Radio Frequency

EM wave that could be radiated via an antenna

From 3(30)kHz to 300GHz

Used in wireless telecommunication systems

Have completely revolutionized our way of life

EE-426: RF circuits design techniques

Passive HF components

Resonant circuits

Impedance matching

HF filters

Noise and Distorsion

S-Parameters

Modeling and Characterization of Transistors in HF

Design of small signal HF amplifiers

Oscillators

Architecture of TX and RX

Radio frequency named according to wavelength

Frequency range	Wavelength range	ITU designation		IEEE bands[6]
		Full name	Abbreviation[7]	
Below 3 Hz	$>10^5$ km	Tremendously low frequency[8]	TLF	—
3–30 Hz	10^5–10^4 km	Extremely low frequency	ELF	—
30–300 Hz	10^4–10^3 km	Super low frequency	SLF	—
300–3000 Hz	10^3–100 km	Ultra low frequency	ULF	—
3–30 kHz	100–10 km	Very low frequency	VLF	—
30–300 kHz	10–1 km	Low frequency	LF	—
300 kHz – 3 MHz	1 km – 100 m	Medium frequency	MF	—
3–30 MHz	100–10 m	High frequency	HF	HF
30–300 MHz	10–1 m	Very high frequency	VHF	VHF
300 MHz – 3 GHz	1 m – 100 mm	Ultra high frequency	UHF	UHF, L, S
3–30 GHz	100–10 mm	Super high frequency	SHF	S, C, X, Ku, K, Ka
30–300 GHz	10–1 mm	Extremely high frequency	EHF	Ka, V, W, mm
300 GHz – 3 THz	1 mm – 0.1 mm	Tremendously high frequency	THF	—

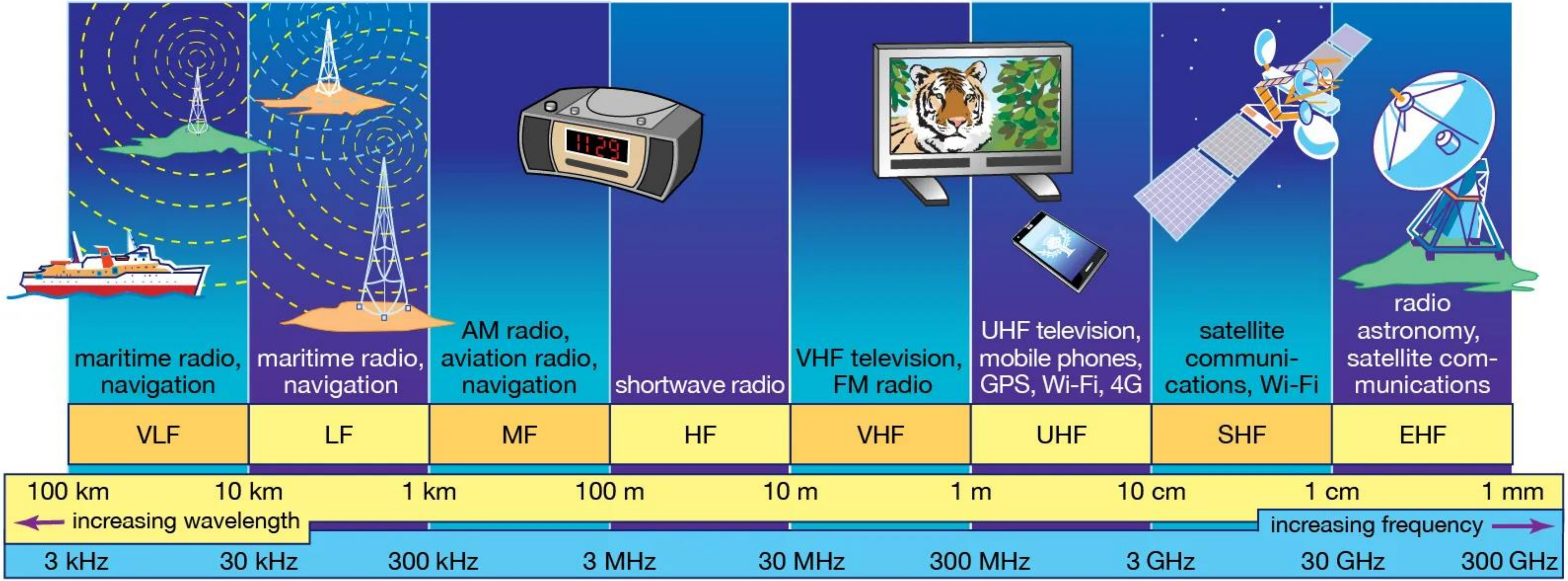
radio frequencies

microwave>1GHz

mm-wave>30GHz

Frequencies of 1 GHz and above are conventionally called microwave,[9] while frequencies of 30 GHz and above are designated millimeter wave. More detailed band designations are given by the standard IEEE letter- band frequency designations[6] and the EU/NATO frequency designations.[10]

Helicopter view of applications vs frequency



UNITED STATES FREQUENCY ALLOCATIONS

THE RADIO SPECTRUM

RADIO SERVICES COLOR LEGEND

- AERONAUTICAL MOBILE
- AERONAUTICAL MOBILE SATELLITE
- AERONAUTICAL RADIONAVIGATION
- AMATEUR
- AMATEUR SATELLITE
- BROADCASTING
- BROADCASTING SATELLITE
- EARTH EXPLORATION SATELLITE
- FIXED
- FIXED SATELLITE
- INTER-SATELLITE
- LAND MOBILE
- LAND MOBILE SATELLITE
- MARITIME MOBILE
- MARITIME MOBILE SATELLITE
- MARITIME RADIONAVIGATION
- METEOROLOGICAL AIDS
- METEOROLOGICAL SATELLITE
- MOBILE
- MOBILE SATELLITE
- RADIO ASTRONOMY
- RADIODETERMINATION SATELLITE
- RADIOLOCATION
- RADIOLOCATION SATELLITE
- RADIONAVIGATION
- RADIONAVIGATION SATELLITE
- SPACE OPERATION
- SPACE RESEARCH
- STANDARD FREQUENCY AND TIME SIGNAL
- STANDARD FREQUENCY AND TIME SIGNAL SATELLITE

ACTIVITY CODE

- GOVERNMENT EXCLUSIVE
- GOVERNMENT/ NON-GOVERNMENT SHARED
- NON-GOVERNMENT EXCLUSIVE

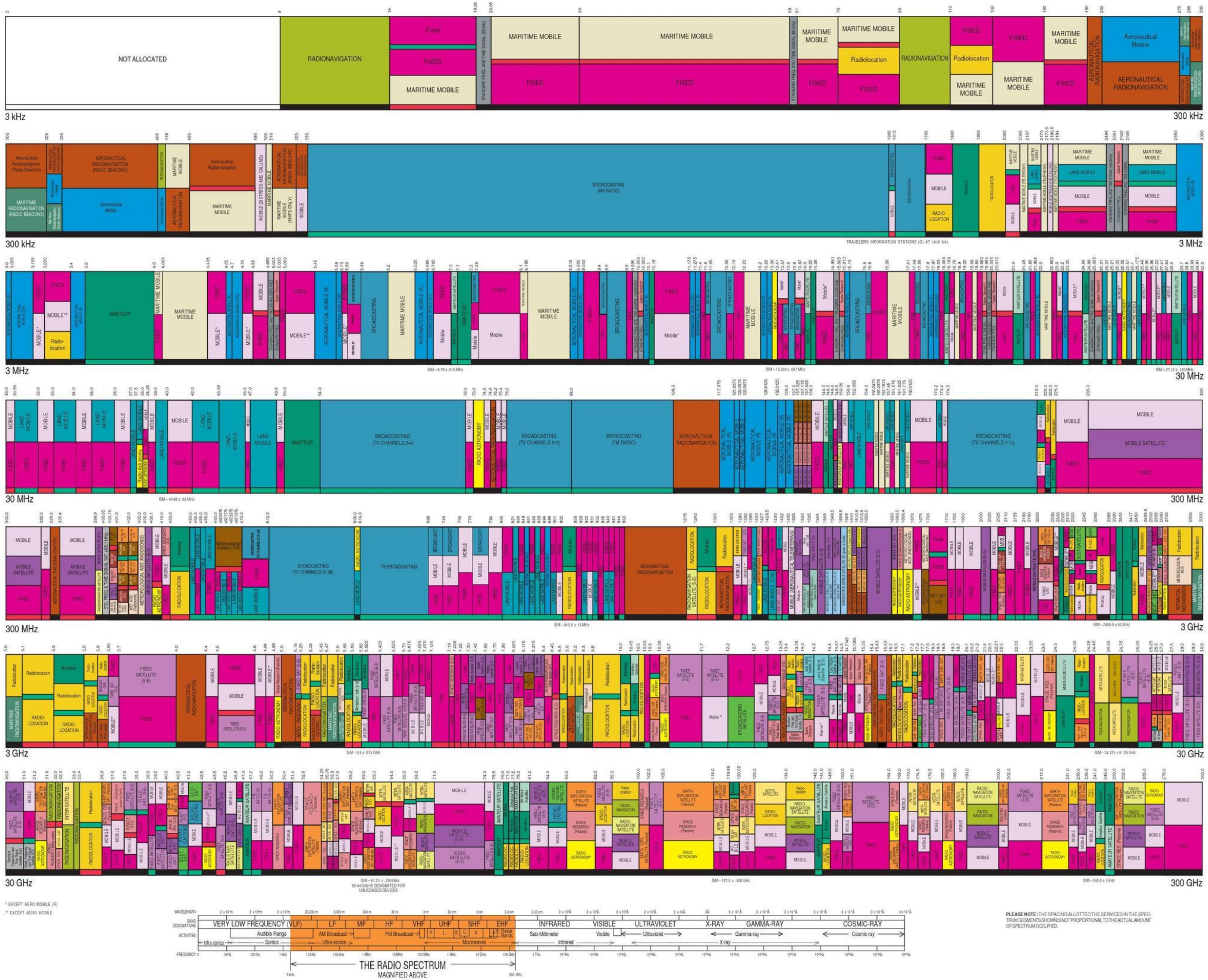
ALLOCATION USAGE DESIGNATION

SERVICE	EXAMPLE	DESCRIPTION
Primary	FIXED	Capital Letters
Secondary	Mobile	1st Capital with lower case letters

This chart is a graphic single-point-in-time portrayal of the Table of Frequency Allocations used by the FCC and NTIA. As such, it does not completely reflect all aspects, i.e., footnotes and recent changes made to the Table of Frequency Allocations. Therefore, for complete information, users should consult the Table to determine the current status of U.S. allocations.

U.S. DEPARTMENT OF COMMERCE
National Telecommunications and Information Administration
Office of Spectrum Management

October 2003



* EXCEPT AERO MOBILE (R)

** EXCEPT AERO MOBILE

PLEASE NOTE: THE SPACING ALLOTTED THE SERVICES IN THE SPECTRUM SEGMENTS SHOWN IS NOT PROPORTIONAL TO THE ACTUAL AMOUNT OF SPECTRUM OCCUPIED.

Mobile: 4G-LTE ~100 bands from 410 to 5900MHz

Band	Duplex mode[A 1]	*f* (MHz)	Common name	Subset of band	Uplink[A 2] (MHz)	Downlink[A 3] (MHz)	Duplex spacing (MHz)	Channel bandwidths (MHz)
1	FDD	2100	IMT	65	1920 – 1980	2110 – 2170	190	5, 10, 15, 20
2	FDD	1900	PCS	25	1850 – 1910	1930 – 1990	80	1.4, 3, 5, 10, 15, 20
3	FDD	1800	DCS		1710 – 1785	1805 – 1880	95	1.4, 3, 5, 10, 15, 20
4	FDD	1700	AWS-1	10, 66	1710 – 1755	2110 – 2155	400	1.4, 3, 5, 10, 15, 20
5	FDD	850	Cellular	26	824 – 849	869 – 894	45	1.4, 3, 5, 10
7	FDD	2600	IMT-E		2500 – 2570	2620 – 2690	120	5, 10, 15, 20
8	FDD	900	Extended GSM		880 – 915	925 – 960	45	1.4, 3, 5, 10
11	FDD	1500	Lower PDC (Japan)	74	1427.9 – 1447.9	1475.9 – 1495.9	48	5, 10
12	FDD	700	Lower SMH	85	699 – 716	729 – 746	30	1.4, 3, 5, 10
13	FDD	700	Upper SMH		777 – 787	746 – 756	−31	5, 10
14	FDD	700	Upper SMH		788 – 798	758 – 768	−30	5, 10
17	FDD	700	Lower SMH	12, 85	704 – 716	734 – 746	30	5, 10
18	FDD	850	Lower 800 (Japan)	26	815 – 830	860 – 875	45	5, 10, 15
19	FDD	850	Upper 800 (Japan)	5, 26	830 – 845	875 – 890	45	5, 10, 15
20	FDD	800	Digital Dividend (EU)		832 – 862	791 – 821	−41	5, 10, 15, 20

21	FDD	1500	Upper PDC (Japan)	74	1447.9 – 1462.9	1495.9 – 1510.9	48	5, 10, 15
24	FDD	1600	Upper L-Band (US)		1626.5 – 1660.5[B 1]	1525 – 1559[B 2]	−101.5	5, 10
25	FDD	1900	Extended PCS		1850 – 1915	1930 – 1995	80	1.4, 3, 5, 10, 15, 20
26	FDD	850	Extended Cellular		814 – 849	859 – 894	45	1.4, 3, 5, 10, 15
28	FDD	700	APT		703 – 748	758 – 803	55	3, 5, 10, 15, 20
29	SDL	700	Lower SMH	44	—	717 – 728	—	3, 5, 10
30	FDD	2300	WCS		2305 – 2315	2350 – 2360	45	5, 10
31	FDD	450	NMT		452.5 – 457.5	462.5 – 467.5	10	1.4, 3, 5
32	SDL	1500	L-Band (EU)	75	—	1452 – 1496	—	5, 10, 15, 20
34	TDD	2000	IMT		2010 – 2025		—	5, 10, 15
37	TDD	1900	PCS		1910 – 1930		—	5, 10, 15, 20
38	TDD	2600	IMT-E	41	2570 – 2620		—	5, 10, 15, 20
39	TDD	1900	DCS–IMT Gap		1880 – 1920		—	5, 10, 15, 20
40	TDD	2300	S-Band		2300 – 2400		—	5, 10, 15, 20
41	TDD	2500	BRS (US)		2496 – 2690		—	5, 10, 15, 20
42	TDD	3500	CBRS (EU, Japan)		3400 – 3600		—	5, 10, 15, 20
43	TDD	3700	C-Band		3600 – 3800		—	5, 10, 15, 20

46	TDD	5200	U-NII-1–4		5150 – 5925		—	10, 20
47	TDD	5900	U-NII-4	46	5855 – 5925		—	10, 20
48	TDD	3500	CBRS (US)	49	3550 – 3700		—	5, 10, 15, 20
50	TDD	1500	L-Band (EU)	45	1432 – 1517		—	3, 5, 10, 15, 20
51	TDD	1500	L-Band Extension (EU)		1427 – 1432		—	3, 5
53	TDD	2400	S-Band		2483.5 – 2495		—	1.4, 3, 5, 10
65	FDD	2100	Extended IMT		1920 – 2010	2110 – 2200	190	1.4, 3, 5, 10, 15, 20
66	FDD	1700	Extended AWS (AWS-1–3)		1710 – 1780	2110 – 2200[B 3]	400	1.4, 3, 5, 10, 15, 20
67	SDL	700	EU 700		—	738 – 758	—	5, 10, 15, 20
69	SDL	2600	IMT-E		—	2570 – 2620	—	5, 10, 15, 20
70	FDD	1700	Supplementary AWS (AWS-2–4)		1695 – 1710	1995 – 2020	295 – 300[B 4]	5, 10, 15, 20[B 5]
71	FDD	600	Digital Dividend (US)		663 – 698	617 – 652	−46	5, 10, 15, 20
72	FDD	450	PMR (EU)		451 – 456	461 – 466	10	1.4, 3, 5
73	FDD	450	PMR (APT)		450 – 455	460 – 465	10	1.4, 3, 5
74	FDD	1500	Lower L-Band (US)		1427 – 1470	1475 – 1518	48	1.4, 3, 5, 10, 15, 20
75	SDL	1500	L-Band (EU)		—	1432 – 1517	—	5, 10, 15, 20

Band	Duplex mode	*f* (MHz)	Common name	Subset of band	Uplink (MHz)	Downlink (MHz)	Duplex spacing (MHz)	Channel bandwidths (MHz)	Notes
76	SDL	1500	L-Band Extension (EU)		—	1427 – 1432	—	5	
85	FDD	700	Extended Lower SMH	12	698 – 716	728 – 746	30	5, 10	
87	FDD	410	PMR (APT)		410 – 415	420 – 425	10	1.4, 3, 5	
88	FDD	410	PMR (EU)		412 – 417	422 – 427	10	1.4, 3, 5	
103	FDD	700	Upper SMH		787 – 788	757 – 758	-30		[3]
Band	Duplex mode	*f* (MHz)	Common name	Subset of band	Uplink (MHz)	Downlink (MHz)	Duplex spacing (MHz)	Channel bandwidths (MHz)	Notes

1. ^ Frequency-division duplexing (FDD); time-division duplexing (TDD); FDD supplemental downlink (SDL)
2. ^ User Equipment transmit; Base Station receive
3. ^ User Equipment receive; Base Station transmit

1. ^ Downlink restricted to 1526–1536 MHz
2. ^ Uplink restricted to 1627.5–1637.5 MHz and 1646.5–1656.5 MHz
3. ^ Downlink between 2180–2200 MHz restricted to intra-band Supplemental Downlink
4. ^ Duplex spacing depends on whether the Uplink is paired with the lower or the upper part of the Downlink, with the remainder of the Downlink available for use as intra-band Supplemental Downlink
5. ^ Carrier aggregation only

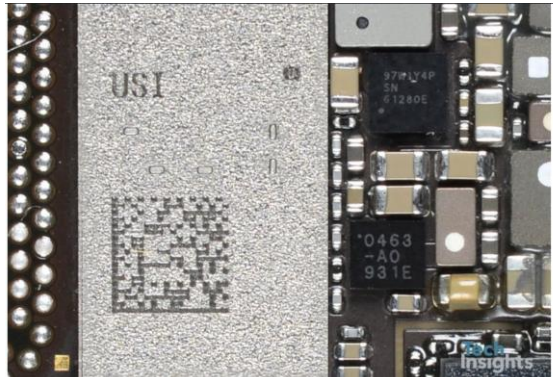
How many radios do you have in your phone?

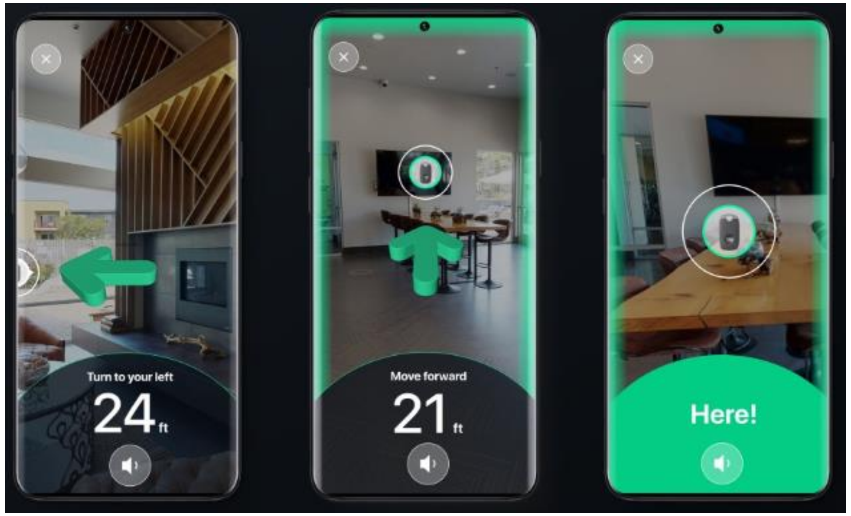
Some cool applications ?

- WIFI for indoor or downtown localisation: sniff SSID of nearby WIFI, send SSID to server via mobile network for high accuracy positioning
  - Used by most apps today ! Know where you are at any time
  - You feed the system with combined GPS+SSID information
- Bluetooth RSSI (received signal strength indicator) to detect proximity
  - Basis for COVID contact tracing app, tile tracker
- Localization of smartphone via base station triangulation (rescue)
- Traffic jam prediction using smartphone density on highways

Tile & AirTags Bluetooth (+UWB) tracker

- May be attached to your keys, wallet, bag, remote and searched via BLE
- AirTags work with the Find My app, which lives natively on every iPhone
- Tile trackers require a separate app but work with any phone
- Have to be within Bluetooth range (roughly 150 feet) of your tracker for it to appear on the app
- If not, use "lost mode" then any smartphone that comes within Bluetooth range of your tracker can help you locate it.
- *Close proximity tracking* with AirTags with UWB soon in Tile Ultra.





UWB in Iphone 11, Apple watch #6, HomePod mini

- Air drop prioritization
- Ranging to within a few inches
- Inter-device communications
- Short-range location tracking
- Available for developers
- While a typical Wi-FI channel width may be 20MHz, 40MHz, or 80MHz in size, UWB instead uses a bandwidth range of 500MHz
- 3.1GHz to 10.6GHz unlicensed use. Apple's U1 chip has two channels at 6.24GHz and 8.2368GHz.
- The FiRa Consortium, (Samsung, Oppo, Xiaomi, …), was formed in 2019 to promote UWB for consumer devices that works across platforms

What’s next with mobiles?
No more cloud, the sky is the limit

Today: Low earth orbiting (LEO) satellites for ubiquitous connectivity

- Deployed in case of earth infrastructure damage
  - Flood in Germany
  - War in Ukraine
- Internet anywhere

Overview of LEO satellites deployment

- Iridium 77 sat, from 1998, refurbished in 2019 LEO 780km L-band, e.g. Garmin
- Starlink >2k sat airborne (42k planned) (partnering with T-mobile)
- Globalstar 48 sat (with Apple)
- Kuiper (Amazon), 3.2k units (with Verizon)
- Oneweb (UK), 650 sat (with AT&T)
- Boeing 150 sat
- EU 6B€ program announced in Feb 22 but lagging behind, 250 sat
- Beidu (Huawei), demonstrated connectivity with Mate Smartphone
- Guowang 13k sat, China
- Sfera Russia

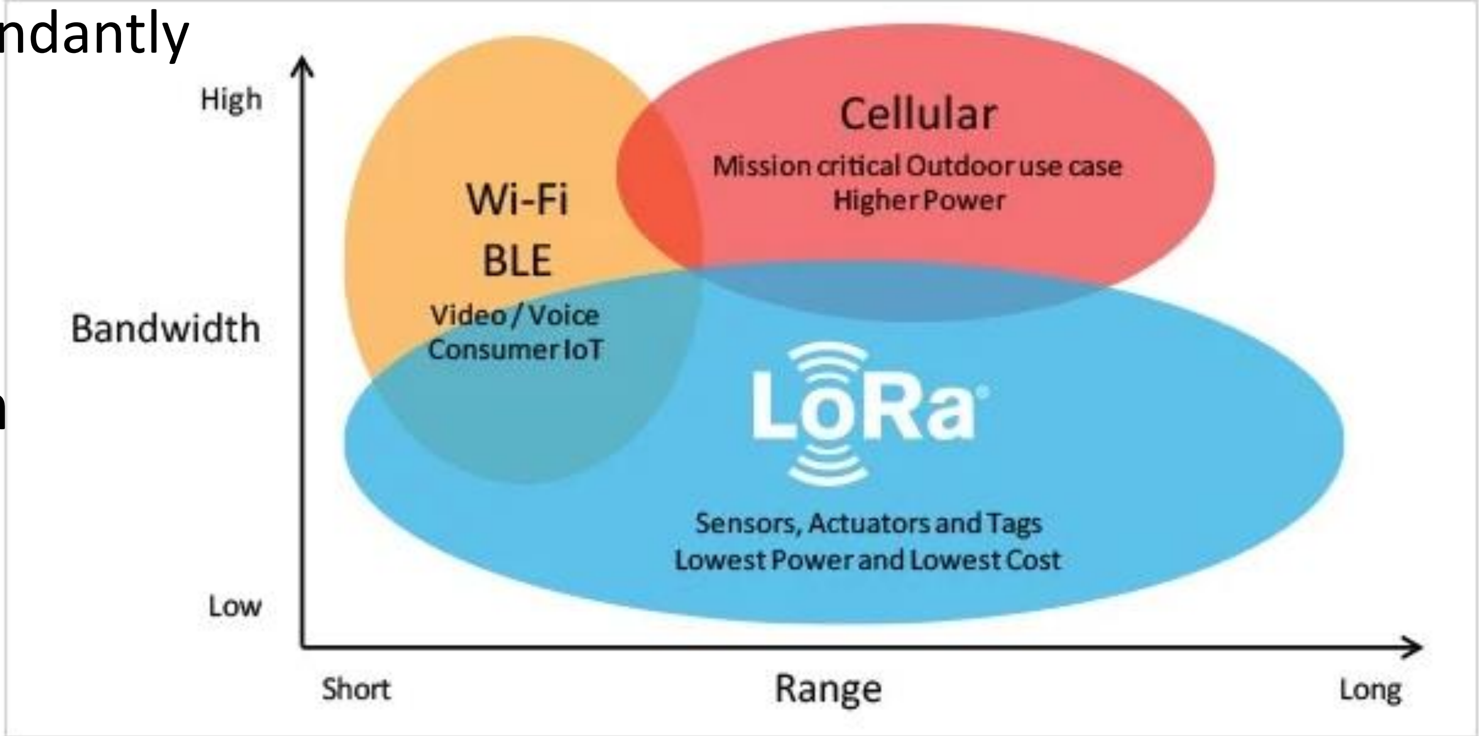
First steps with mobile to space !

- iPhone 14 and iPhone 14 Pro have Emergency SOS feature
- Send distress messages and share location
- User must be outdoors with a clear view of the sky
- Message sent in 15 seconds (LOS)
  a few minutes (foliage)
- Need to point towards satellite
- Latitude overage ±70° (no poles !)

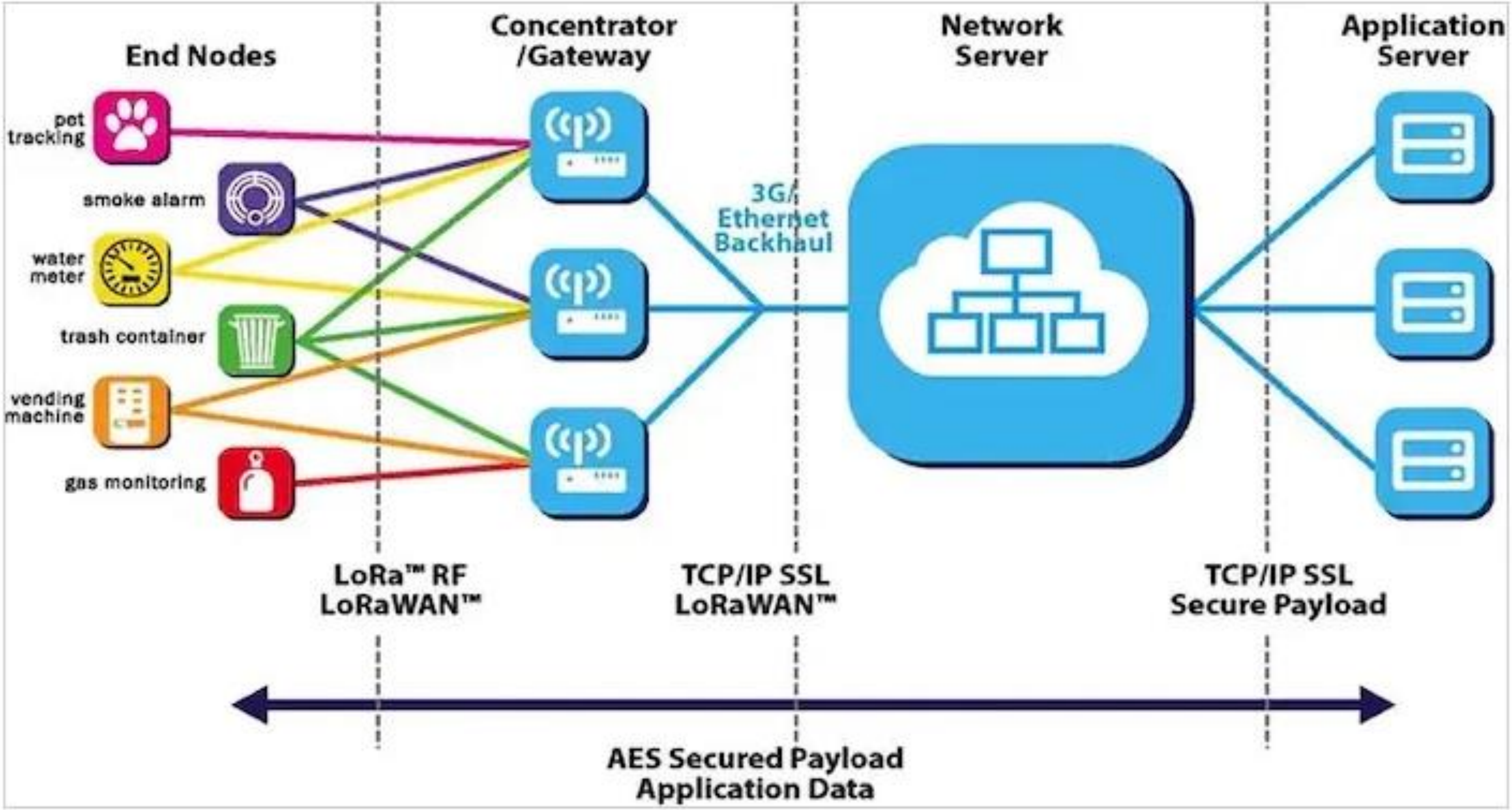
- Huawei Mate 50 with Beidu too!
- Qualcomm, Thales et Ericsson alliance for 5G

IoT with LoRa LPWAN

- Internet of Things with Long Range Low Power Wide Area Network
- Goal: connect your IoT Device to a gateway at city level (10km)
- Very high link budget due to spreading factor
  - Transmit the same bit redundantly
  - FM Chirp in ISM bands
  - Sub-GHz
- Low datarate application
- Started by Cycleo-Semtech
  - Very low hardware cost
  - Very high link budget



LoraWAN network topology



Examples of LoRa system and applications. Image used courtesy of Digi-Key

LoRa Applications

- Electricity meters
- Gas meters
- Water meters

Smart metering

- Irrigation control
- Environmental sensing
- Animal tracking

Agriculture

- Motorcycles, bicycles
- Cars
- Shipping containers
- Kids, pets
- Insurance – valuable assets
- Find my stuff

Tracking

- Fault management
- Anti-theft solutions for cables
- Metering

Smart grids

- Medical wearables
- Connected bracelets
- Condition monitoring
- Connected clothes

Wearables & mHealth

- Earthquake sensors
- Avalanche & flooding
- Heating & AC
- Equipment status
- Forest fires
- Air pollution
- Worker wellness

Industrial

- Street lighting
- Infrastructure monitoring
- Waste management
- Advertising displays
- Smart parking
- Vending machines

Smart city

- Smoke detectors
- Security systems
- Smart appliances
- Heating
- Control & monitoring

Connected home

- Traffic information
- Traffic light
- Vehicle status

Vehicle telematics

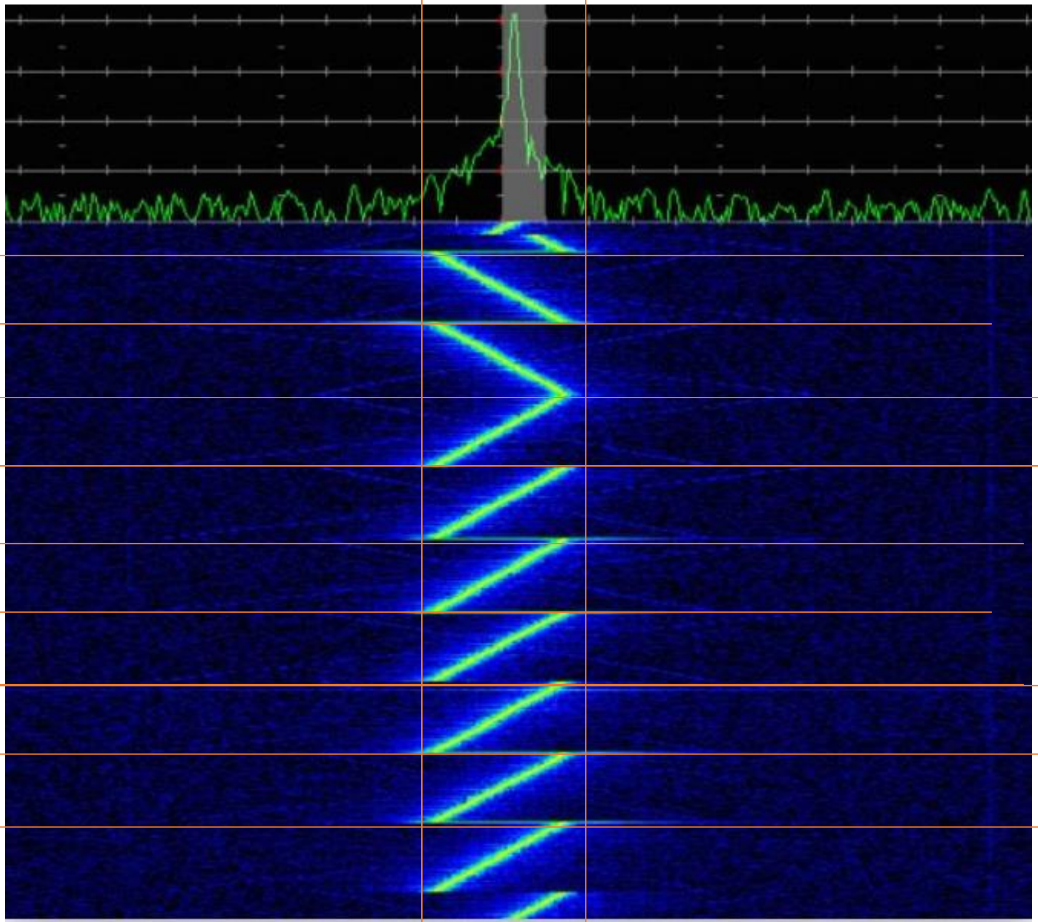
LoRa processing gain with spreading factor

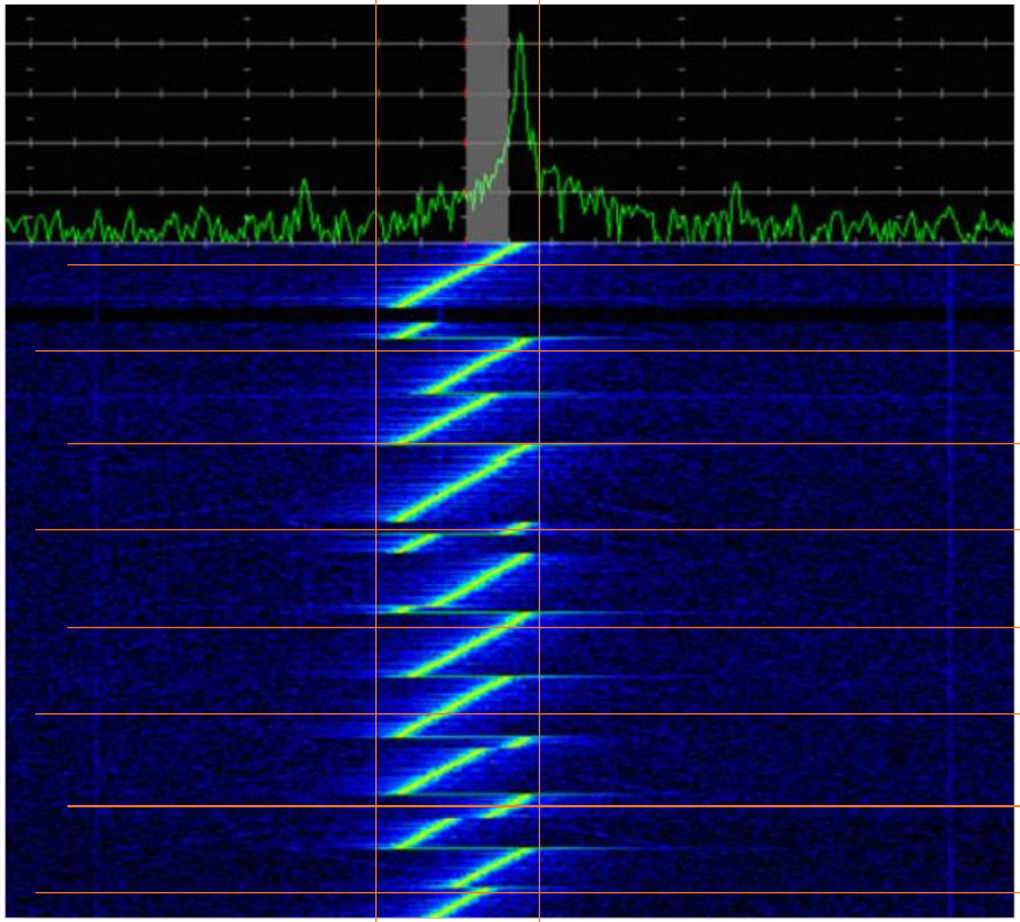
LoRa Spreading Factors (125kHz bw)

Spreading Factor	Chips/symbol	SNR limit	Time-on-air (10 byte packet)	Bitrate	Sensititivity
7	128	-7.5	56 ms	5469 bps	-123 dBm
8	256	-10	103 ms	3125 bps	-126 dBm
9	512	-12.5	205 ms	1758 bps	-129 dBm
10	1024	-15	371 ms	977 bps	-132 dBm
11	2048	-17.5	741 ms	537 bps	-134.5 dBm
12	4096	-20	1483 ms	293 bps	-137 dBm

LoRa modulation

- Long preamble for sync
- FM chirp with phase mod





LoRa going to direct satellite connectivity

- **Adding LR-FHSS to LoRaWAN**
- For years, engineers had sought LoRaWAN for satellite communications, which there had been nothing more than proof of concepts.
- However, in 2020, the LoRa Alliance released LoRaWAN of Regional Parameters RP2-1.0.2.
- The new Regional Parameters included the addition of support for new long range-frequency hopping spread spectrum (LR-FHSS) parameters. This addition effectively made LoRaWAN capable of global satellite communication.
- Including LR-FHSS effectively allows LoRaWAN communications to occupy multiple frequency bands during a single transmission, allowing LoRaWAN to be more reliable. It is less susceptible to local interference and an increased capacity, which are essential for long-range communications.
- Satellites by: Swarm Technology (Space-X), Fossa Systems

How does RF propagate ? Friis Equation

- G: TX and RX antenna gain
- D: distance for line of sight propagation
- P: TX and RX power

$$P_{rx} = P_{tx} G_{tx} G_{rx} \left(\frac{c}{4\pi D_r f_0} \right)^2$$

$$P_{rx}(dB) = P_{tx} + G_{tx} + G_{rx} + 20\log_{10}\left(\frac{\lambda}{4\pi D_r} \right)$$

Sensitivity calculation

- -174 dBm for 1Hz BW
- 1MHz BW, 60dB
- Eb/No is modulation dependent: e.g. 5-10dB
- Processing gain: spreading factor
- NF RX added noise 1-5dB

$$S_{in}\ (\mathrm{dBm}) = NF\ (\mathrm{dB}) + KTB_{RF}\ (\mathrm{dBm}) + E_b/N_o\ (\mathrm{dB}) - PG\ (\mathrm{dB})$$

Exercise

- Calculate the max line of sight propagation range for a given TX power or the required link budget for a given distance for a particular RF application
- E.g. BLE, 1MHz BW, 2.4GHz, P_{TX} =0dBm (1mW), NF+Eb/No=14dB, $G_{RX,TX}$=0dBi
- Solution
  - Sensitivity (min det sig = -174dBm (kT)+60dB (1MHz)+14dB (NF+Eb/No) = -100dBm
  - D=(c/4π/fo)/sqrt(P_{RX}/P_{TX}) ~ 1km or 8k·λ (λ ~ 12.5cm)

- Calculate the corresponding voltage at the LNA input
- Calculate the RX gain to drive a 10-b ADC with a 1V FS voltage