

IOT Online Course

Fundamentals of IoT

F-IOT-2a: Wireless Communication Essentials

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🔗 <http://diy.waziup.io>

IOT COURSES

WAZIUP IoT Courses

For users who wants to gain knowledge on IoT in a step-by-step lecture mode, we have defined the following curriculum with materials from both existing sources and specific materials produced by WAZIUP/WAZIHUB project.

«Fundamental of IoT»

F-IOT-1a: What is IoT ?

- WAZI 📺 Quick introduction to
- WAZI 📺 IoT and Big Data Platf
- Intel IoT -- What Does The Inte
- Edureka -- Internet of Things (I
- Geospatial IoT -- IoT- What is I
- IBM Think Academy -- How It V

F-IOT-1b: Introduction to

- WAZI 📺 Introduction To Basic
- Introduction To Basic Electroni
- Basic Electronics - Instructable
- WAZI 📺 Introducing physical s
- WAZI 📺 Introducing physical s

F-IOT-2: IoT ecosystem an

- WAZI 📺 F-IOT-2a: Wireless Communication Essentials
- WAZI 📺 F-IOT-2b: Understanding IoT Devices, Architecture & Ecosystem
- WAZI 📺 F-IOT-2c: Introduction to IoT hardware

F-IOT-1b: Introduction to Basic Electronics

- WAZI 📺 Introduction To Basic Electronics -
- Introduction To Basic Electronics - MakerSpaces
- Basic Electronics - Instructables
- WAZI 📺 Introducing physical sensors, part 1
- WAZI 📺 Introducing physical sensors, part 2

F-IOT-2: IoT ecosystem and hardware

- WAZI 📺 F-IOT-2a: Wireless Communication Essentials
- WAZI 📺 F-IOT-2b: Understanding IoT Devices, Architecture & Ecosystem
- WAZI 📺 F-IOT-2c: Introduction to IoT hardware

F-IOT-3: Introduction to Arduino IDE

- Introduction to Arduino IDE - YouTube
- WAZI 🌐 Presentation of the Arduino IDE
- WAZI 📺 Setting up the Arduino IDE

F-IOT-4: WAZIUP IoT ecosystem

- WAZI 📺 F-IOT-4: WAZIUP Open Technologies for Low-cost IoT

Wireless networks: WiFi



<p>1973</p> <p>Ethernet developed at Xerox's Palo Alto Research Center (PARC)</p>	<p>1977</p> <p>Ethernet patented by Xerox</p>	<p>1997</p> <p>802.11 Standard</p> <p>The 802.11 standard is created. Products using the 2.4 GHz band have a maximum data rate of 2 Mbps</p> <p>2.40 GHz</p> <p>Max Data Rate: 2 Mbps</p>	<p>2007</p> <p>802.11n Standard (I)</p> <p>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.</p> <p>5.0 GHz</p> <p>Max Data Rate: 450 Mbps</p>	<p>2009</p> <p>802.11 Standard (II)</p> <p>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.</p> <p>5.0 GHz</p> <p>Max Data Rate: 600 Mbps</p>	<p>2011</p> <p>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.</p>
<p>1999</p> <p>802.11a Standard</p> <p>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.</p> <p>5.0 GHz</p> <p>Max Data Rate: 54 Mbps</p>	<p>2003</p> <p>802.11g Standard</p> <p>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.</p> <p>2.40 GHz</p> <p>Max Data Rate: 54 Mbps</p> <p>>> Throughput of 5 GHz devices</p>	<p>2005</p> <p>802.11e Standard</p> <p>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.</p> <p>5.85 GHz</p>	<p>2013</p> <p>802.11ac Standard (I)</p> <p>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.</p> <p>5.0 GHz</p> <p>Max Data Rate: 1.3 Gbps</p>	<p>2014</p> <p>802.11ac Standard (II)</p> <p>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.</p> <p>5.0 GHz</p> <p>Max Data Rate: 6.93 Gbps</p>	<p>TechTarget</p> <p>For up-to-date news, analysis and advice on networking visit SearchNetworking.com.</p> <p>Information by Sonia Graf/TechTarget Design by Brian Linnahay/TechTarget</p>

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



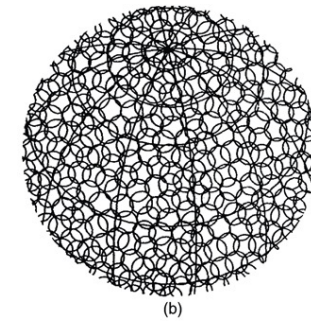
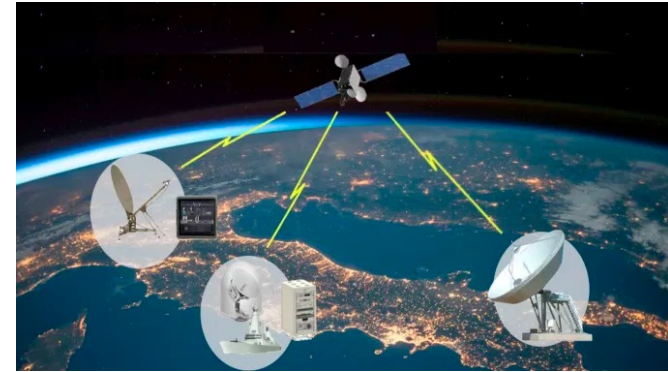
Wireless networks: Bluetooth

How Bluetooth is Transforming Consumer Electronics



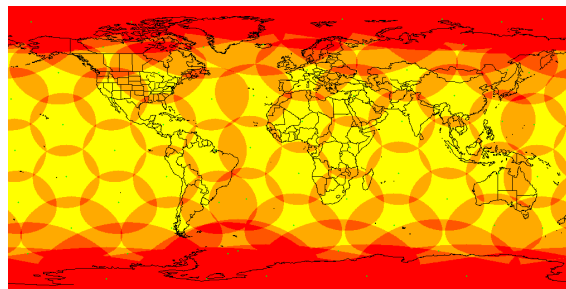
Wireless networks: Satellites

Altitude (km)	Type	Latence (ms)	Satellites nécessaires
35 000	GEO	270	3
15 000 - 20 000	Ceinture de Van Allen extérieure		
10 000	MEO	35-85	10
5 000 - 10 000	Ceinture de Van Allen intérieure		
1-7	LEO	1-7	50

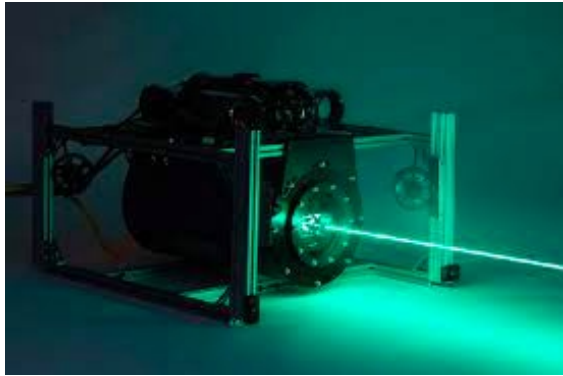


© Pearson Education France

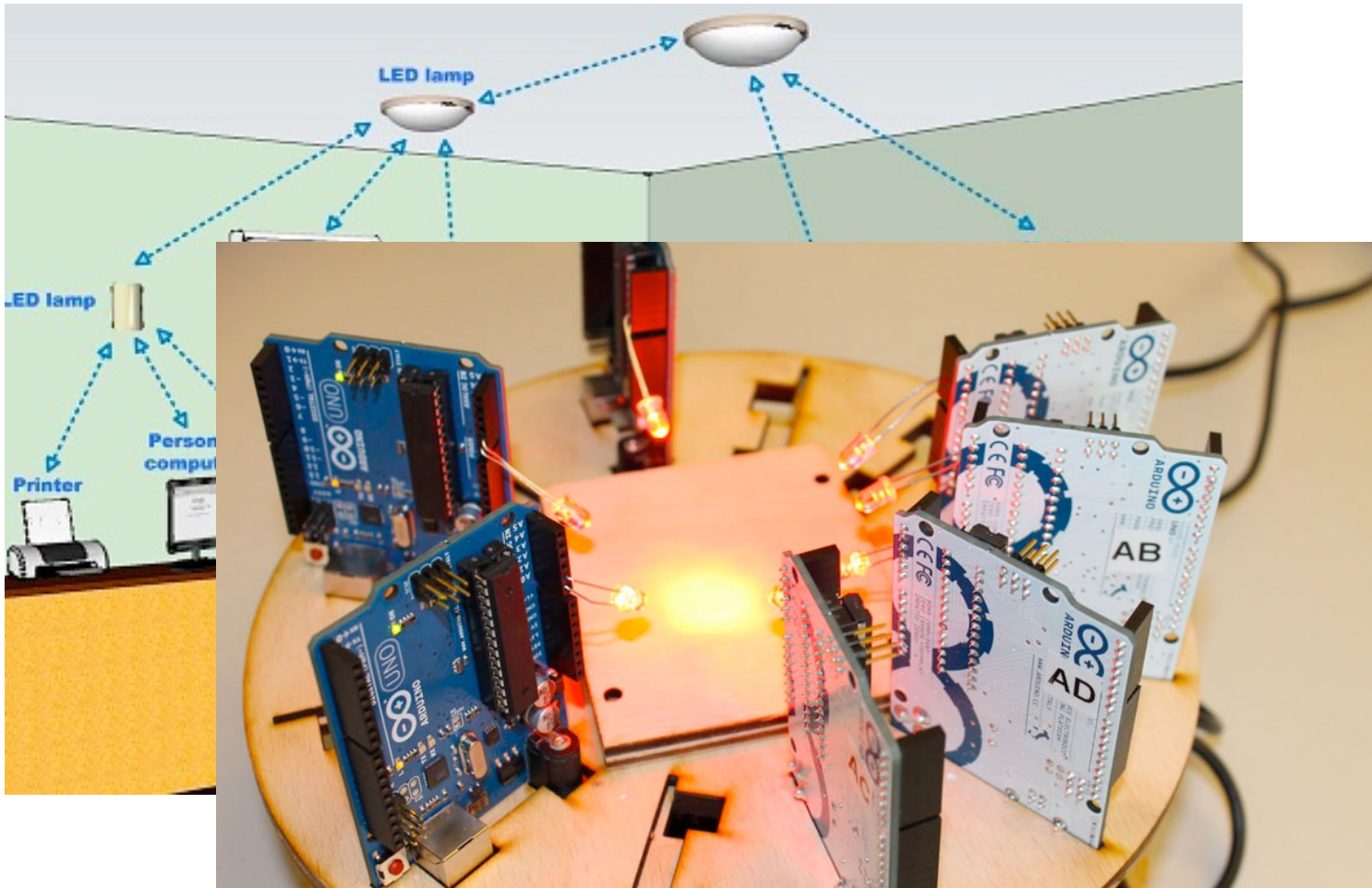
Iridium, 66 satellites
Initially 77



Wireless networks: Laser/Optical



Wireless networks: Visible Light



Visible Light Communications, cont

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

How li-fi sends data

The visible light spectrum is 10,000 times larger than the radio waves we use for wi-fi today. Information can be encoded in light pulses, just like in traditional TV remote controls.



Modern LEDs, however, could transmit enough data for a stable broadband connection - but still look like normal white light



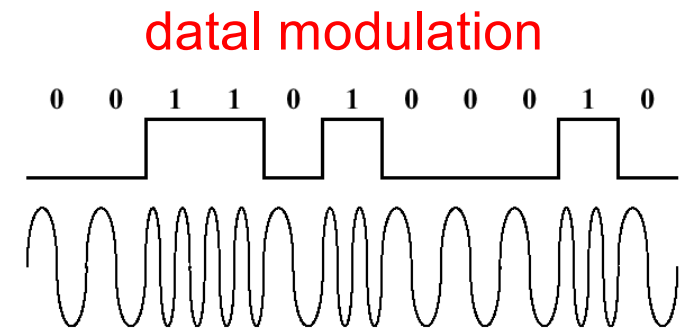
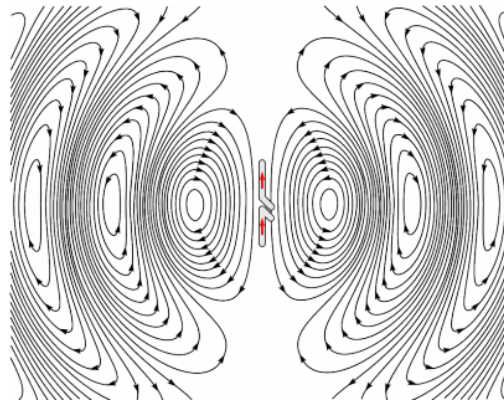
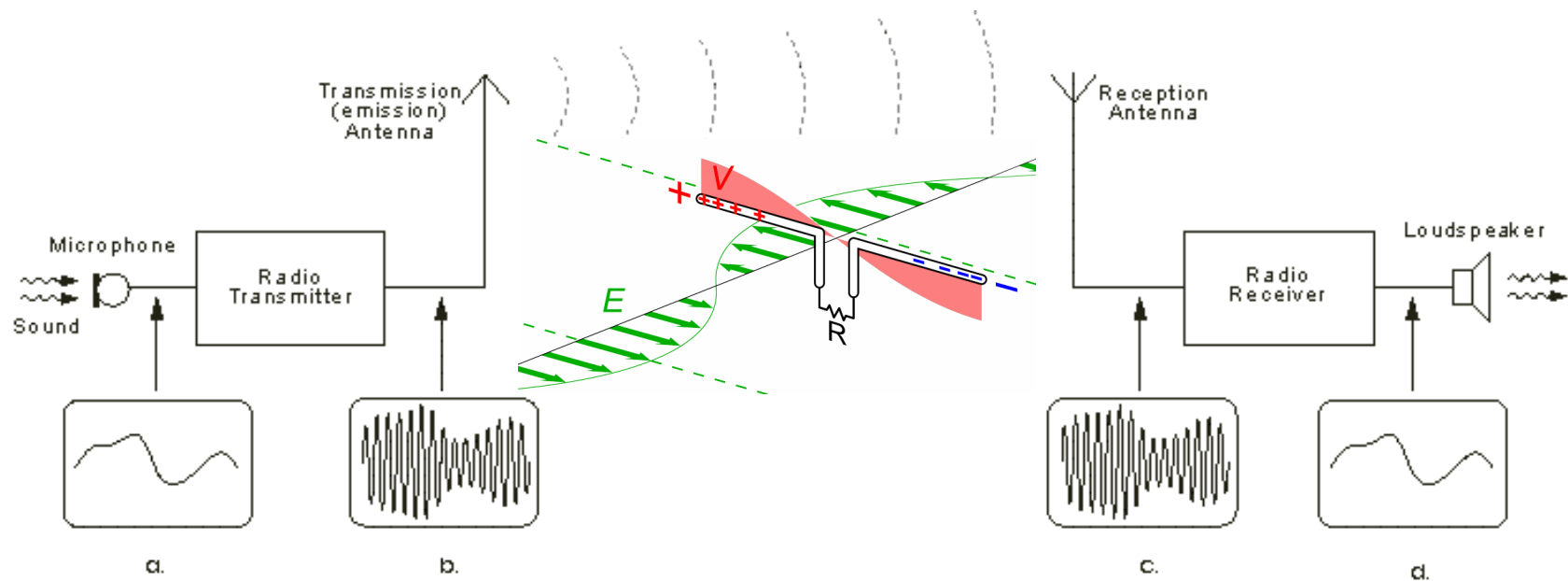
*bits per second

Source: Professor Harald Haas

BBC



Wireless radio transmission basics

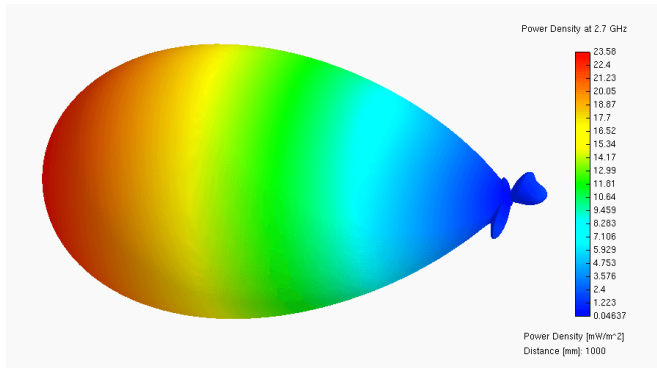


(b) Frequency-shift keying

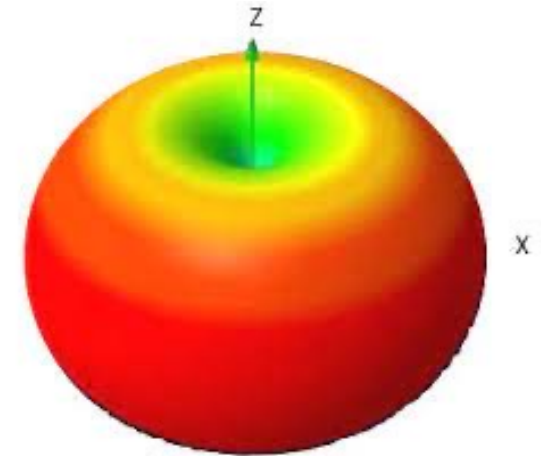
Antenna types



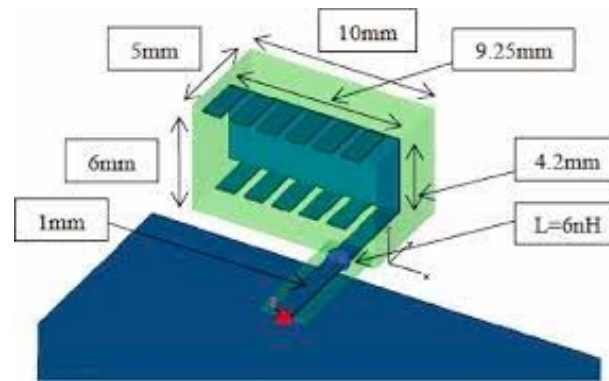
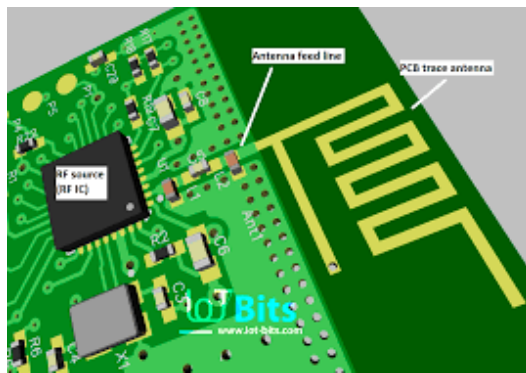
Omni-directional antennas



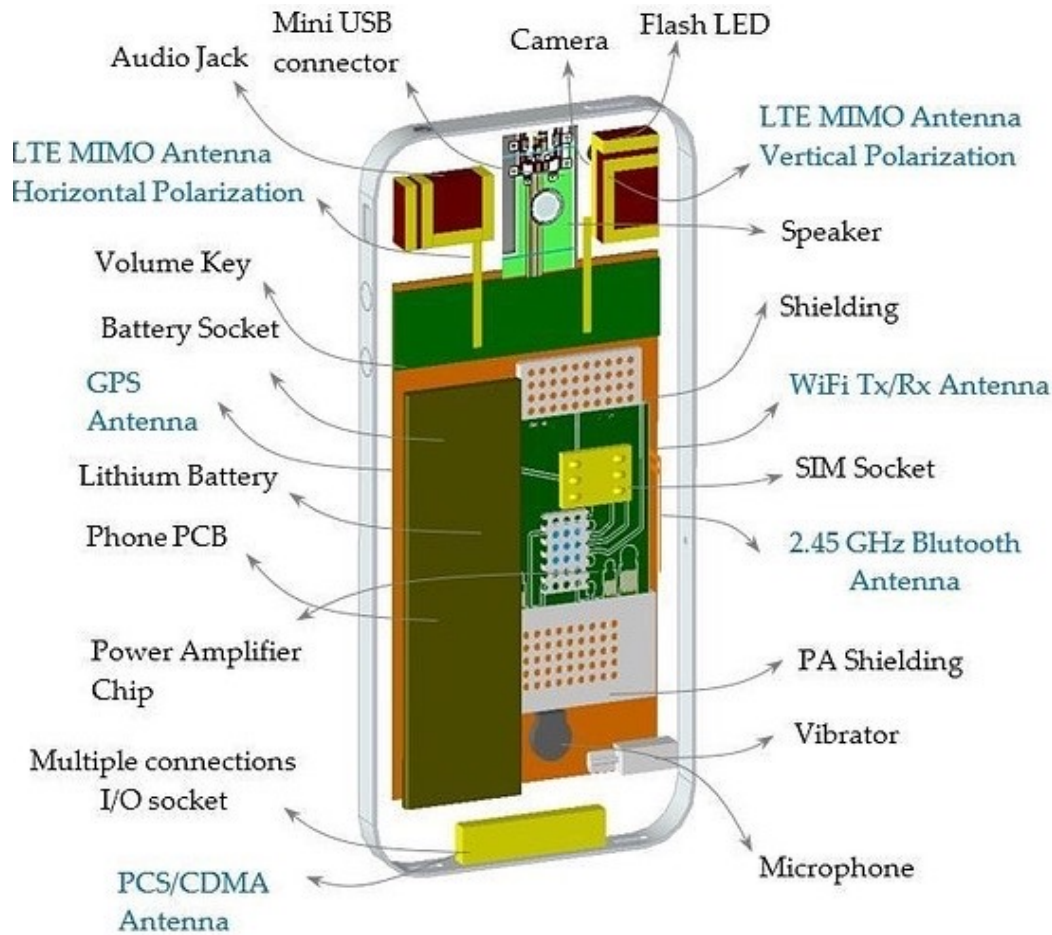
Directional antenna



PCB, patch, ceramic,...

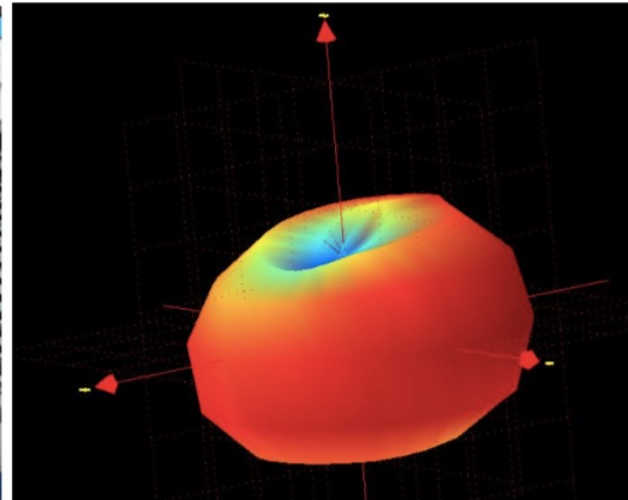
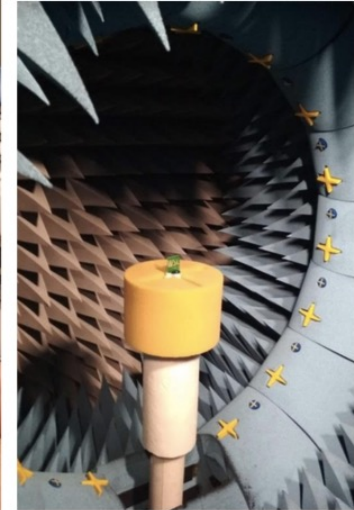
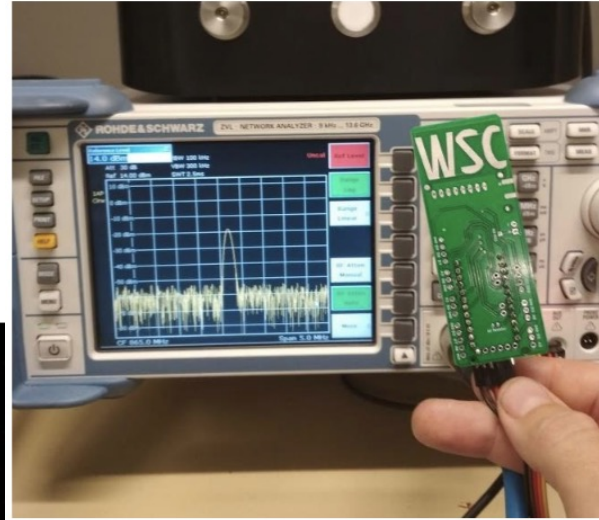
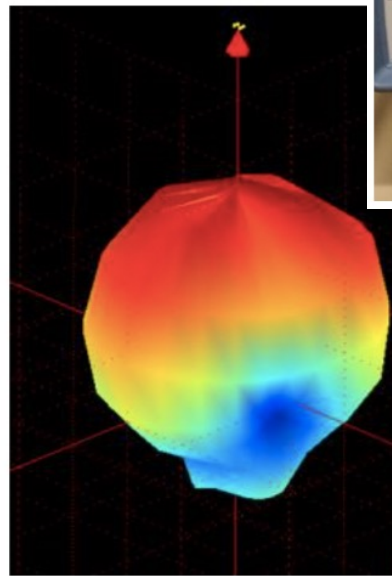


Antennas in a smartphones!



Testing antennas

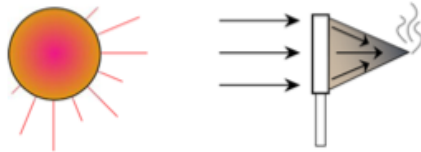
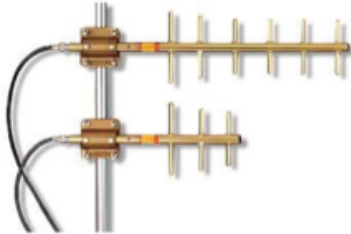
Source: F. Ferrero,
University of Nice



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



Antenna gain (2)

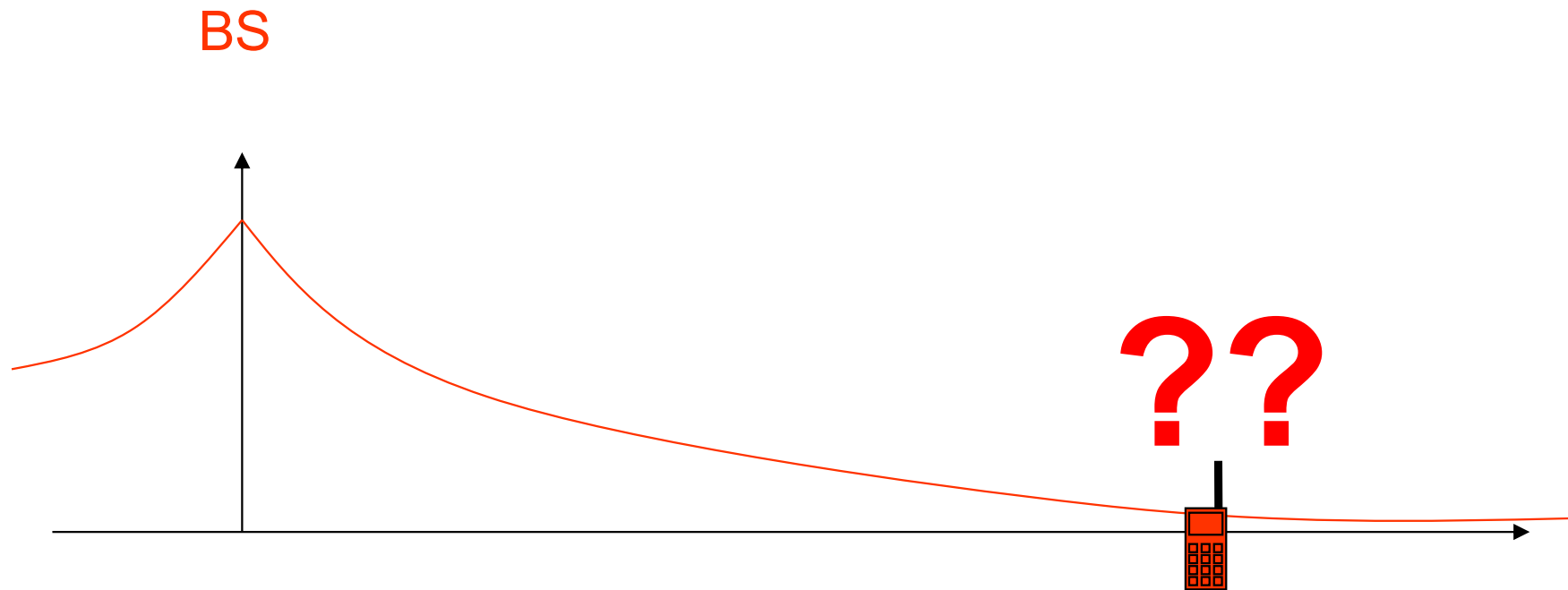
- ⦿ Antenna gain and its effective surface

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

- ⦿ with

- G = gain
- A_e = effective surface
- f = signal frequency
- c = light speed in space $3 \cdot 10^8$ m/s
- λ = wave length of the signal = c/f

1st challenge: signal attenuation



Attenuation limits the range!

- ⦿ Attenuation depends mainly on distance

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

- ⦿ 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)

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

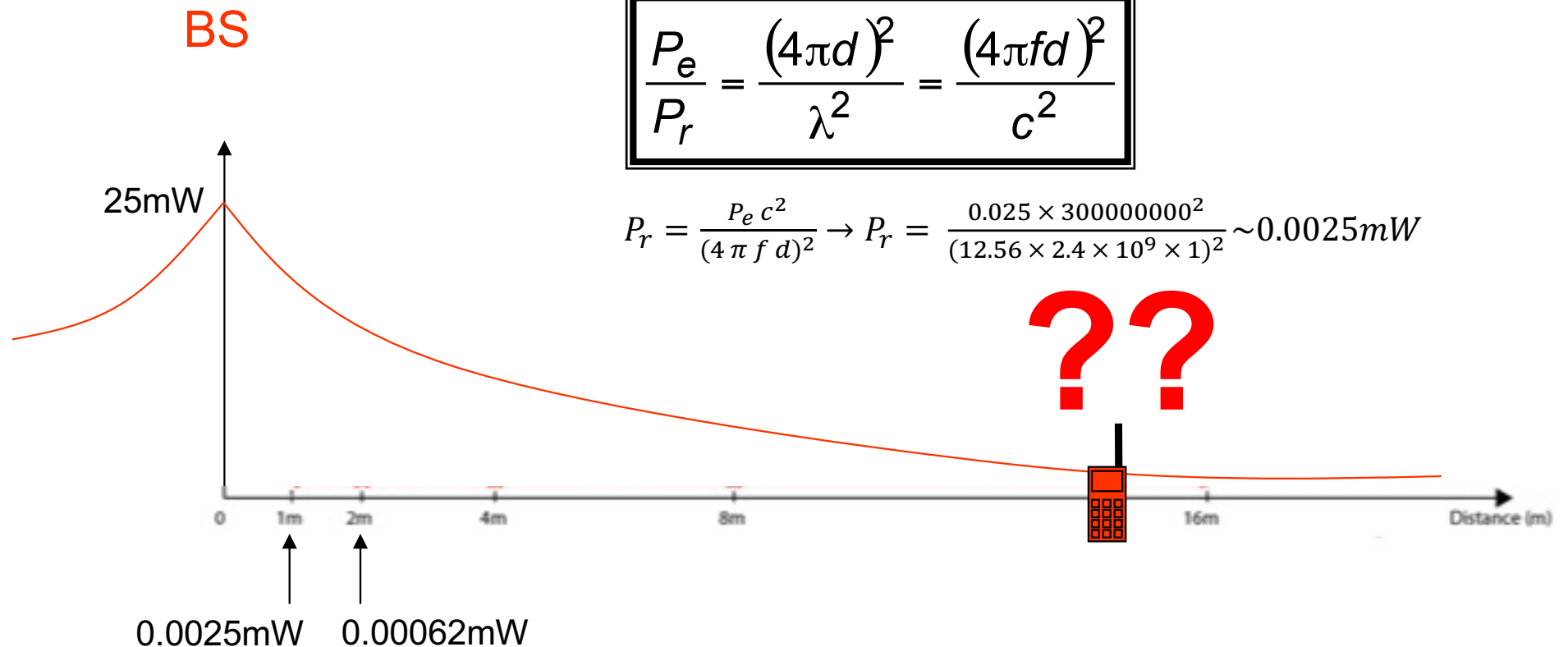
- P_e = transmitted power
- P_r = received power
- P_e / P_r is high when P_r is small → high attenuation
- d = distance between antennas
- c = light speed in space $3 \cdot 10^8$ m/s
- λ = wave length of the signal = c/f
- Higher frequencies f means higher attenuation!

Attenuation, value in watts

- Free Space Path Loss model

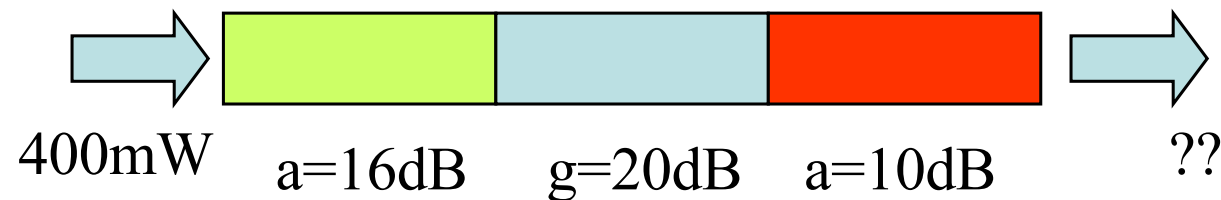
$$\frac{P_e}{P_r} = \frac{(4\pi d)^2}{\lambda^2} = \frac{(4\pi f d)^2}{c^2}$$

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



Attenuation in decibel (dB)

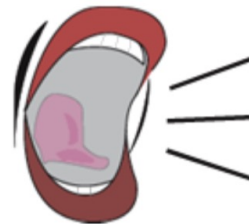
- ⊙ Decibel uses logarithmic scale as attenuation values can be very large
- ⊙ Attenuation in dB: $10\log_{10}(P_e/P_r)$, P_e and P_r in watts
 - ⊙ So $P_e/P_r = 10^{\text{dB}/10}$
 - ⊙ Difference of 3dB \approx half (divided by 2) as $P_e/P_r = 10^{3/10} = 10^{0.3} = 1.99526\dots$
- ⊙ \blackrightarrow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



$-16\text{dB} + 20\text{dB} - 10\text{dB} = -6\text{dB}$, so it is an attenuation
 $P_e/P_r = 10^{6/10} = 10^{0.6} = 3.98 \blackrightarrow P_r = P_e/3.98 \approx 100\text{mW}$

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 = $10\text{Log}_{10}(\text{mW}/1000) + 30$).

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

dBm to mW conversion

$$P(\text{dBm}) = 10 \cdot \log_{10}(P(\text{mW})/1\text{mW})$$

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

Ex:

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

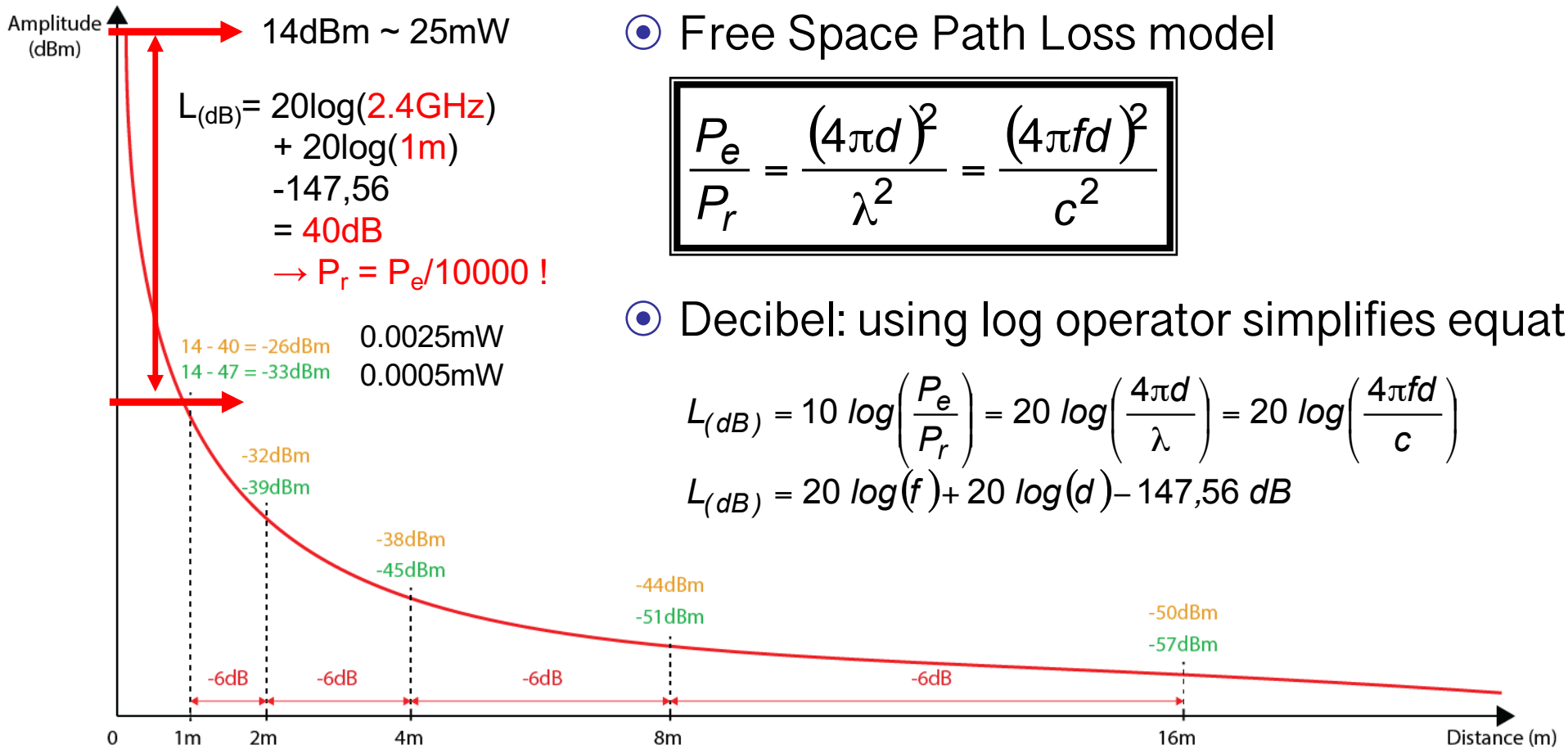
dBm	Watts
0	1.0 mW
1	1.3 mW
2	1.6 mW
3	2.0 mW
4	2.5 mW
5	3.2 mW
6	4 mW
7	5 mW
8	6 mW
9	8 mW
10	10 mW
11	13 mW
12	16 mW
13	20 mW
14	25 mW
15	32 mW

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

Attenuation, using dBm & dB

2.4GHz EIRP = 14dBm
5GHz EIRP = 14dBm



$$L_{(dB)} = 20 \log(2.4 \text{GHz}) + 20 \log(1 \text{m}) - 147,56 = 40 \text{dB}$$

→ $P_r = P_e / 10000$!

- Free Space Path Loss model

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

- Decibel: using log operator simplifies equation

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

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

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

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

Additional advantage of log scale: very large and very small values can be plotted on the same graph 24

Impact of signal frequency

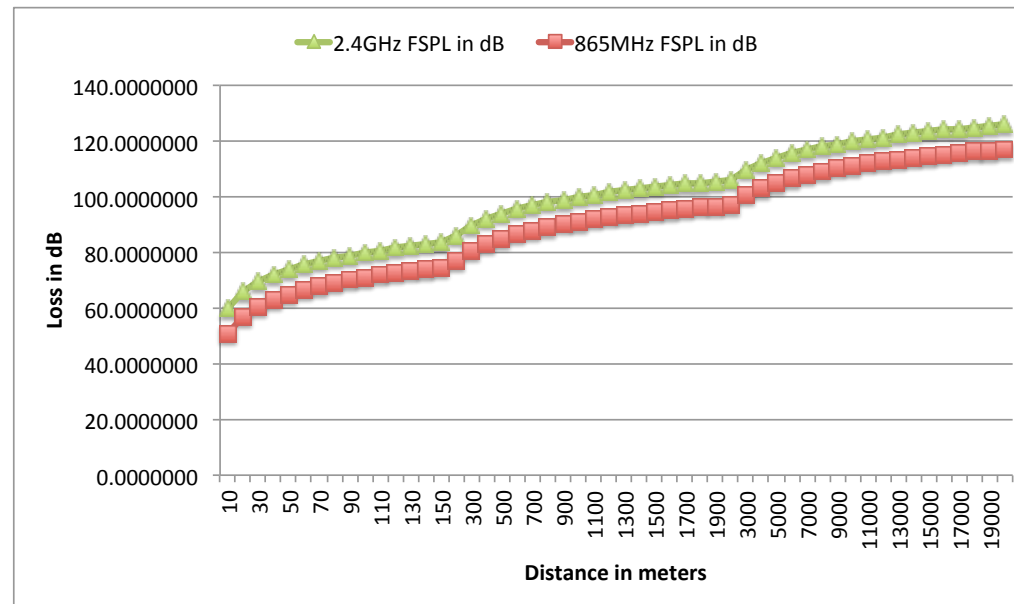
Free Space Path Loss model

$$FSPL = \left(\frac{4\pi d}{\lambda}\right)^2 = \left(\frac{4\pi d f}{c}\right)^2 \quad FSPL = \frac{P_t}{P_r} G_t G_r$$

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

FSPL assume $G_t=G_r=1$

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

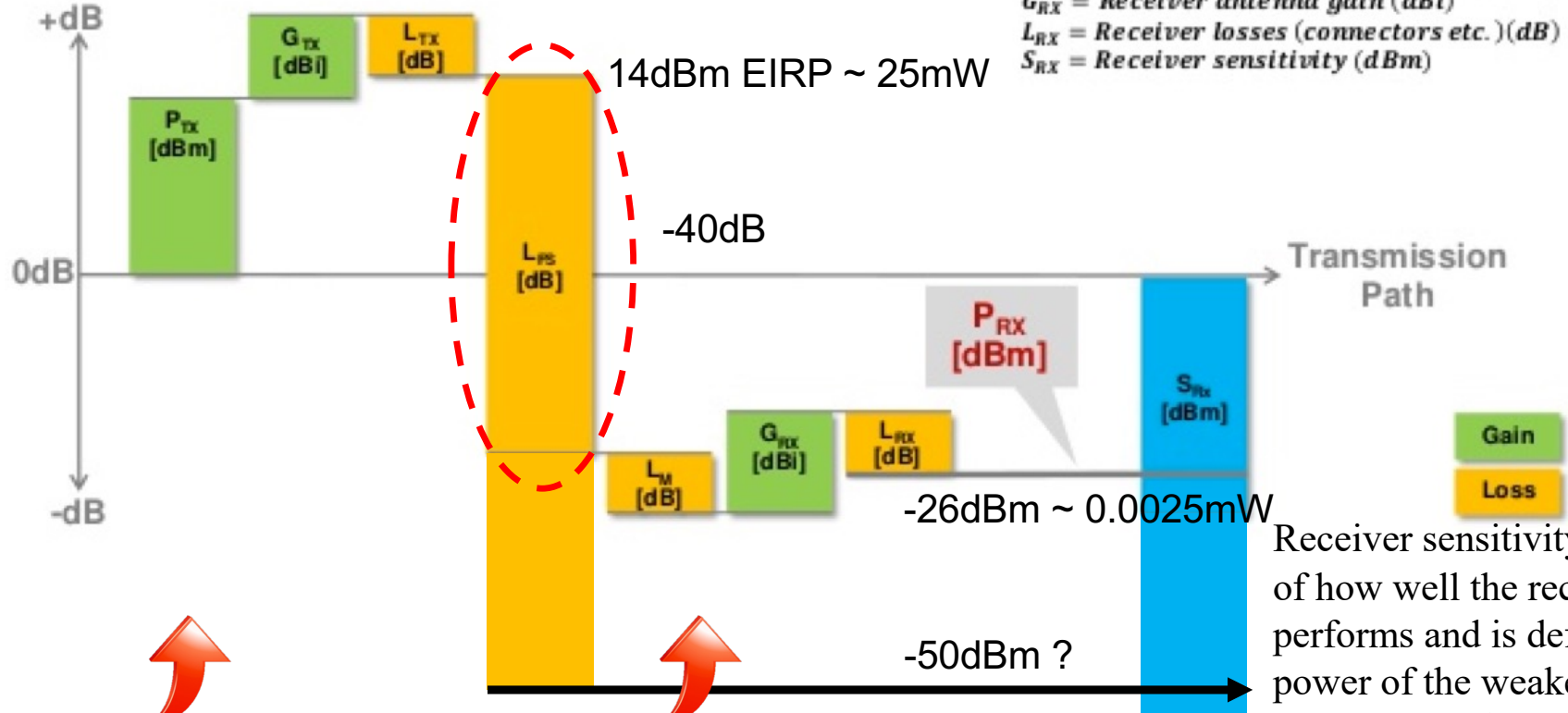


Link budget in wireless system

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

- 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

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

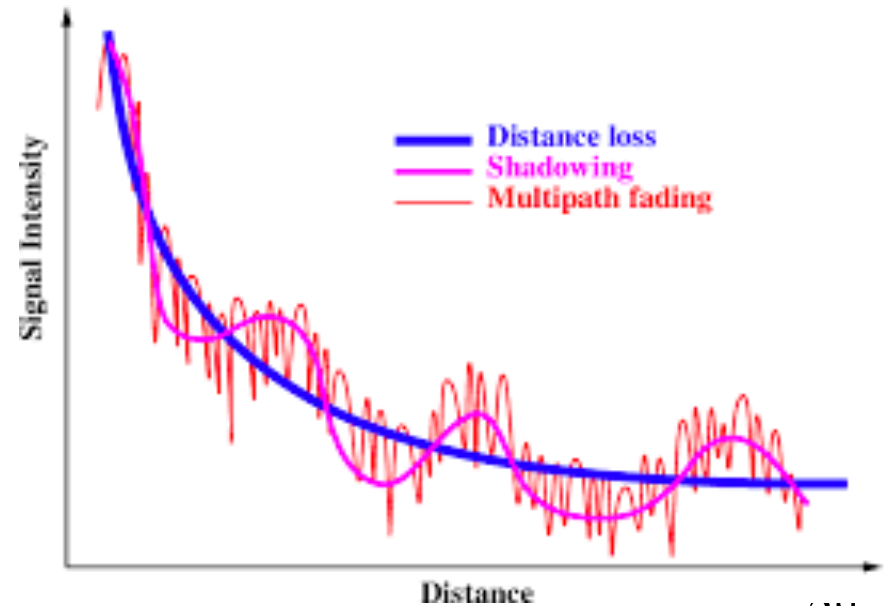
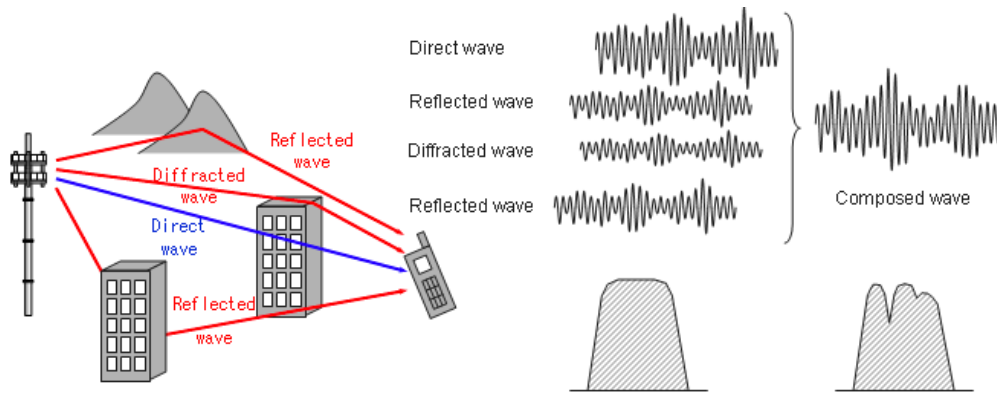
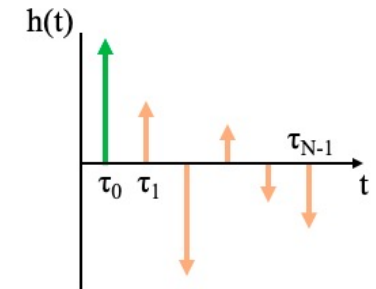
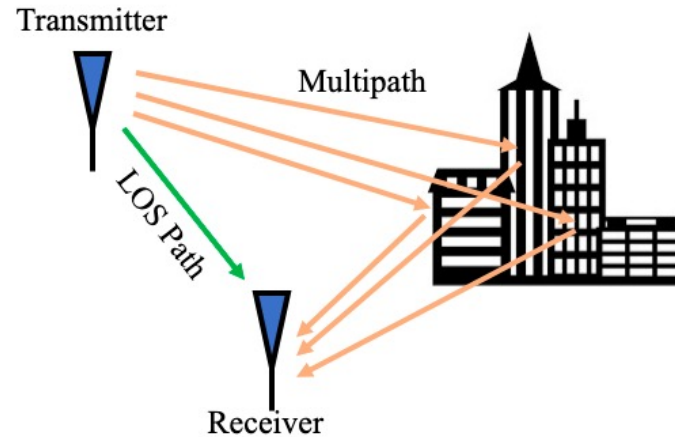
Receiver's sensitivity

- 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?

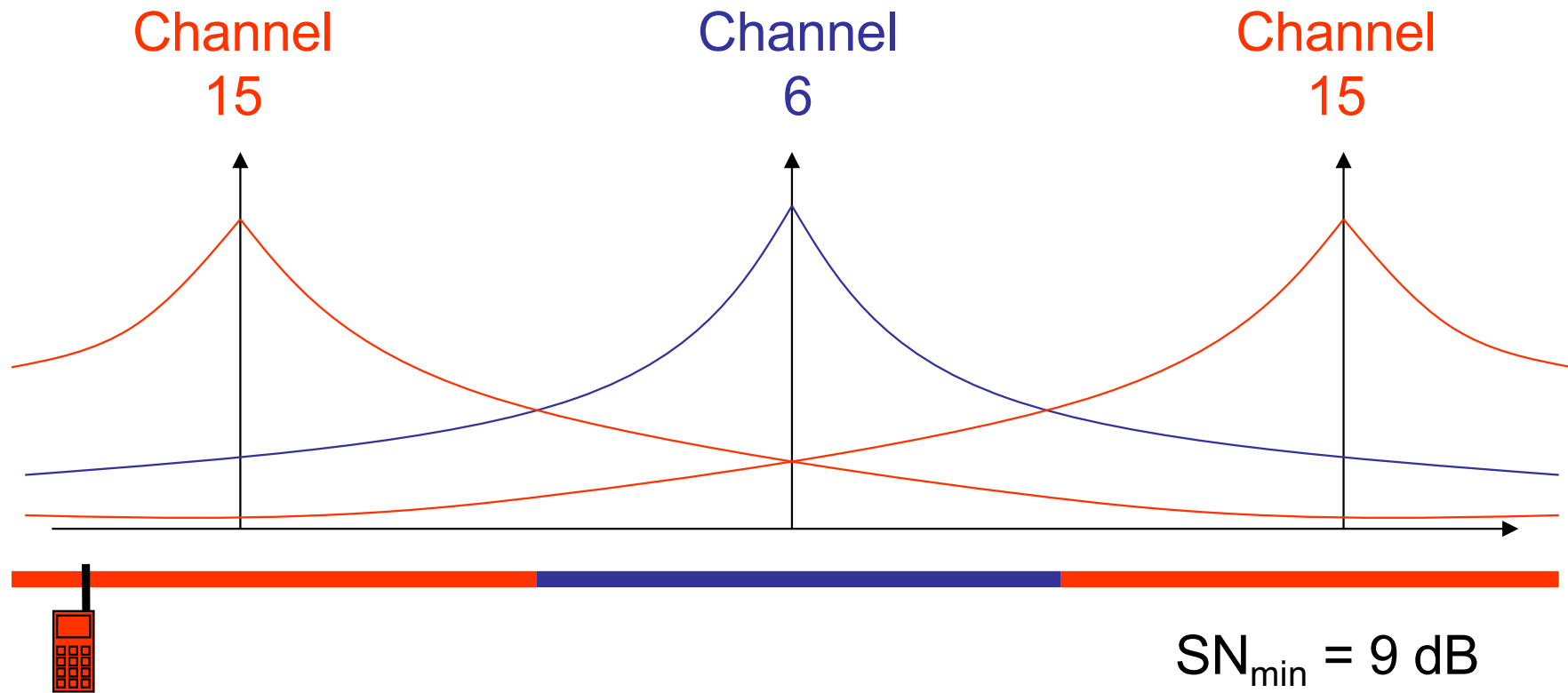


Shadow fading & Multi-path fading

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



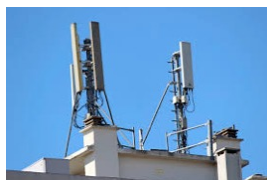
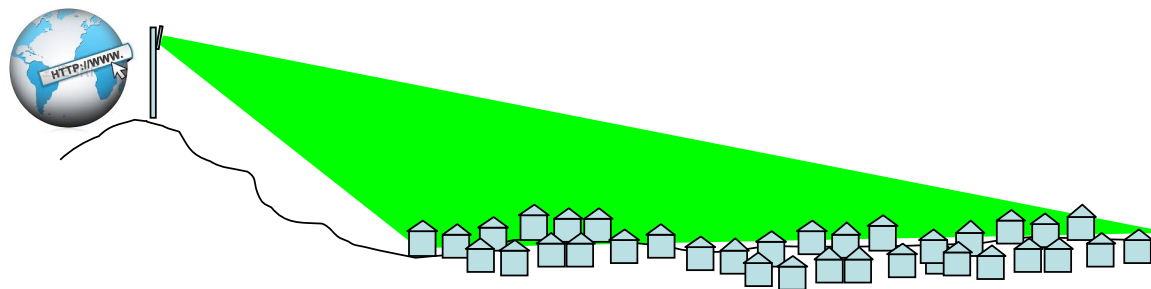
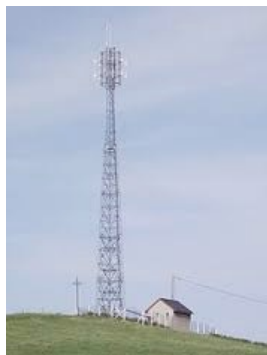
Frequency re-use



$$SN_{\min} = 9 \text{ dB}$$
$$S/N = 10^{9/10} = 7.94$$

2nd challenge: energy cost

Moisture/
Temperature of
storage areas

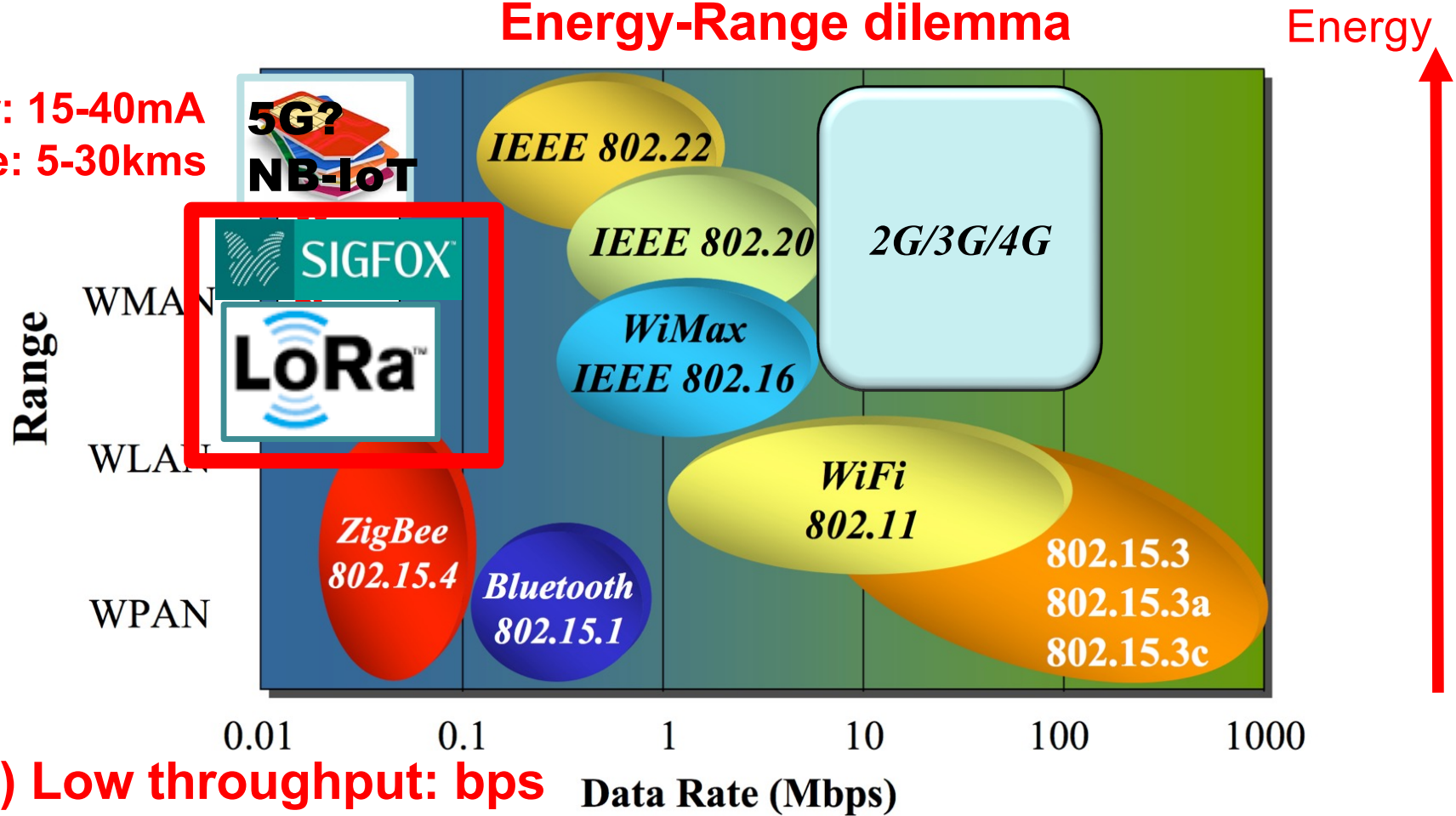


Technology	2G	3G	LAN
Range (I=Indoor, O=Outdoor)	N/A	N/A	O: 300m I: 30m
Tx current consumption	200-500mA	500-1000mA	100-300mA
Standby current	2.3mA	3.5mA	NC

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

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

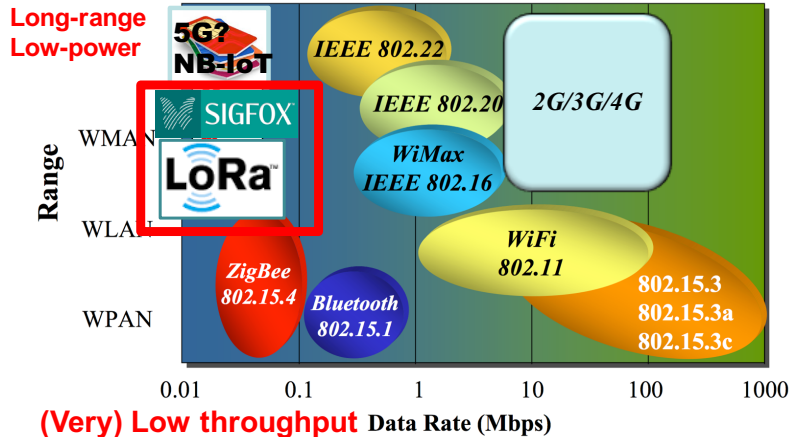
Energy-Range dilemma



(Very) Low throughput: bps Data Rate (Mbps)

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: $(8s \times 500 + 3592s \times 0.005) / 3600 = 1.11mA$

$2500 / 1.11 = 2252h = 93 \text{ days} = 3 \text{ months} \text{ ☹️}$

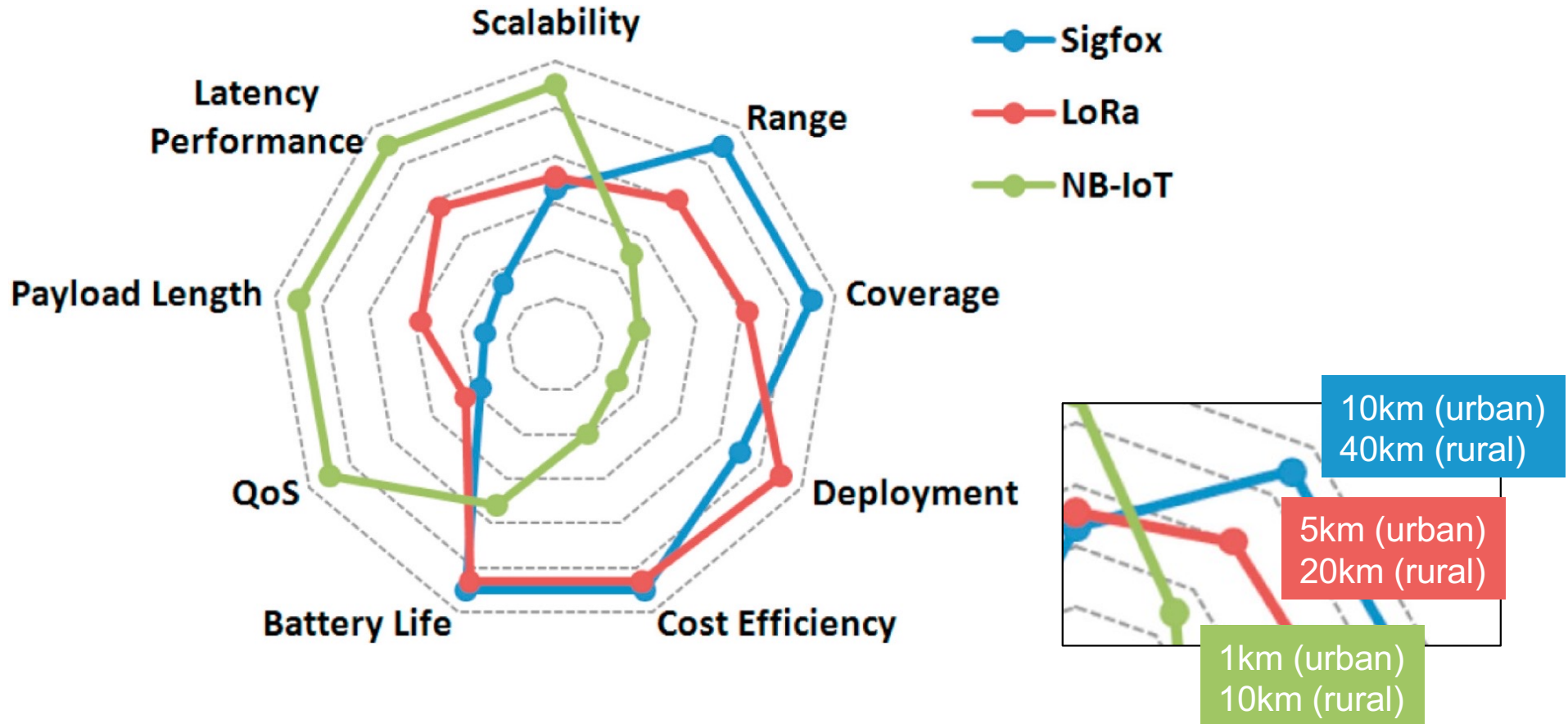
In most cellular networks, the device is still maintaining communication with BS even if it is inactive

TX power: 40mA. Mean consumption: $(2s \times 40 + 3598s \times 0.005) / 3600 = 0.027mA$

$2500 / 0.027 = 92592h = 3858 \text{ days} = 10 \text{ y.} \text{ 😊}$

LPWAN does not need to maintain connection if not in used

Expected range?



How can we increase range?

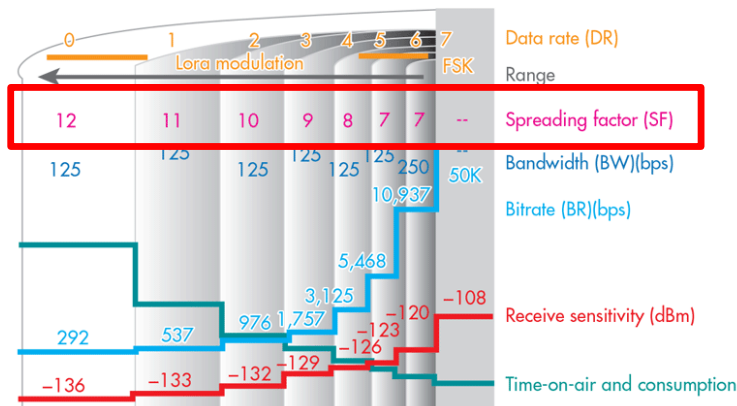


I'm not fluent in idiot
could you please speak



more slowly?

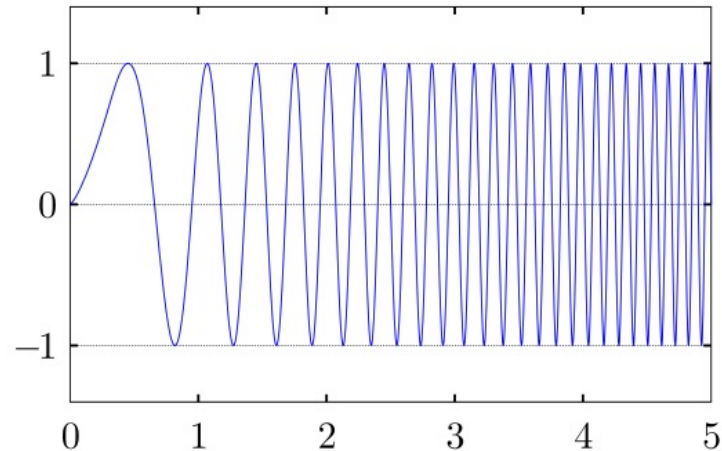
- ⦿ Increase TX power and/or improve RX sensitivity
- ⦿ Generally, RX sensitivity (\sim robustness) can be increased when transmitting (much) slower (like speaking slower!)
- ⦿ LoRa uses spread spectrum approach to increase RX sensitivity
 - ⦿ Spreading Factor defines how many chips will be used to code a symbol. More chip/symbol=longer transmission time \Rightarrow 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

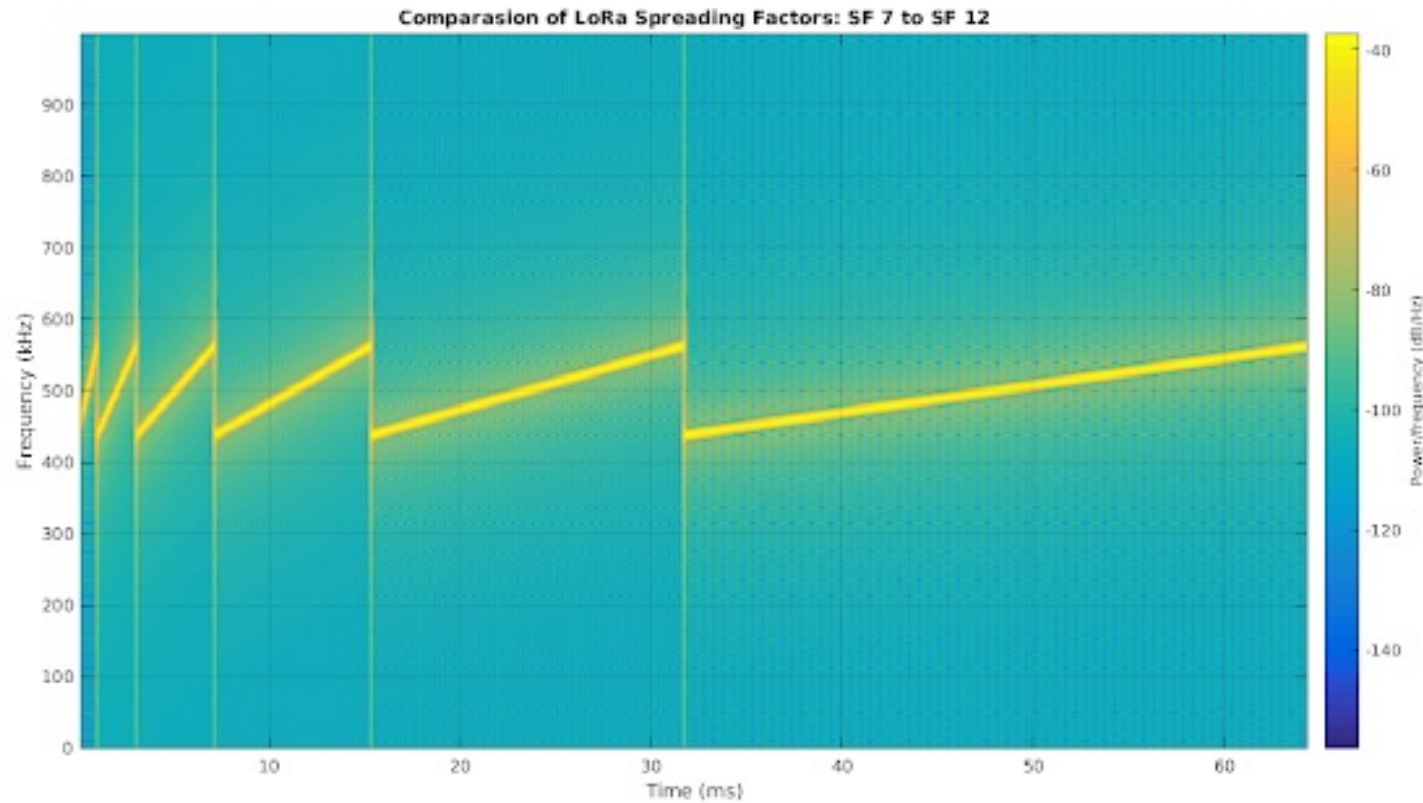
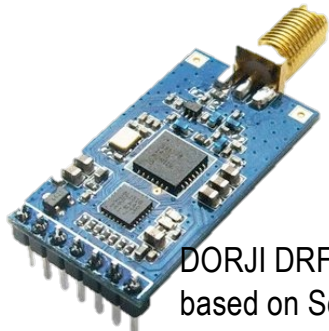


Figure from "All About LoRa and LoRaWAN", <https://www.sghosly.com>

LoRa modules with Semtech's SX127x



DORJI DRF1278DM is based on Semtech SX1278 LoRa 433MHz



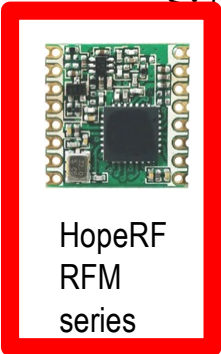
Libelium LoRa is based on Semtech SX1272 LoRa 863-870 MHz for Europe



inAir9 based on SX1276



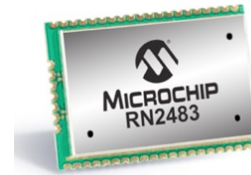
Froggy Factory LoRa module (Arduino)



HopeRF RFM series

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



LoRa™ Long-Range Sub-GHz Module (Part # RN2483)

Microship RN2483



Multi-Tech MultiConnect mDot



ARM-Nano N8 LoRa module from ATIM



SODAQ LoRaBee Embit

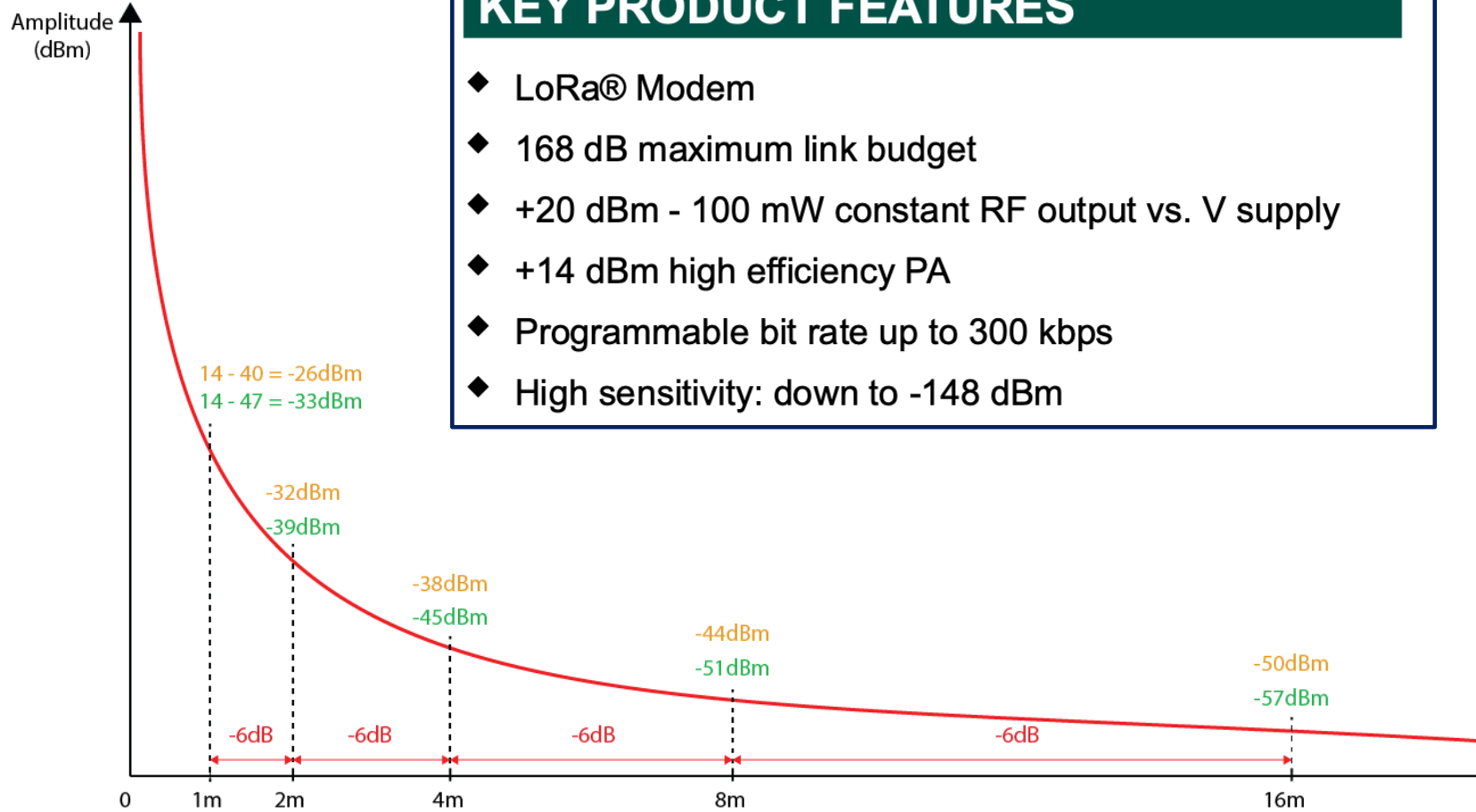


SODAQ LoRaBee RN2483

What distance for -148dBm?



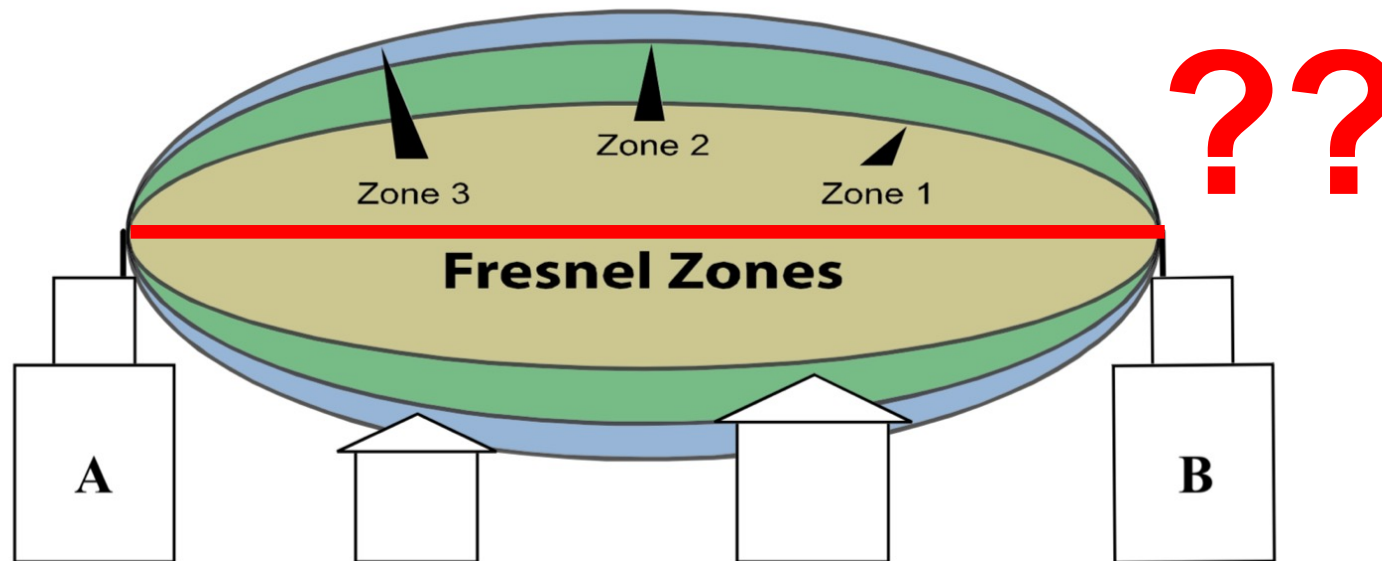
2.4GHz EIRP = 14dBm
5GHz EIRP = 14dBm



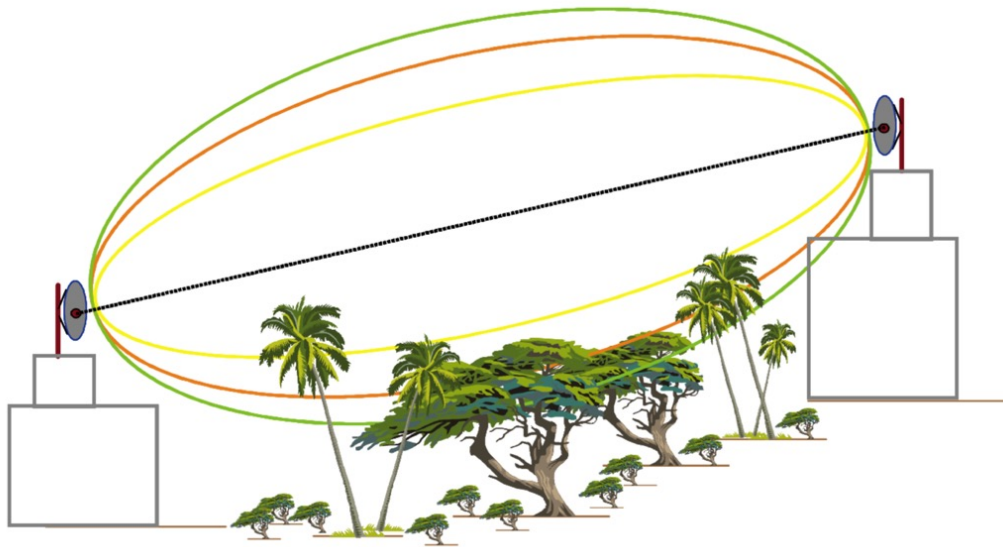
-26	1
-32	2
-38	4
-44	8
-50	16
-56	32
-62	64
-68	128
-74	256
-80	512
-86	1024
-92	2048
-98	4096
-104	8192
-110	16384
-116	32768
-122	65536
-128	131072
-134	262144
-140	524288
-146	1048576
-152	2097152

Line-of-Sight & Fresnel zone

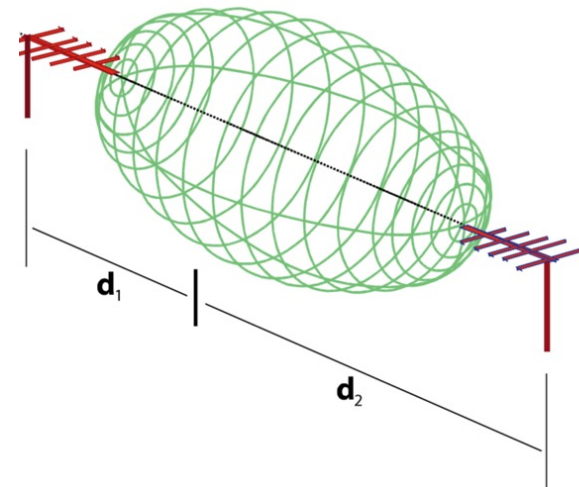
- LoS means clear Fresnel zone
- Football (american) shape
- Acceptable = 60% of zone 1 + 3m



Clearing the Fresnel zone? Raise antennas!



$$r_n = \sqrt{\frac{d_1 d_2}{d_1 + d_2}}$$


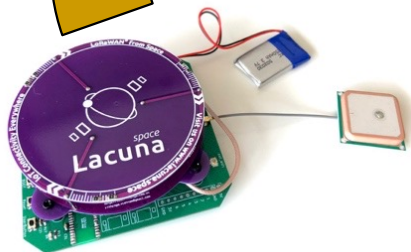
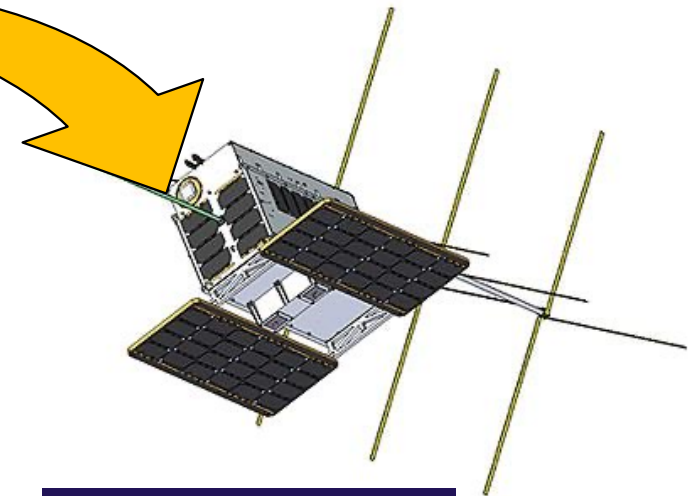
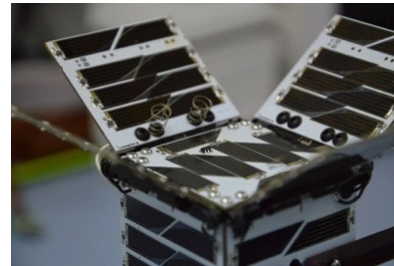


Range Distance	900 MHz Modems Required Fresnel Zone Diameter	2.4 GHz Modems Required Fresnel Zone Diameter
1000 ft. (300 m)	16 ft. (5 m)	11 ft. (3.4 m)
1 Mile (1.6 km)	32 ft. (10 m)	21 ft. (6.4 m)
5 Miles (8 km)	68 ft. (21 m)	43 ft. (13 m)
10 Miles (16 km)	95 ft. (29 m)	59 ft. (18 m)

Clearing the Fresnel zone? Let's use satellite!

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

LoRa over 1200kms!



space
Lacuna

Low-cost, simple and reliable global connections to sensors and mobile equipment. It just works everywhere, and all the time, so you can focus on using your data.

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

IOT Online Course

Fundamentals of IoT

Continue with

F-IOT-2b: Understanding IoT Devices, Architecture & Ecosystem



IoT – from idea to reality

