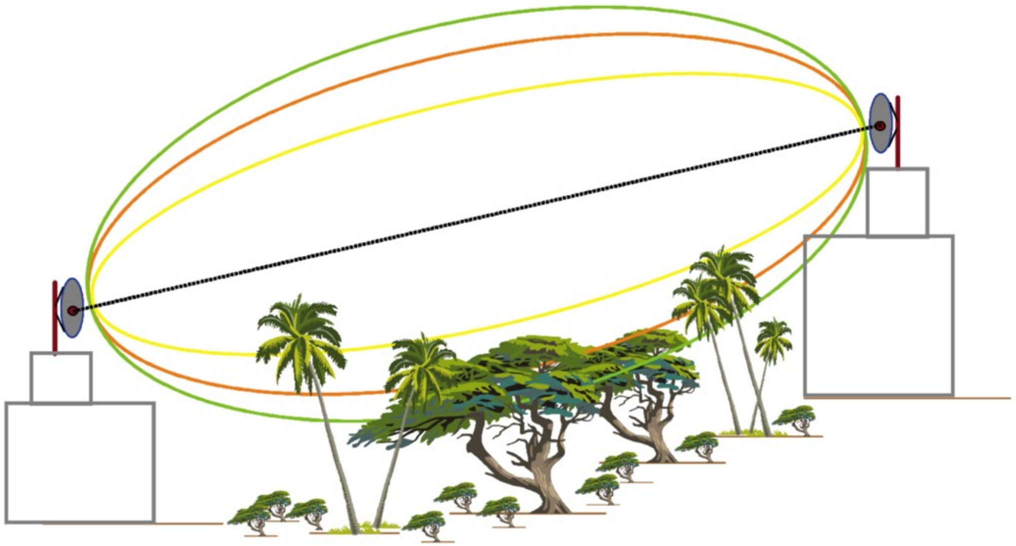
Line-of-Sight & Fresnel zone

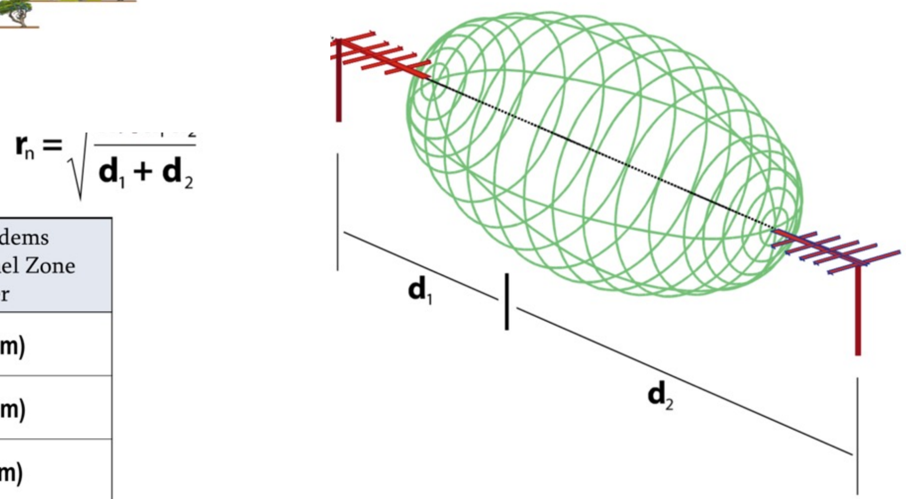
- LoS means clear Fresnel zone
- Football (american) shape
- Acceptable = 60% of zone 1 + 3m



RF Essentials from Digi

Clearing the Fresnel zone? Raise antennas!





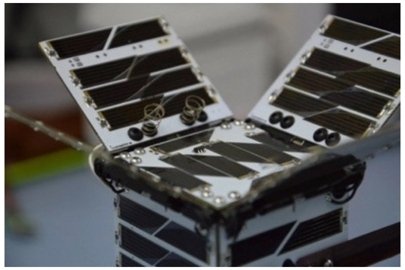
Range Distance	900 MHz Modems Required Fresnel Zone Diameter	2.4 GHz Modems Required Fresnel Zone Diameter
1000 ft. (300 m)	16 ft. (5 m)	11 ft. (3.4 m)
1 Mile (1.6 km)	32 ft. (10 m)	21 ft. (6.4 m)
5 Miles (8 km)	68 ft. (21 m)	43 ft. (13 m)
10 Miles (16 km)	95 ft. (29 m)	59 ft. (18 m)

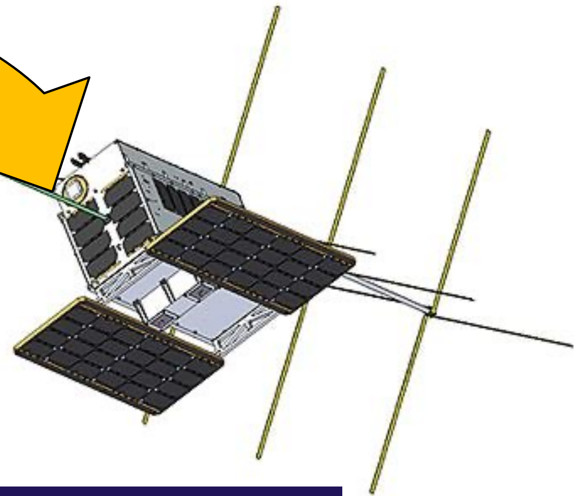
RF Essentials from Digi

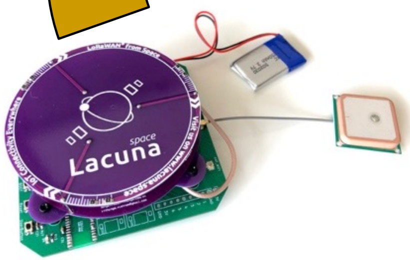
Clearing the Fresnel zone? Let's use satellite!

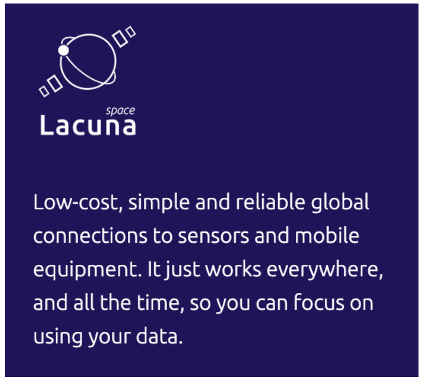
- Low-orbit, low-cost; compact satellite for global coverage

LoRa over 1200kms!









https://lacuna.space/first-successful-lacunasat-launch-in-2021/

Prof. Congduc Pham
http://www.univ-pau.fr/~cpham

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IoT – from idea to reality