CS 4222/5422 WIRELESS NETWORKING

Prof. Chan Mun Choon
School of Computing
National University of Singapore
Jan 15, 2021 (Week 1)

Course Description

- Introduce students to wireless networks, energy efficient protocols, use of sensors and programming on mobile/wearable devices
- Emphasis on programming and system implementation on mobile devices and sensor data processing

Course Pre-requisites

- Assume students have taken undergraduate networking classes like CS2105 or EE3204/EE4204 or equivalent
- Familiarity with programming in C (or Jave/Python)

Course Information

- IVLE: CS4222/CS5422
  - *General information, reading list*
  - *Class notes, discussion forum*
- Schedule
  - *Class time: Friday, 1400-1600*
  - *E-Learning*
  - *Exam: 03 MAY 2021 13:00-15h:00*

References

- References Books
  - *Wireless Communications Networks and Systems, Cory Beard & William Stallings*
  - *Wireless Communications: Principles and Practice, T.S. Rappaport, 2nd Edition*
- Reference Papers:
  - To be given before weekly lecture

Lecturer/TA

Chan Mun Choon

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Teaching Assistants (part time)

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Evaluation (CS4222/CS5422)

- Continuous Assignments (70%)
  - *programming assignments + projects* *55%*
    - 2 individual programming assignments (10%)
    - Groups of 2 to 4 members
      - *2 group programming assignments (20%)*
      - *1 group project (25%)*
  - *Written Assignment* *10%*
  - *Tutorial* *5%*
- Final Assessment, open book (30%)

Topics

1. Wireless communications basics
2. Mobile devices and Sensing
3. Programming on SensorTag (introduction to Contiki)
4. Understanding energy consumption on mobile devices
5. Localization
6. Neighbor discovery
7. MAC protocols for wireless networks
8. MAC protocols for low power wireless networks
9. Routing protocol for wireless networks
10. Wireless wide/local area networks

Programming Assignments & Projects

Individual

- Week 2: Collect device (SensorTag)
- Week 4: Assignment 1 (5%): installation, “Hello World” program
- Week 6: Assignment 2 (5%): Timer and sensors

Group

- Week 8: Assignment 3 (10%): RSSI as proximity/distance measure
- Week 10: Assignment 4 (10%): Duty Cycling and neighbor discovery
- Week 13/Reading Week (25%)
  - *Put together what your have learnt to build your own “TraceTogether” token*

Outline

- History of Wireless Network Development
- Wireless Transmission Basics
- Characteristics of Wireless Networks → Features

Early Days: Some Milestones

1893: Nikoli Tesla gave a public demonstration of "wireless" radio communication at St. Louis, Missouri, USA

1896: Guglielmo Marconi's first radio transmissions, coded signals that were transmitted only about 1.6 km (a mile)

over the sea

1899: Marconi sends a signal over the English Channel ~50km

1901: Trans-Atlantic transmission from England to Newfoundland (>3000km)

Early Days: Some Milestones (cont’d)

1906: (AM radio) first audio broadcast of music/voice from shore to ship

1912: The RMS Titanic sank. After this, wireless telegraphy quickly became universal on large ships

1915: AT&T sent speech from Arlington (Virginia) to Paris (>6,000km)

Radio/Audio Broadcasting

1916: Regular broadcast of weather information using Morse code

odvessing for weather • Agricultural

1917 - 1919: Clear transmission of music, voice and human speech

Early Radio Stations

1922: France, UK

1936: Malaya, Singapore

1935: Frequency modulation (FM) demonstrated by Armstrong

1980s: Digital Audio Broadcasting (DAB)

TV Broadcast

1923: First wireless TV transmission

1941: NTSC (National Television System Committee), 525 lines per inch at 30 fps in a bandwidth of 6 MHz

1962: AT&T launches Telstar, the first satellite to carry TV broadcasts

1963: PAL or Phase Alternating Line standardized, uses 625 lines

1963: First TV broadcast in Singapore (channel 5)

1996: US. HDTV standardized

It ~~take~~ this long to set up 2 way ⇒ ~~video~~ / voice call

Voice Communications

→ expensive

1946 - First interconnection of mobile users to public switched telephone network (PSTN), "zero" generation

1983 - Advanced Mobile Phone System (AMPS) deployed in US in 900 MHz band

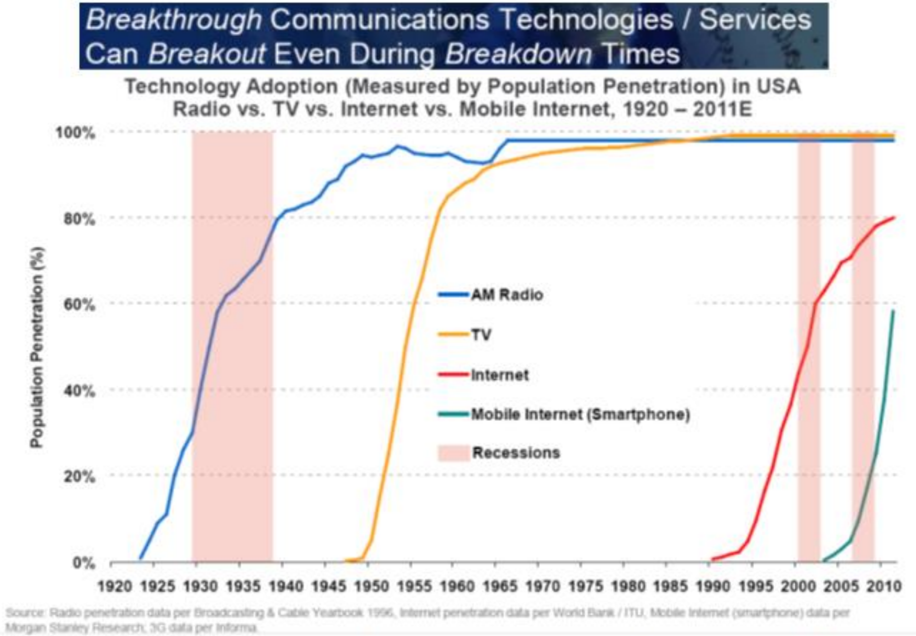
1989 - Groupe Spècial Mobile defines European digital cellular standard, GSM

1993 - IS-95 code-division multiple-access (CDMA) digital cellular system deployed in US

- voice first

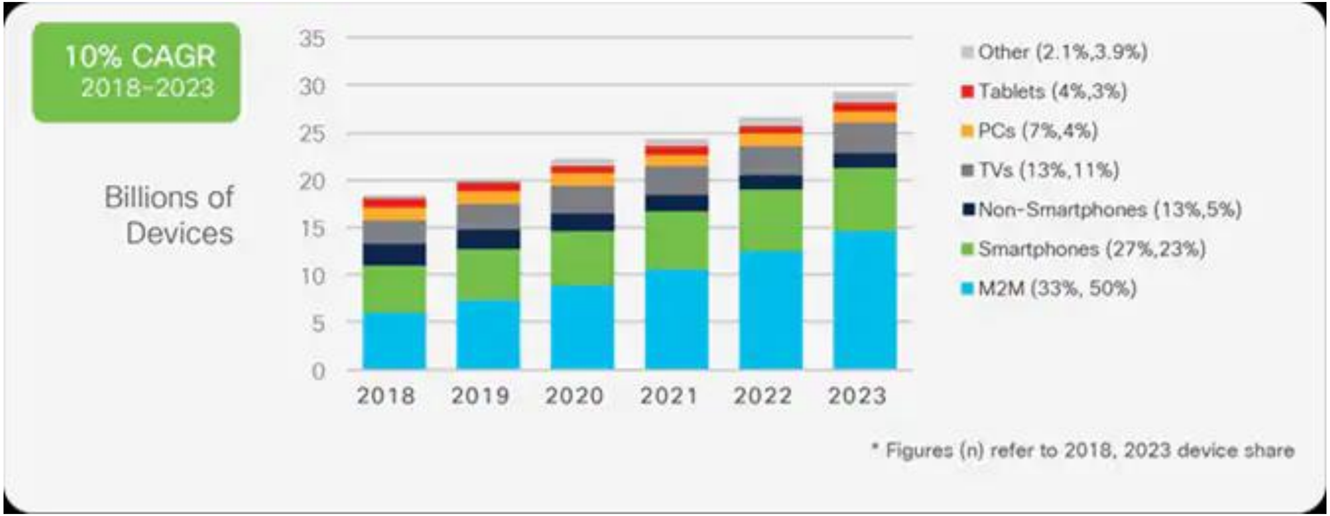
1G (Analog)
↓
2G (Digital) → IS95 (US)
→ GSM (Europe)
↓ ...

Communication Technology Adoption in the USA



Source KPCB, Mary Meeker Web 2.0 presentation on Internet Trends 10-18-11

Data Source: Radio penetration data per Broadcasting & Cable Yearbook 1996, Internet penetration data per *World Bank/ITU*, Mobile Internet (smartphone) data per Morgan Stanley Research; 3G data per Informa.



Source: Cisco Annual Internet Report, 2018–2023

https://www.cisco.com/c/en/us/solutions/collateral/executive-perspectives/annual-internet-report/white-paper-c11-741490.html

References for this lecture

- Wireless Communications Networks and Systems, Cory Beard & William Stallings (Chapter 5: Overview of Wireless Communications) or Wireless Communications & Networks, William Stallings, 2nd Edition.
- Wireless Communications: Principles and Practice, T.S. Rappaport, 2nd Edition (Chapter 5: Mobile Radio Propagation)

Propagation Modes

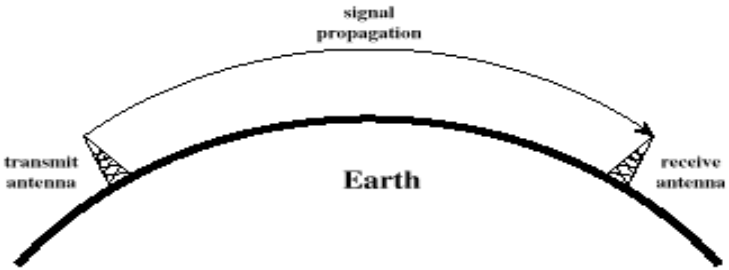
→ spreading

- Ground-wave propagation
- Sky-wave propagation
- Line-of-sight propagation

Note:

More bandwidth = More Freq

Ground Wave Propagation



- Follows contour of the earth
- Can propagate considerable distances
- Frequencies up to 2 MHz
- Example: AM radio
  - Medium Wave: 520 kHz–1,610 kHz

→ Must be low freq

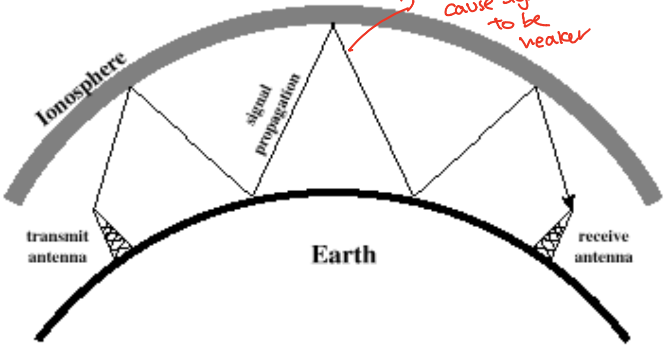
→ can go far distances

But:

Since is up to 2MHz, not alot of data can be sent in this method per sec

Sky Wave Propagation

Ionosphere
refracts waves
> 30MHz



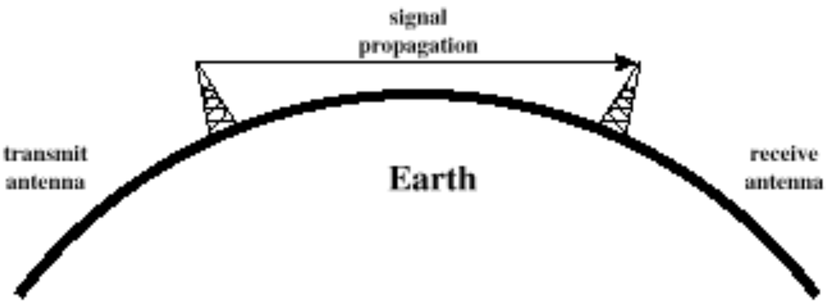
→ can go longer dist
→ ≤ 30MHz, not high bitrate

- Signal reflected from ionized layer of atmosphere back down to earth
- Signal can travel a number of hops, back and forth between ionosphere and earth's surface
- Reflection effect caused by refraction, 3 to 30MHz
- Examples: Short wave AM (1.711 MHz–30.0 MHz), amateur/CB radio

Civilian Band

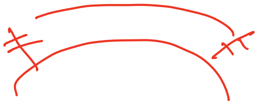
Line-of-Sight Propagation

↳ satalite = long distance + LOS



- Transmitting and receiving antennas must be within line of sight
  - Satellite communication – signal above 30 MHz not reflected by ionosphere
  - Ground communication – antennas within *effective* line of site due to refraction

Line-of-Sight Equations



- Maximum distance between two antennas for LOS propagation:

$$3.57\left(\sqrt{Kh_1} + \sqrt{Kh_2}\right)$$

(KM)

  - h_1 = height of antenna one
  - h_2 = height of antenna two
  - K = adjustment factor to account for refraction (default value is 4/3)

Example

- Transmitter is 50m high, receiver is at ground level (0m), what is the maximum distance between receiver and transmitter using LOS?
  - $D = 3.57 \, (4/3 * 50)^{1/2} = 29.15km$

$\frac{4}{3} * 0 = 0$

- Raise the receiver by 10m, how high does the transmitter antenna needs to be to maintain same transmission distance?
  - $29.15 = 3.57 \, ((4/3 * H)^{1/2} + (4/3 * 10)^{1/2})$
  - $H = 15.26m$
- Raise the transmitter and receiver are placed at the same height and the transmission needs to be at least 30km, how high do the antennas need to be placed?
  - $30 = 3.57(2(4/3 * H)^{1/2})$
  - $H = 13.24m$

Free Space Propagation Model

Higher freq = faster drop [If i double the f_c, the loss x4 (Due to α)]

↳ Predict recieved signal strength when trans & reciever have clear LOS

- For line-of-sight path

reciever

$$P_r = G_r G_t \left(\frac{c}{4\pi f_c d} \right)^{\alpha} P_t$$

quality of signal depends

Transm

Dominant factor

2.4 – 2.44

f_c : 2.42

– f_c is the center frequency in Hz

– c is speed of light

– d is the distance between transmitter and receiver

Omni directional

signal drop = go less distance

– α is the path loss component → default : 2 (vacumm)

– G is antenna gain (quality of anthenna)

Dependent

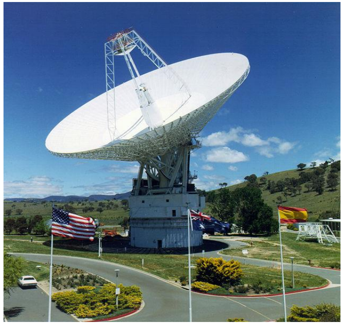
- ↑ Dist = ↓ signal strength
- Frequency ↑ = Degrad ↑ = ↓ sig stre

Antenna

- An electrical conductor or system of conductor
  - *For transmission, radio frequency electrical energy is converted into electromagnetic energy*
  - *For receiving, the reverse occurs, electromagnetic energy is converted into electrical energy*
  - *In two-way communication, the same antenna can be used for transmission and reception*
- Two radiation patterns: omni-directional, directional

Common Antennas

How big is our antlena?, → base on wavelength



Signal wavelengh x2 = Anthena length
↳ Antn more eff

Dipole antenna - simplest practical antenna, two wires pointed in opposite directions arranged either horizontally or vertically, with one end of each wire connected to the radio and the other end hanging free in space

Half-wave dipole - A more efficient variation is the half-wave dipole, which radiates with high efficiency when <u>**the signal wavelength is twice the electrical length of the antenna**</u>

(pictures from wiki)

Half Wave Dipole Antenna Length

↑ The freq, the ↓ the wavelength

Frequency	Half Wavelength
1 MHz	150m
10 MHz	15m
FM station 100 MHz	1.5m
433 MHz	~35cm
900 MHz	~17cm
wifi 2.4 GHz	~6cm
5 GHz	~3cm
60 GHz	~2.5mm

Antenna Gain

- **Antenna gain** - power output, in a particular direction, compared to that produced in any direction by a perfect omni-directional antenna (isotropic antenna)
- **Effective area** - related to physical size and shape of antenna
- Relationship between antenna gain and effective area

Depends on freq

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

1). High freq = more loss

↳ antn: smaller if freq ↑

- G = antenna gain
- A_e = effective area
- f = carrier frequency
- c = speed of light ($\approx 3 \times 10^8$ m/s)
- λ = carrier wavelength

decline in power density of given electromagnetic wave as it propagate through space

- Path Loss in $\boxed{\text{dB}}$

ratio bet trans : Recieve power

Drops with the distance

$$10\log\left(\frac{P_t}{P_r}\right)$$

trans

recieve

- Also simplifies to

$$P_r \sim \left(\frac{1}{d}\right)^{\alpha} P_t$$

only Dominant factor?

⇒ No in practice

- Implies a circular disk model for radio propagation. True in practice?

"α" Path Loss Exponent

How fast Signal degrades

Environment	Path Loss Exponential (α)
Free Space (Ideal ☆)	2 (Double dist)
Urban area cellualr radio	2.7 to 3.5
Shadowed urban cellular radio	3 to 5
In building LOS	1.6 to 1.8 (Signal might get reflected & make original stronger by combi)
Obstructed in building	4 to 6 (freq Drops faster)
Obstructed in factory	2 to 3
Rapport, Table 4.2, pp139	

reciever

$$P_r = G_r G_t \left(\frac{c}{4\pi f_c d}\right)^{\alpha} P_t$$

Dominant

- What if distance is 0 in the Free Space Propagation Model?
- Assume a reference distance d_0, chosen to be smaller than any practical distance used (e.g. 1m for indoor, 100m for outdoor)

- Units in dBm

$$P_r \sim \left(\frac{d_0}{d}\right)^{\alpha} P_t \quad \text{, iff } d > 0$$

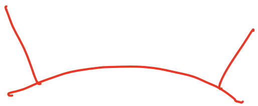
0?

- Distance = 0, Power = ∞?
  - ↳ No, the eq does not hold anymore

Line of Sight Transmission

Not clear visabilty

→ Dep factors

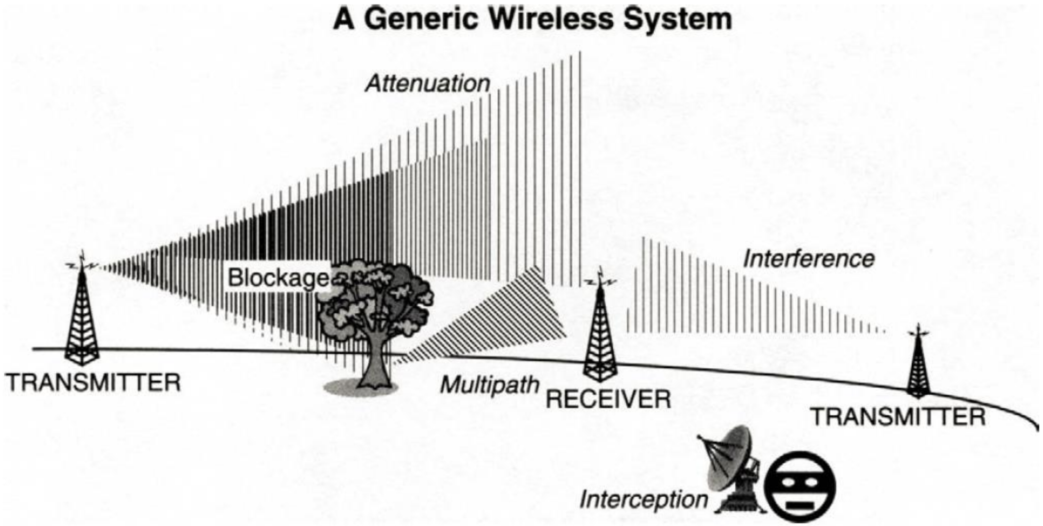


- Free space loss
  - *Signal disperses with distance*
  - *Larger loss for higher frequencies*
  - *Loss at higher frequencies can be compensate with antenna (gain)*

- Atmospheric Absorption
  - *Water vapour and oxygen absorb radio signals*
  - *Water greatest at 22GHz, less below 15GHz*
  - *Oxygen greater at 60GHz, less below 30GHz*
  - *Rain and fog scatter radio wave*

Mobile Radio Propagation

∘ low freq can penetrate obj easily



- Building/obstacle penetration (frequency dependent)
- Receiver can receive multiple copies of a transmission with different delays (multiple path)

Multipath Propagation

- Reflection
  - *e.g. earth surface, buildings*
- Diffraction
  - *Radio wave bends around the obstacle*
- Scattering
  - *Obstacles smaller than wavelength of wave (e.g. foliage), signal is scattered into several weaker signals*

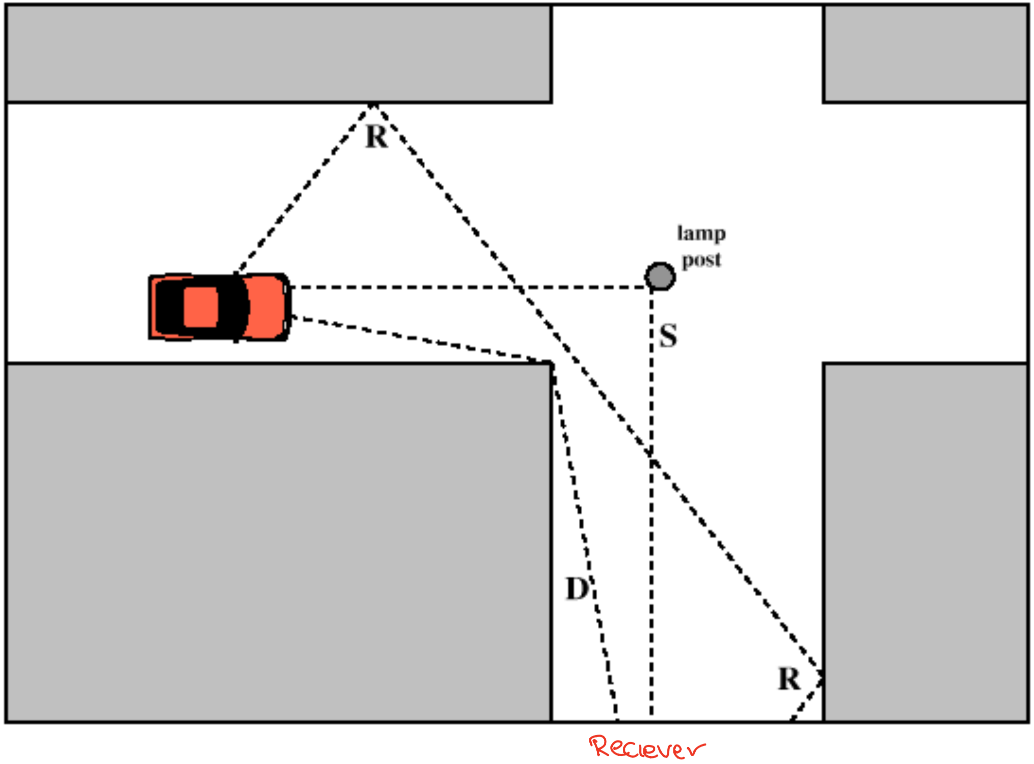


Figure 5.5 of Beard and Stallings (R – Reflection, S – Scattering, D - Diffraction)

The Effects of Multipath Propagation

- Multiple copies of a signal may arrive at different phases
  - *If phases add destructively, the signal level relative to noise declines, making detection more difficult*
- Intersymbol interference (ISI)
  - *One or more delayed copies of a pulse may arrive at the same time as the primary pulse for a subsequent bit*

Fading

- Fading refers to the time variation of received signal power caused by changes in the transmission medium or paths.
- Large scale fading
  - *Over longer distances (in excess of a wavelength), environment changes causing changes in (average) received power*
- Small scale fading
  - *Doppler spread causes signal performance to change with time due to movement of users and obstacles*
  - *Multipath fading causes the signal to vary due to combination of delayed signal arrivals*

Channel quality varies over multiple time-scales.

Every change in environment will cause fluctuation

• RSI → channel quality

→ natural fluctuation

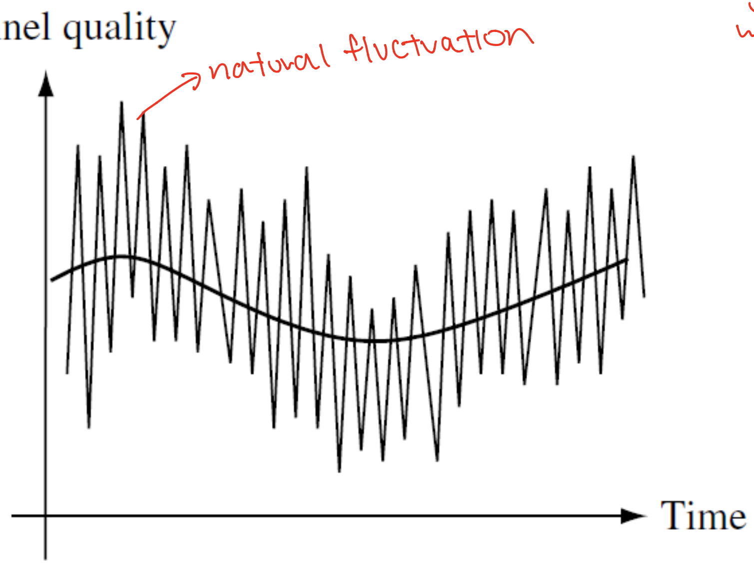


Figure from: https://web.stanford.edu/~dntse/Chapters_PDF/Fundamentals_Wireless_Communication_chapter2.pdf

Electromagnetic Spectrum

1) which freq to send data

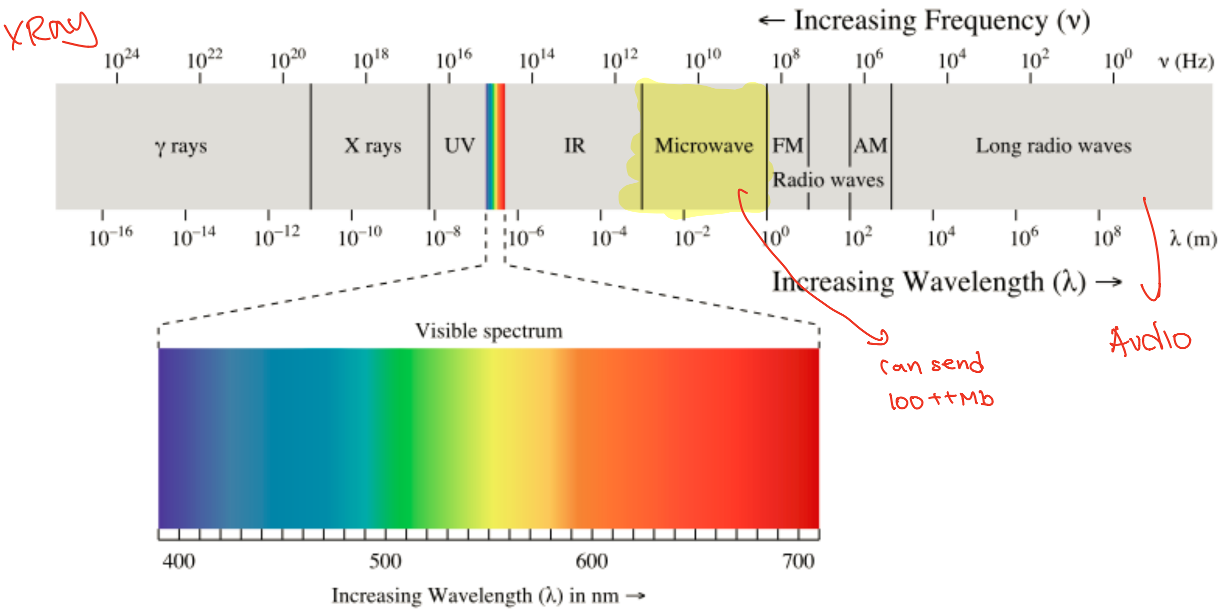
- More data = ↑ Freq
  = Deg rad ↑

$$P_r = G_r G_t \left(\frac{c}{4\pi f_c d} \right)^{\alpha} P_t$$

reciever

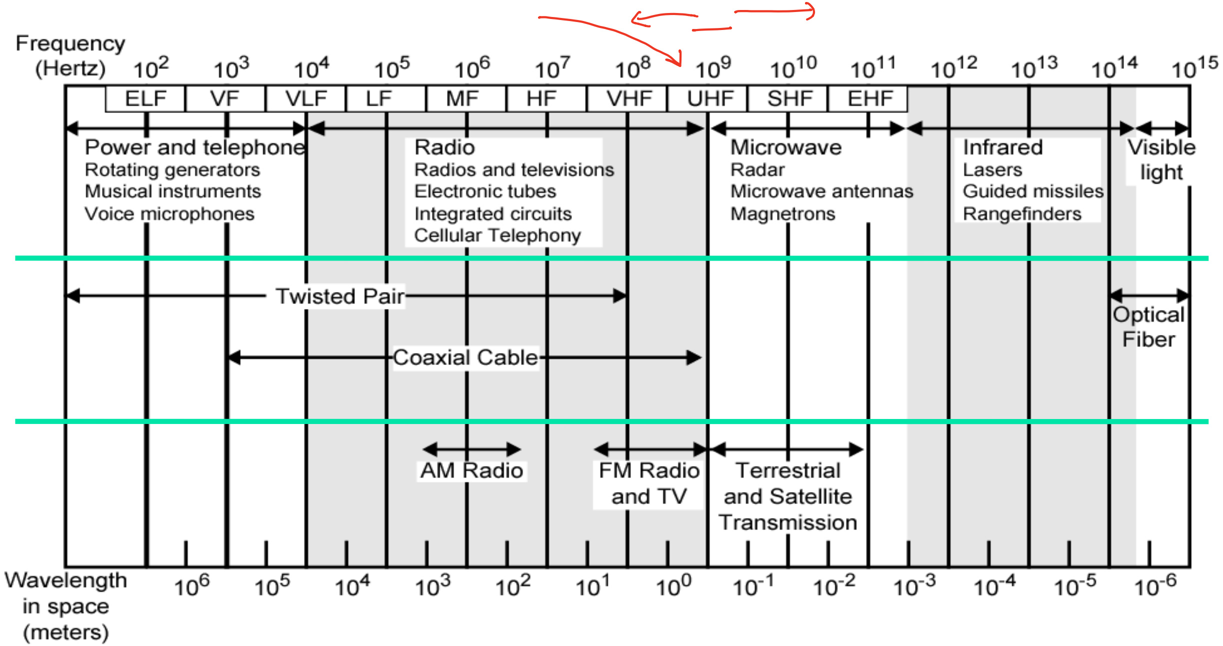
signal

Dominant



Electromagnetic Spectrum

Amt of data can be sent ↑



ELF = Extremely low frequency
VF = Voice frequency
VLF = Very low frequency
LF = Low frequency
MF = Medium frequency
HF = High frequency
VHF = Very high frequency
UHF = Ultrahigh frequency
SHF = Superhigh frequency
EHF = Extremely high frequency

↑ Freq ↑ Band

Usage	Frequency Band
AM Radio	(Medium Wave) 500 - 1600 kHz with 9-10 kHz spacing
FM Radio	87.5 - 108.0 MHz, channel spacing varies, usually > 100kHz
VHF (TV)	54 - 216MHz
UHF (TV)	470 - 806 MHz, 6MHz channel spacing
Data Transmission (e.g. Bluetooth, Wifi, cellular)	300MHz – 6GHz, 60GHz → loss is high comp to 5GHz 802.11ac defines use of 160MHz band 802.11ad runs in the 60GHz band

Noisy Channel: Shannon Capacity

The bandwidth available (B) Depend

The quality of the channel (the level of noise, SNR)

B:
How much my signal can be stretch across diff spectrum

$$C = B * \log_2(1+SNR)$$

Intuitively, capacity increases with available bandwidth (linear) and increases with SNR (log)

Putting the Equations together

Max power on send by phone: 2W upto

$\boxed{C} = \boxed{B} * \log_2(1+SNR)$

Data Rate

SNR – $\boxed{\text{signal}}$-to-noise ratio

→ interference
→ multipath

$$\boxed{P_r} = \underbrace{G_r G_t}_{\text{can improve antenna design}} \left(\frac{c}{4\pi \boxed{f_c} \boxed{d}} \right)^{\alpha} \boxed{P_t}$$

→ env

can improve antenna design

increase in B = ↑ fc
thus we will ↓ d
∴ The higher bandwidth, the shorter the distance

- **Power** is (usually) a constraint
  - Increase in power can result in higher range/data rate
- Increase **data rate (C)**
  - **Range** decreases and vice versa
- Increase throughput by using a **larger bandwidth** (B)
  - Probably needs to transmit at **higher frequencies** (f)
- Improve design to increase gain (G)
  - e.g. OFDM, MIMO etc.

Types of Wireless Networks

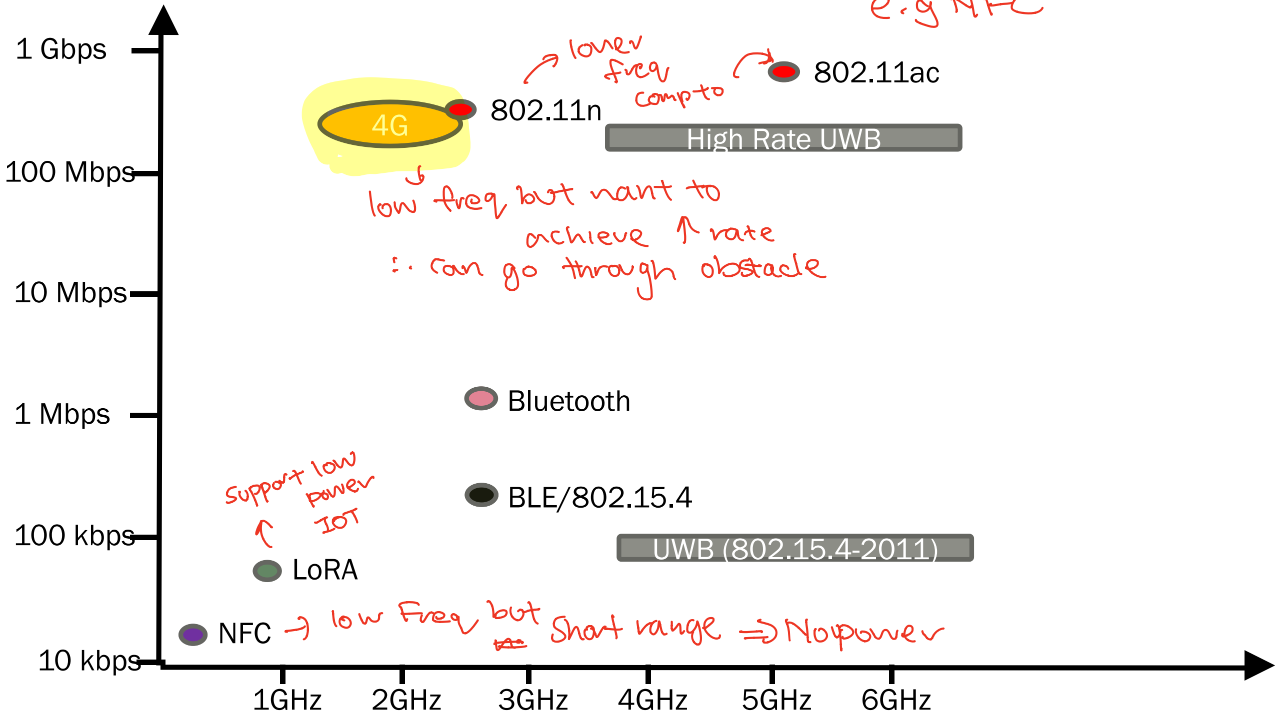
- Wireless Personal Area Network (WPAN)
  - *NFC (Near-Field Communication), RFID, Bluetooth, ZigBee*
- Wireless Local Area Network (WLAN)
  - *IEEE 802.11 (WiFi)*
- Wireless Metropolitan Area Network (WMAN)
  - *IEEE 802.16 (WiMAX)*
- Wireless Wide Area Network
  - *GSM, 3G/4G/LTE*

Characteristics of Wireless Networks

- Range
- Data Rate
- Power (consumed)
- Frequency Band (spectrum)

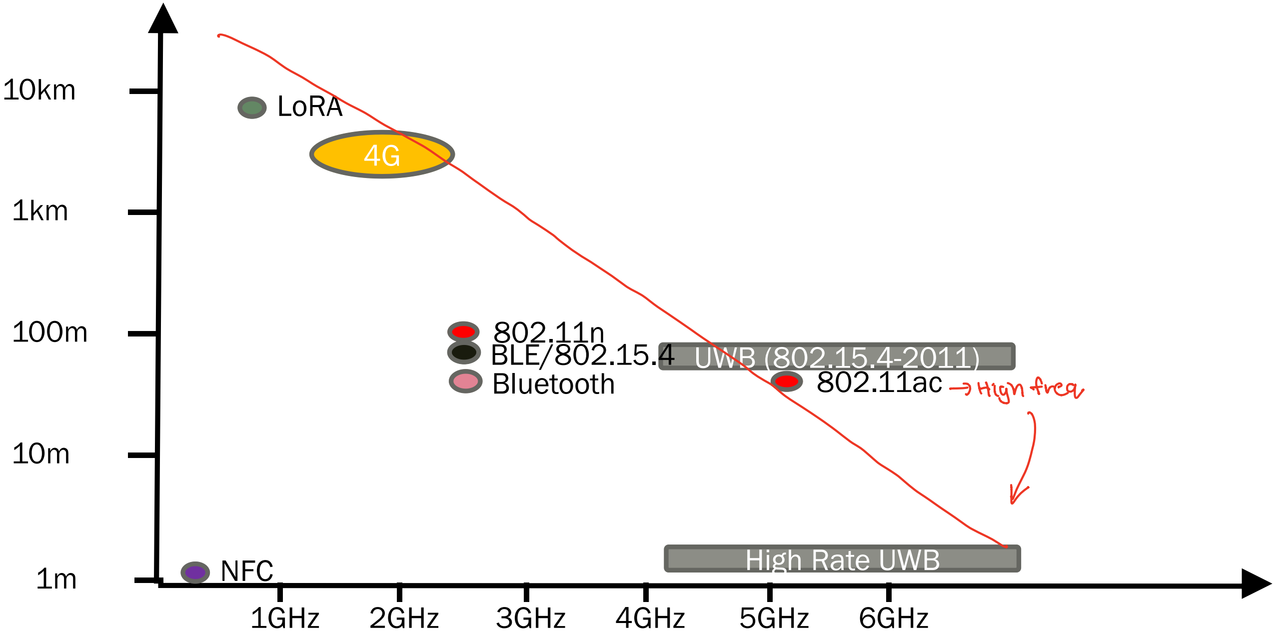
Data Rate

We do not need power to send data all the time e.g NFC



Range

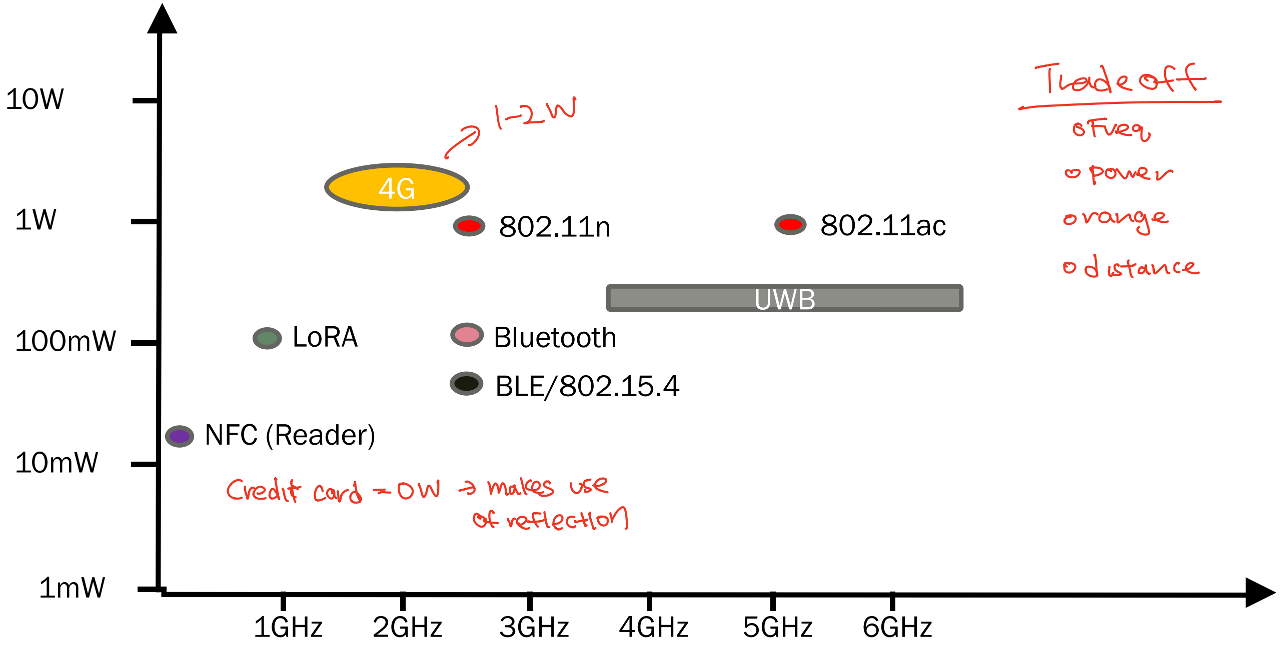
2) what is the range that we want



Power

≤ 1-2 Watts

long range / high data
→ consume more
power



Tradeoff
- Freq
- power
- range
- distance