Example technologies and standards

Slides used in TDDE48 (Mobile Networks) @ LiU, Sweden, Fall 2025
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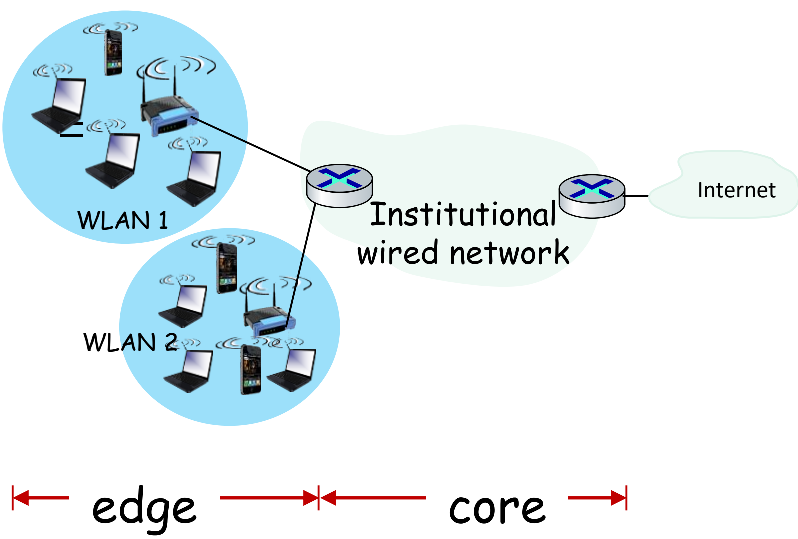
Slides in this course are adapted or based on various on-line resources (including lectures notes by Juha Takkinen, Anirban Mahanti, Carey Williamson, Jim Kurose, and Keith Ross)

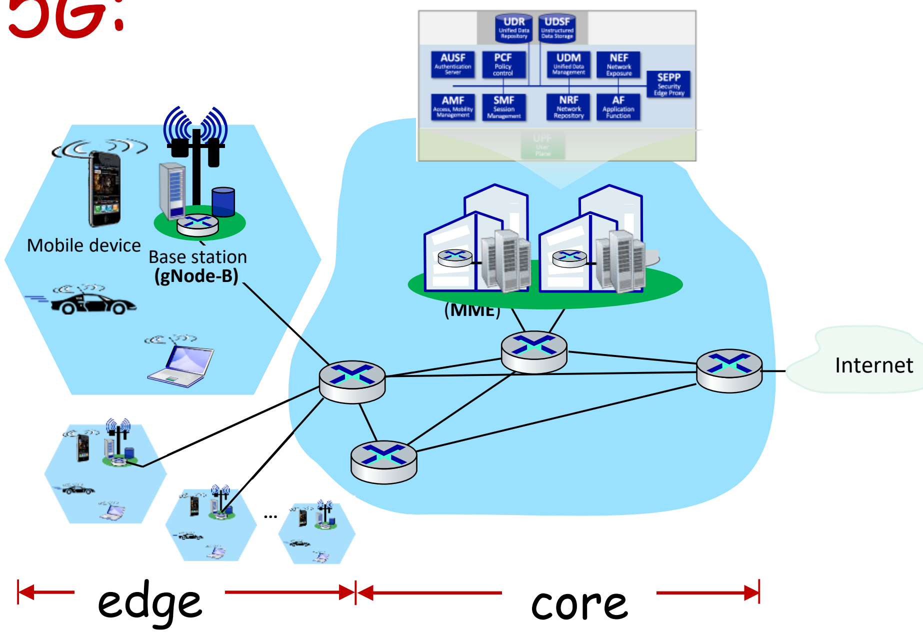
- The right technology/standard for the problem/environment??

Wireless networks: edge and core networks

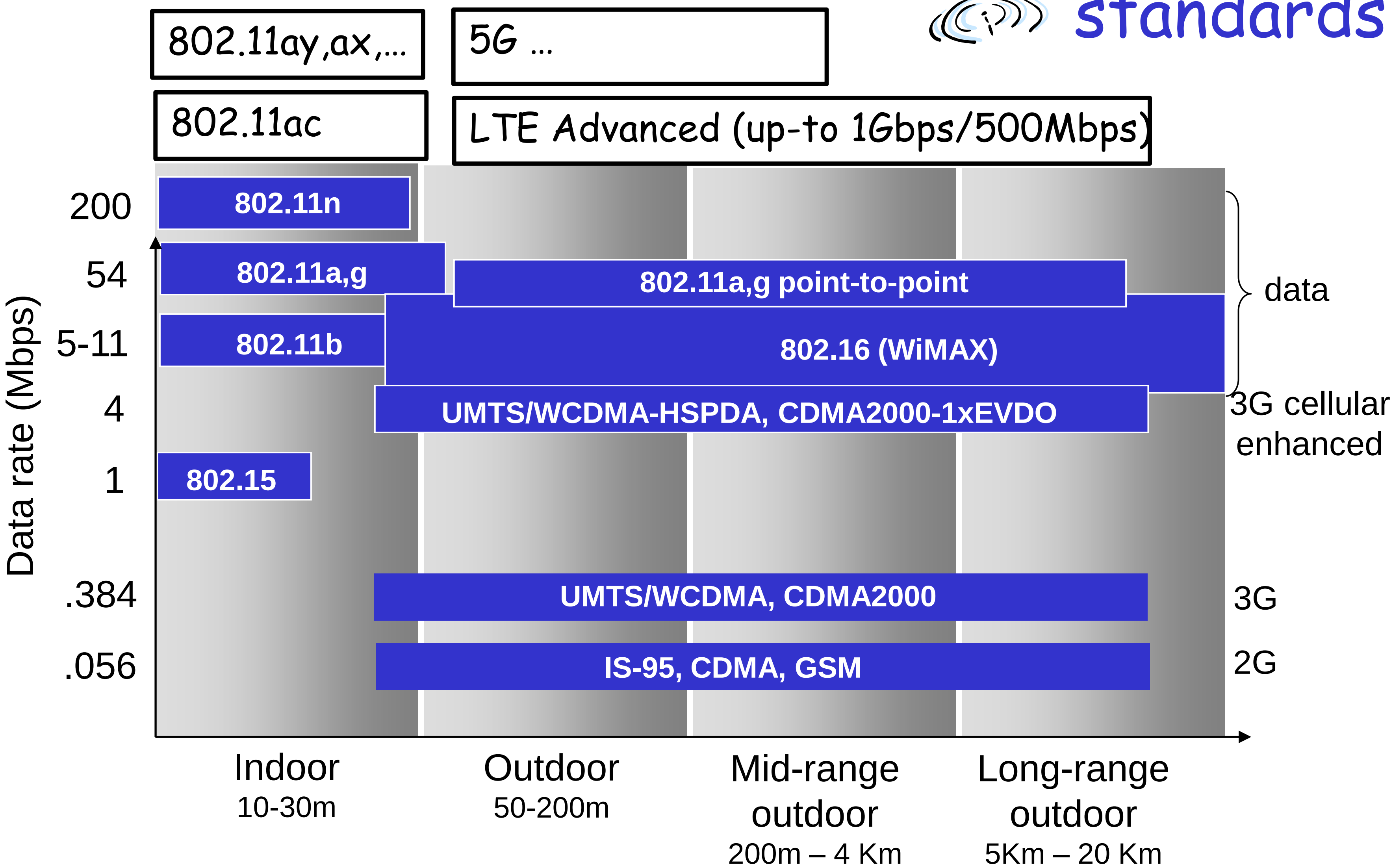
WiFi:



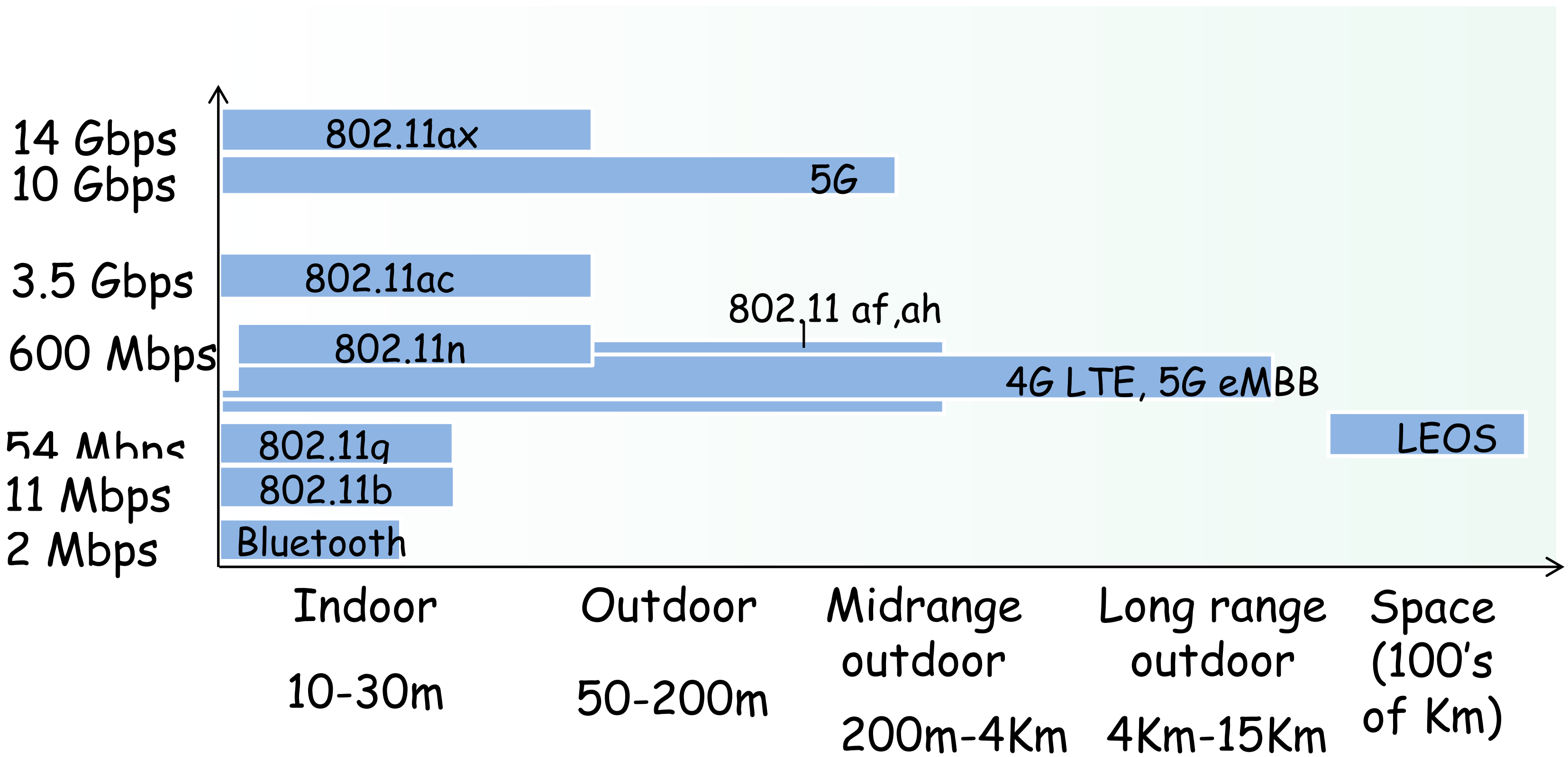
5G:



Characteristics of selected wireless link standards



Characteristics of selected wireless links



Differences in bandwidths primarily from …

- Physical layer
  - Spectrum allocation (wave length)
  - Frequency; channel width; time multiplexing
  - Signal-to-Noise; BER; Error correction; etc.

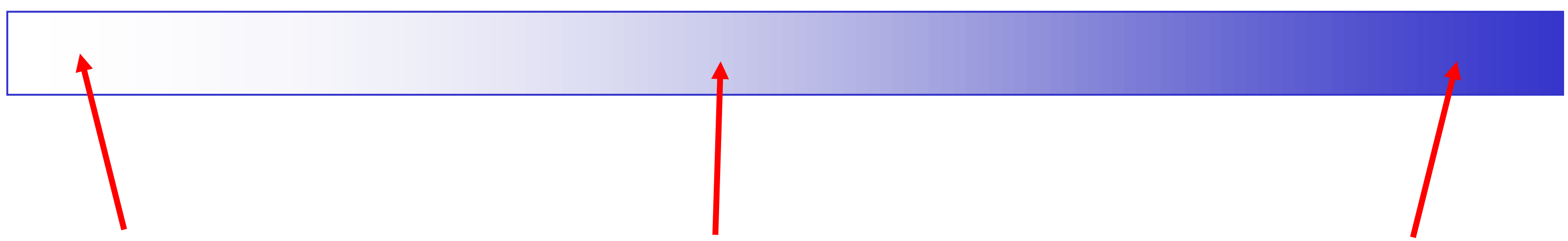
- MAC layer (sub-layer in data link layer)
  - Multiple access techniques
  - E.g., FDMA, TDMA, CDMA, SDMA, OFDMA,…

Frequency band spectrum

- spectrum allocated by global and national agencies

(Less sensitive to obstacles)
Low frequency

(More sensitive to obstacles)
High frequency



ELF (30-300Hz)

Telephone;
AM broadcast
Cell phone;
Satellite
Microwave links

Visible light
(400-900THz)

Wireless radio spectrum:

- radio spectrum: national asset, owned by the nation
- national government determine how spectrum is used "locally"
- different spectrum use types:

licensed:
- dedicated use, typically by one "owner" (e.g., cellular carrier such as AT&T, Verizon)
- often allocated by spectrum auction

shared:
- spectrum dynamically shared among users
- "incumbent" may get preferential access, others "back off"

unlicensed:
- open (free) for anyone to use, conforming to rules (e.g., power transmission levels)
- 2.4GHz and 5 Ghz WiFi
- 3.5GHz "Private 5G" (aka CBRS)

WiFi spectrum bands

6 GHz range
- most recently added
- more than 250 configurable/selectable WiFi channels of different transmission rates

802.11
ax/be

5 GHz range
- More than 150(configurable/selectable WiFi channels) of different transmission rates

802.11
a/h/n/ac/ax

2.4 GHz
- Divided into 11-14 channels, depending on country

802.11
b/g/n/ax

- other 802.11 WiFi spectrum bands, but not in widespread use

* No single, well-accepted ranges for "low", "mid" and "high"

5G spectrum: three spectrum bands*

High band frequencies: 25-66 GHz range (aka **mmwave**) — 5G

- 26 GHz, 40 GHz, 50 GHz, 66 GHz bands popular
- short distances (< mile), high speeds (<3 Gbps)
- line of sight transmission: poor penetration of trees, buildings, …

Mid-band frequencies: 1 - 6 GHz ranges

- balance distances (~5 miles ?) and transmission rates (100-900 Mbps)
- 1.8, 3.3 GHz to 3.8 GHz, 6 GHz bands popular

3.4 - 6 GHz — 5G, 4G

1-2.6 GHz — 5G, 4G, 3G, 2G

Low band frequencies: (< 1 GHz range) — 5G, 4G, 3G, 2G

- covers longer distances (10's of miles), but at lower speeds (50-250 Mbps)

Antennas

MIMO: Multiple input multiple outpu antenna

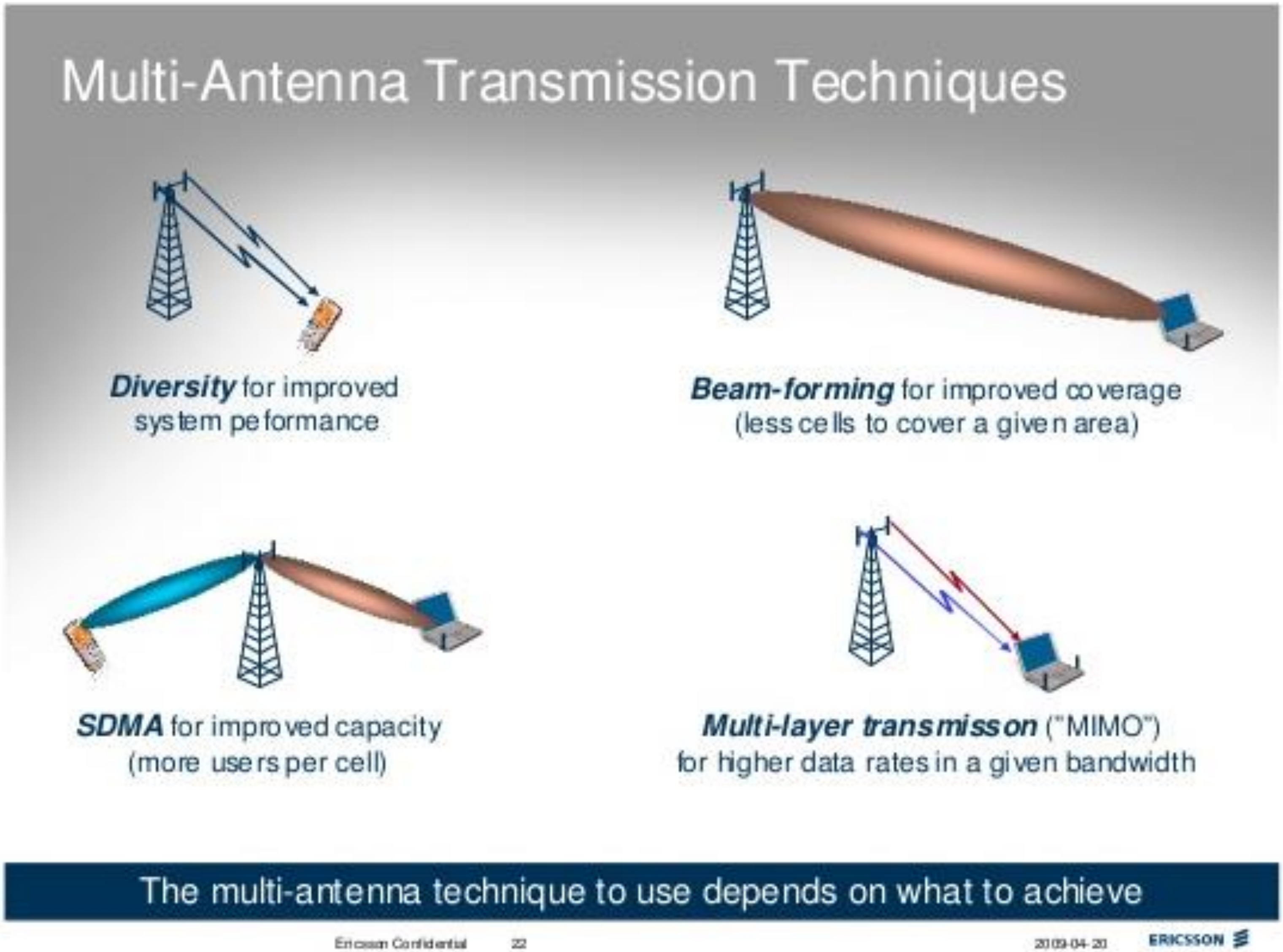
Antennas both transmit and receive radio waves

single antenna: old school

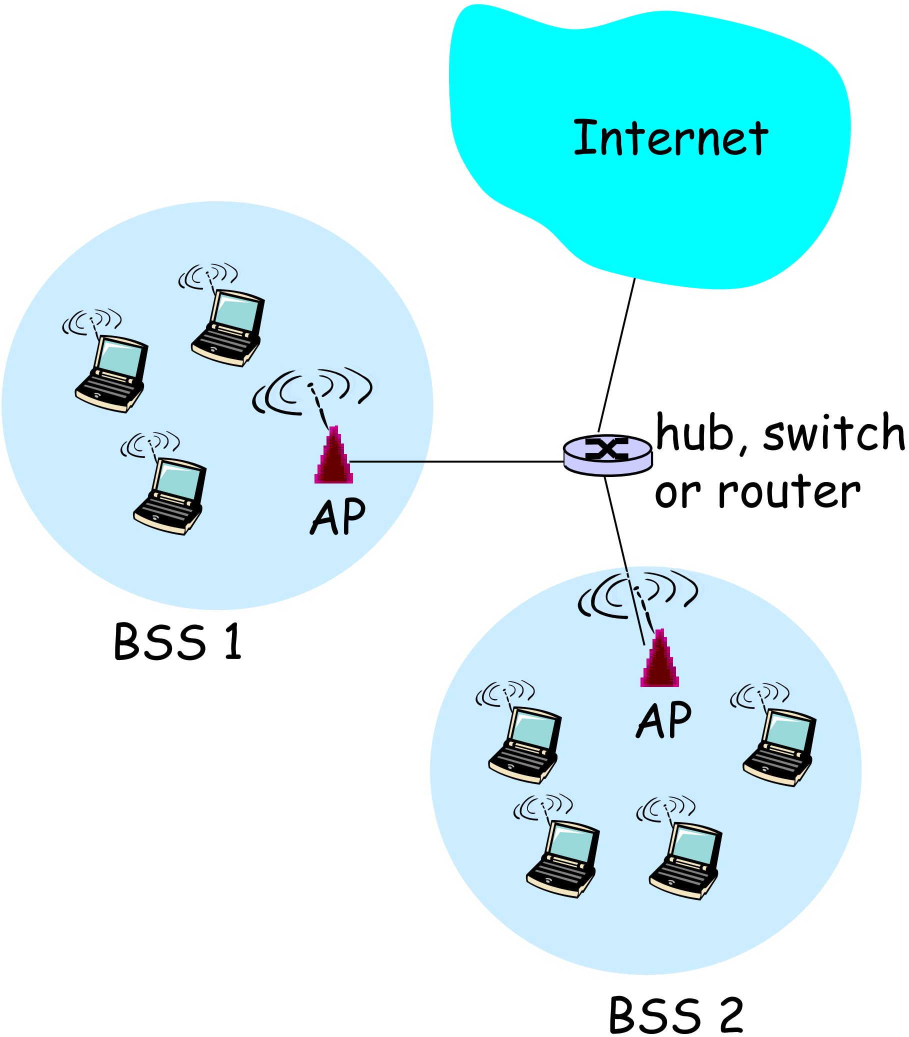
multiple antenna: common now in wireless networks

- Gigabit LTE with 4x4 MIMO
- Wi-Fi 6 (802.11ax) with 2x2 MIMO

Multi-antenna (*slide from Ericsson)



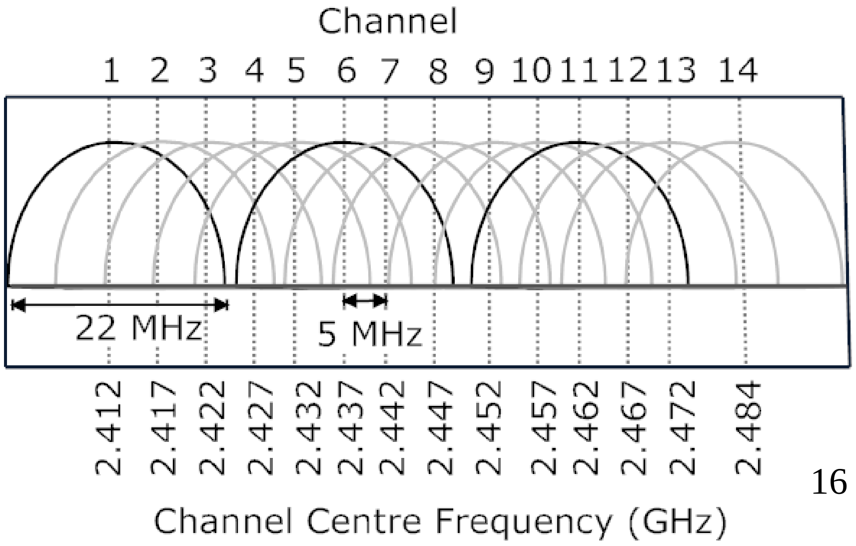
802.11 LAN architecture



- Wireless host communicates with base station
  - base station = access point (AP)
- Basic Service Set (BSS) (aka "cell") in infrastructure mode contains:
  - wireless hosts
  - access point (AP)
  - ad hoc mode: hosts only

802.11: Cells, channels, association

- 802.11b has 11 channels
- Channels 1, 6, and 11 are non-overlapping



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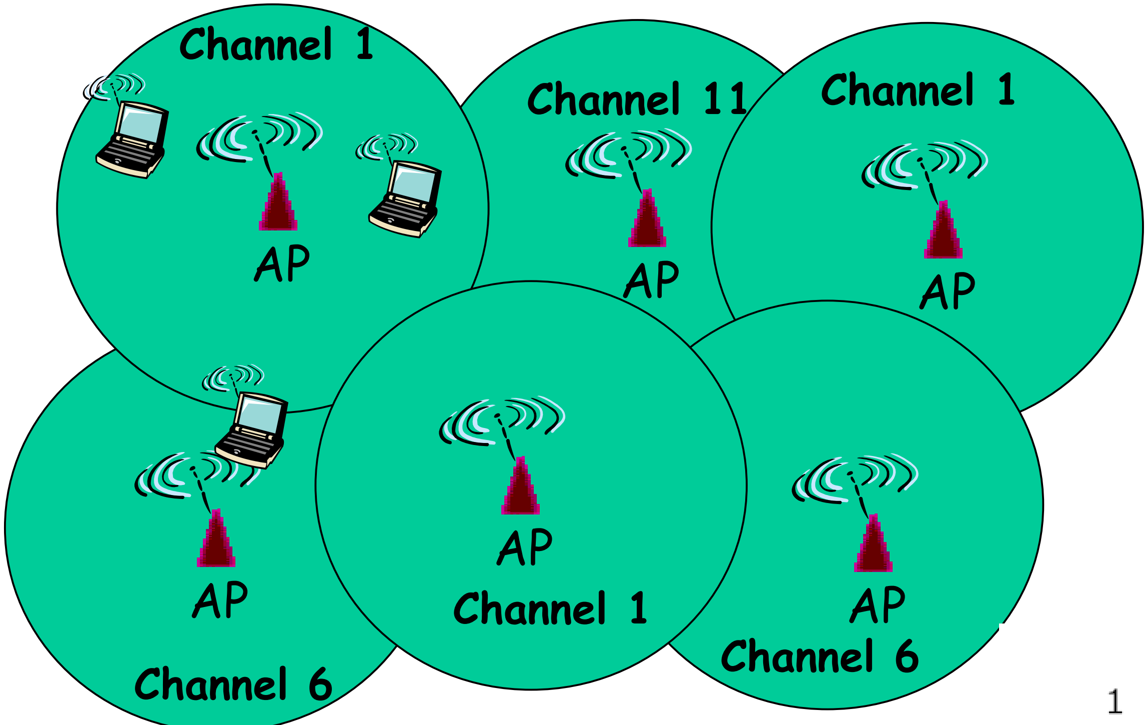

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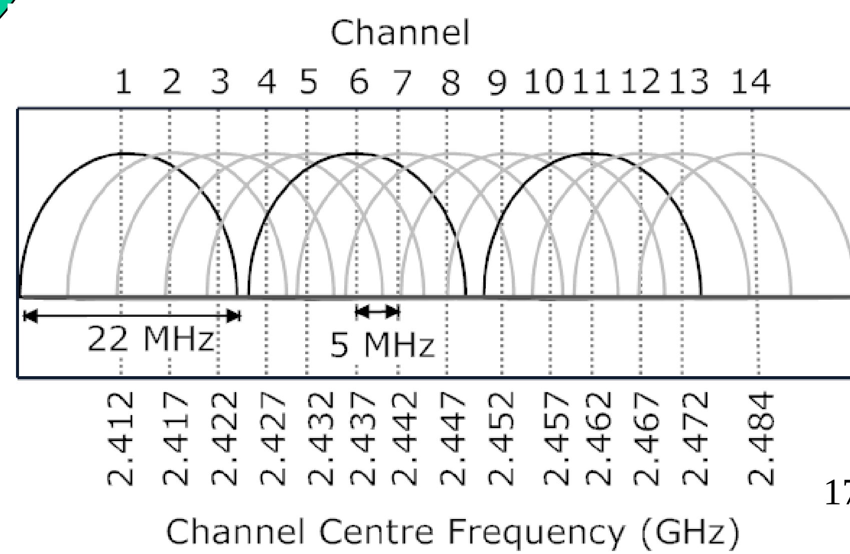
- Wireless nodes can roam between cells



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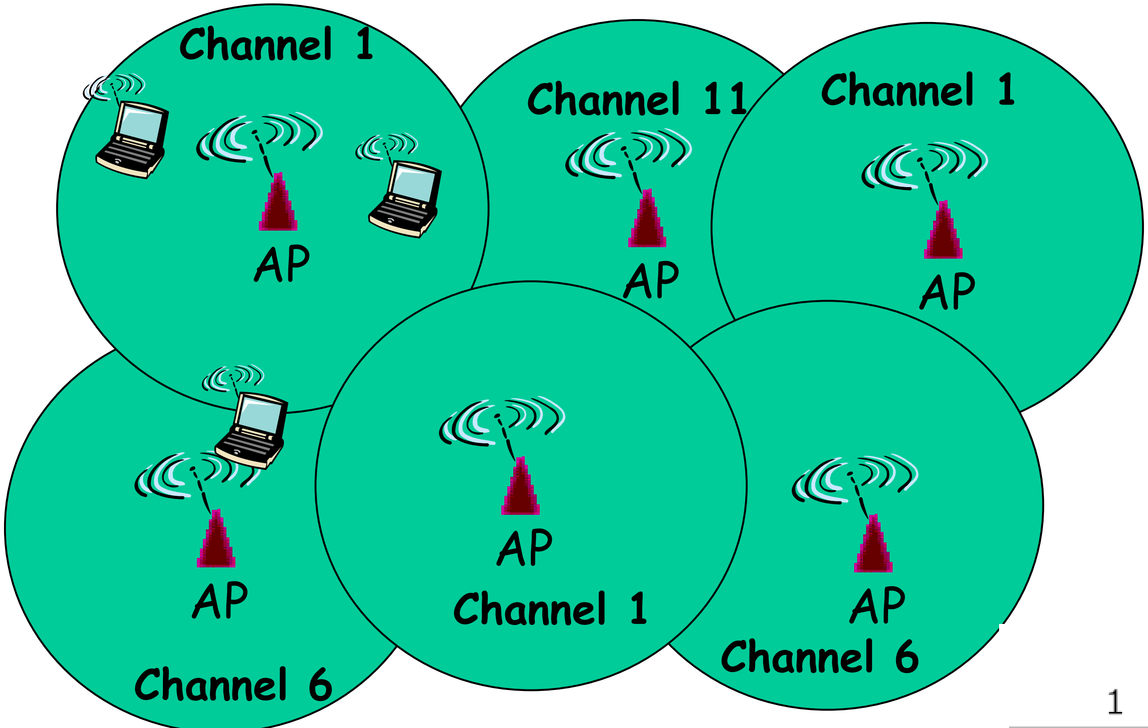

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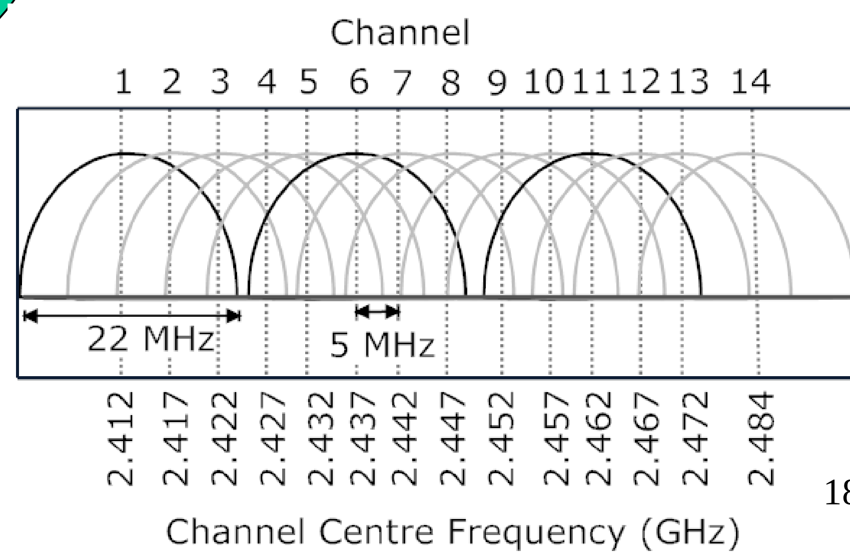

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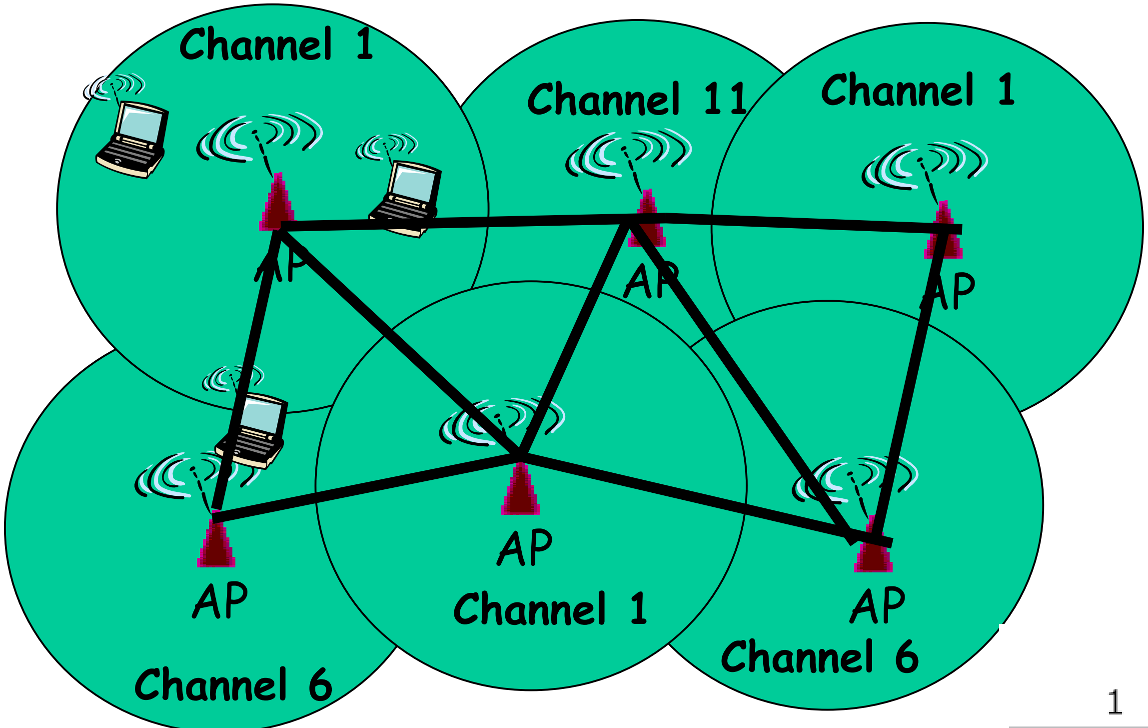

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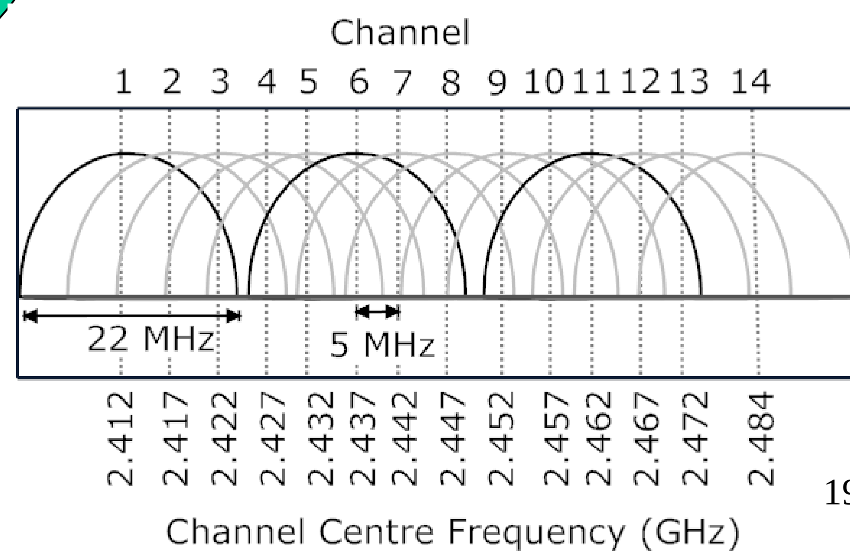

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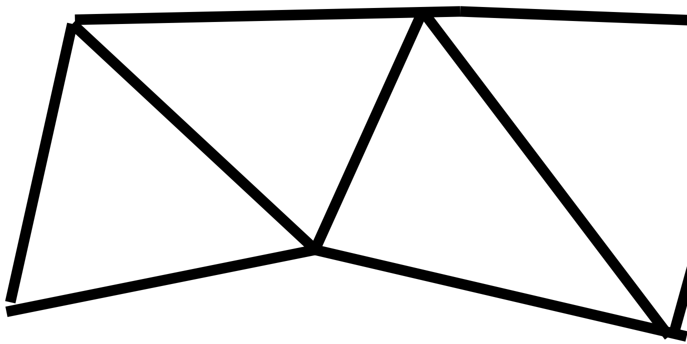

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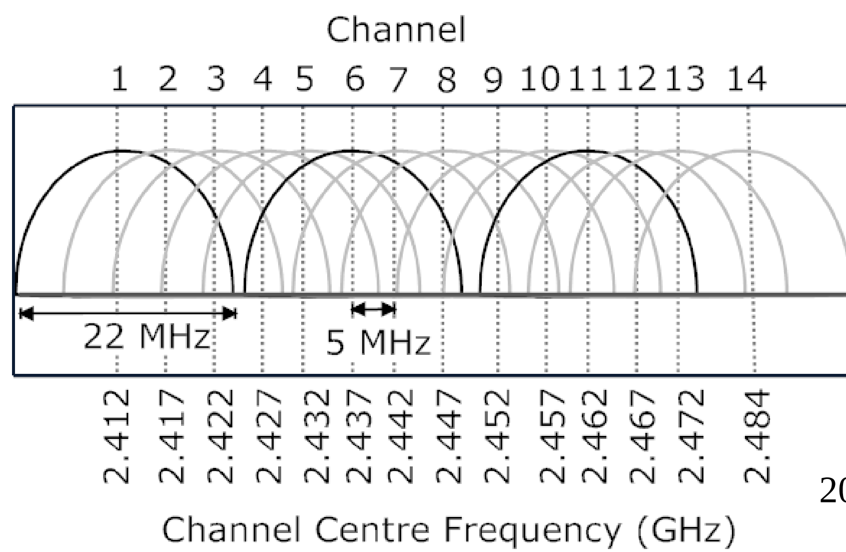

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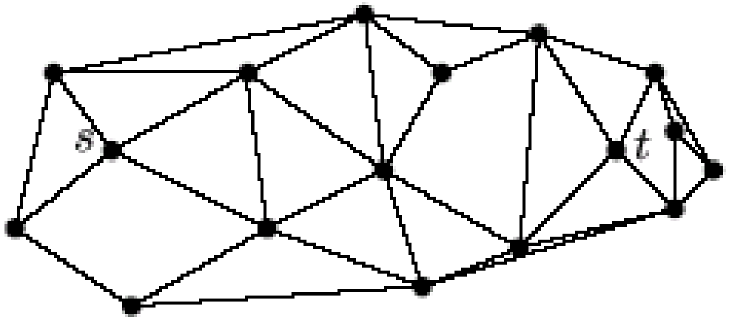

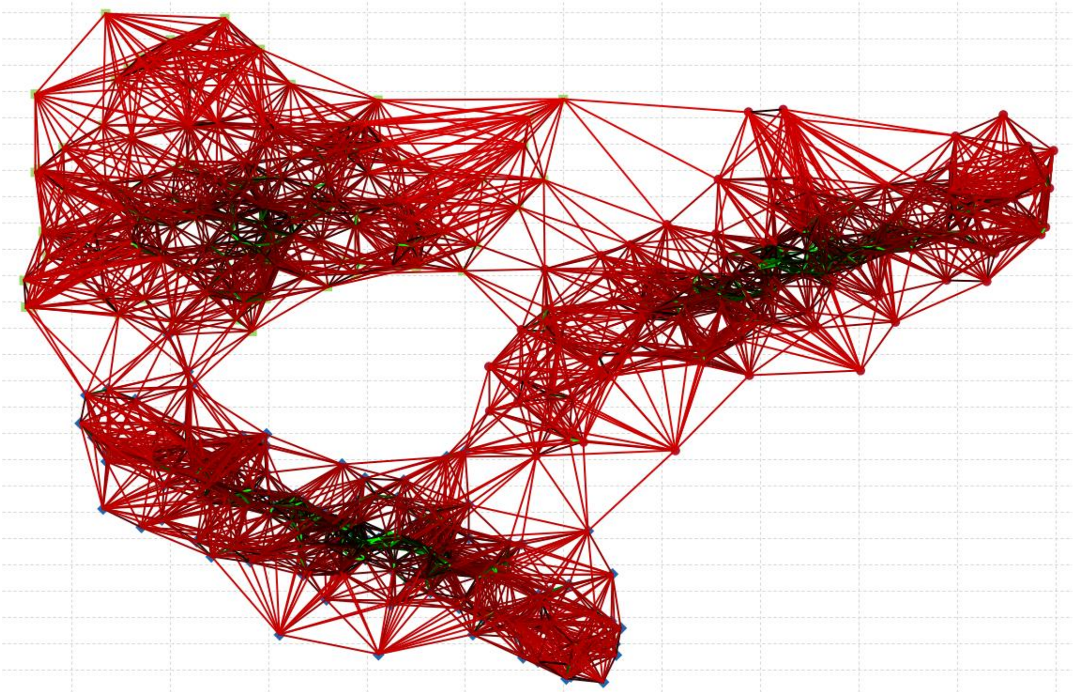

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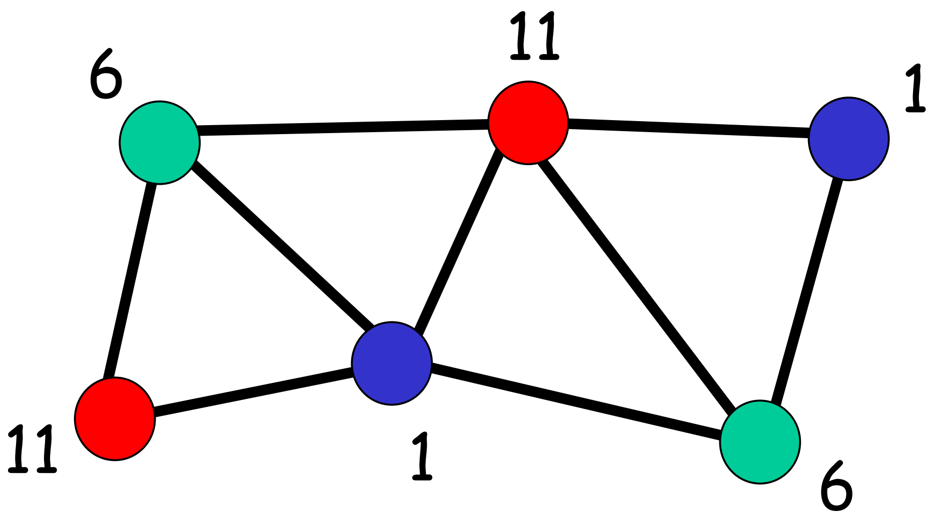
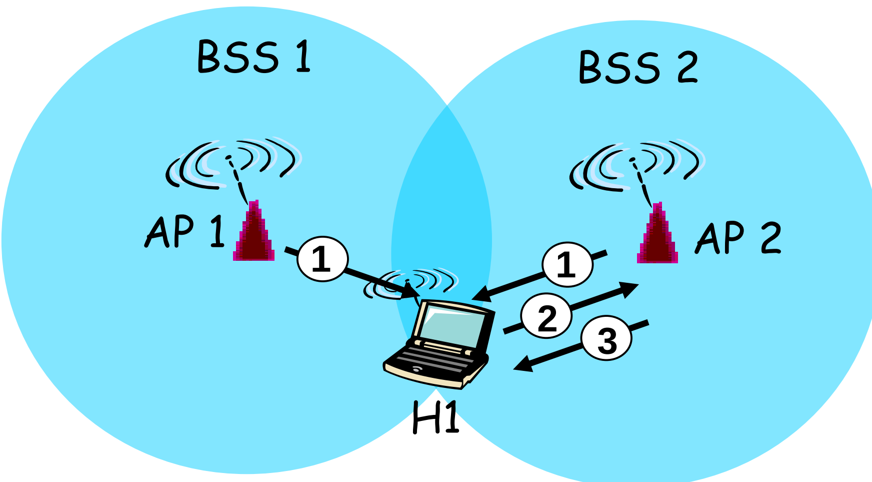


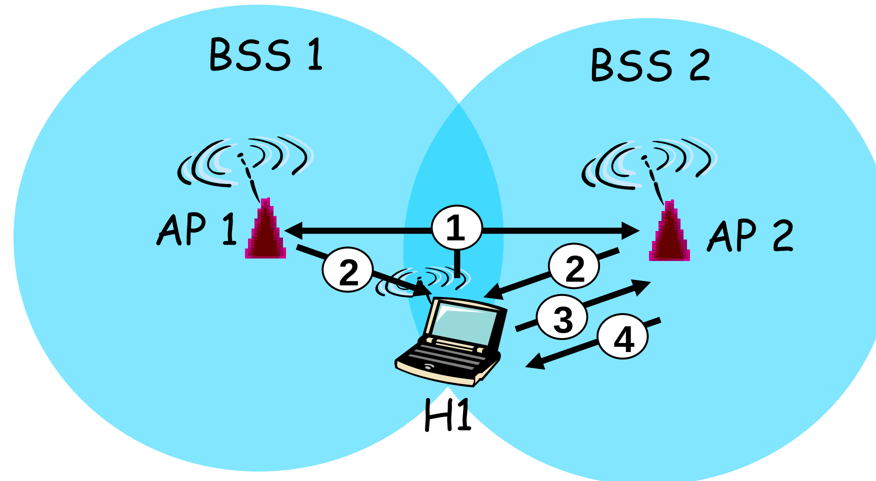
- Graph abstraction and coloring …
- A non-interfering solution exists if there exists a 3-coloring of the neighbor graph
- Of course. similar problems occurs in other wireless networks (and their applications) …

802.11: Channels, association

- host: must *associate* with an AP
  - scans channels, listening for *beacon frames* containing AP's name (SSID) and MAC address
  - selects AP to associate with
  - may perform authentication
  - typically run DHCP to get IP address in AP's subnet

802.11: passive/active scanning





Passive Scanning:

(1) Beacon frames sent from APs
(2) Association Request frame sent: H1 to selected AP
(3) Association Response frame sent: selected AP to H1

Active Scanning:

(1) Probe Request frame broadcast from H1
(2) Probes response frame sent from APs
(3) Association Request frame sent: H1 to selected AP
(4) Association Response frame sent: selected AP to H1

802.11 frame: addressing

2	2	6	6	6	2	6	0 - 2312	4
frame control	duration	address 1	address 2	address 3	seq control	address 4	payload	CRC

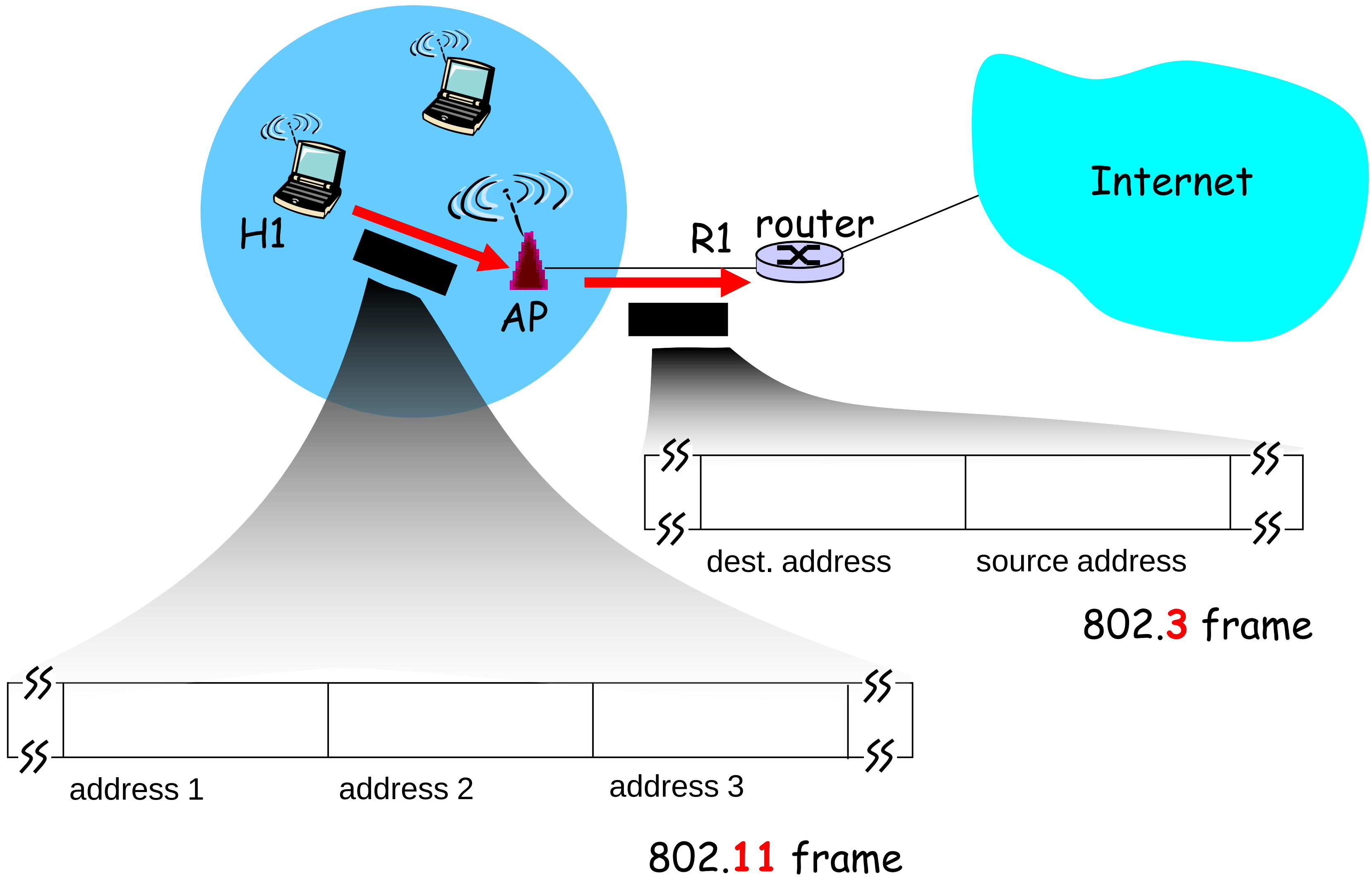
Address 1: MAC address of wireless host or AP to receive this frame

Address 2: MAC address of wireless host or AP transmitting this frame

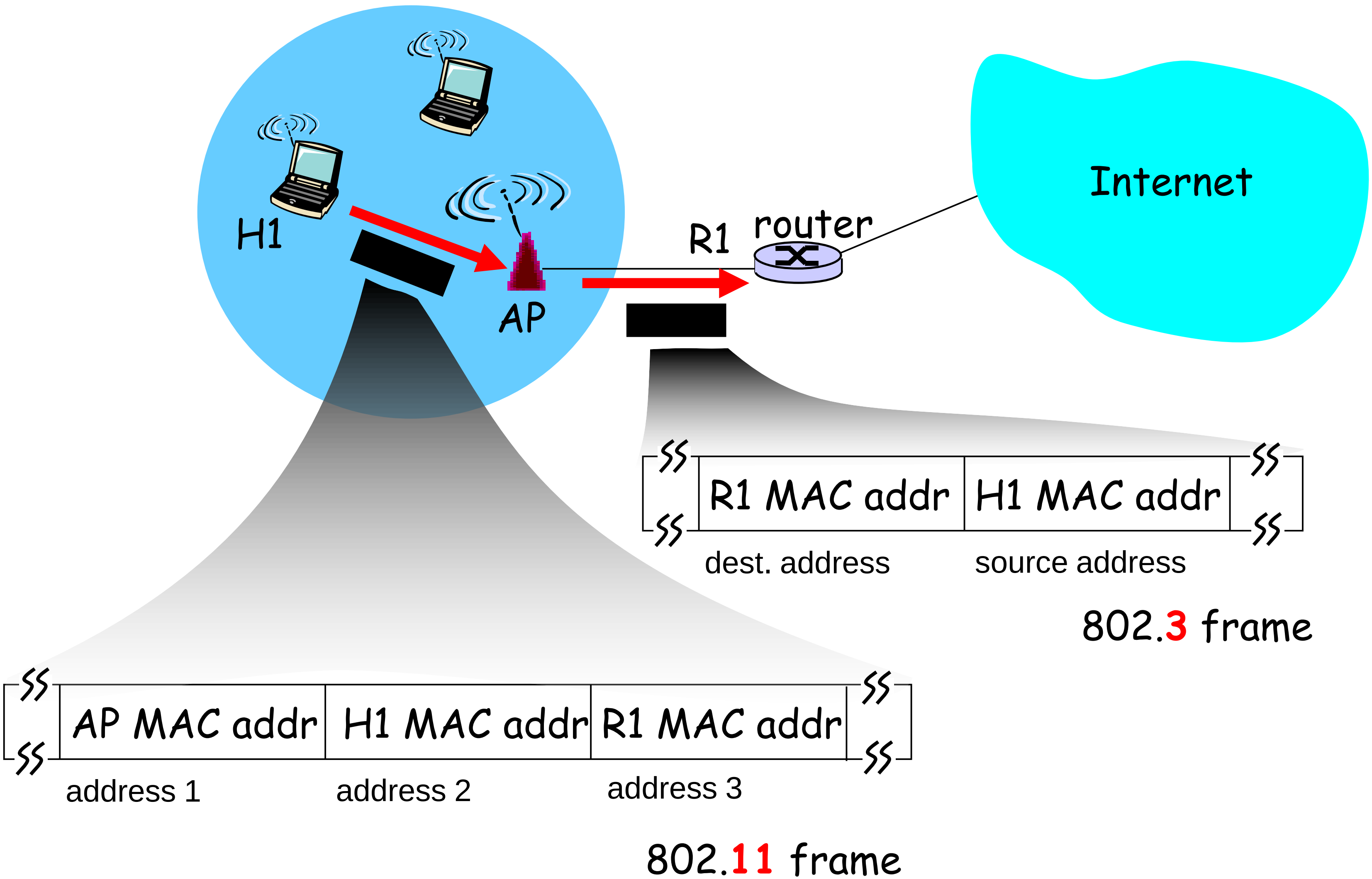
Address 3: MAC address of router interface to which AP is attached

Address 4: used only in ad hoc mode

802.11 frame: addressing



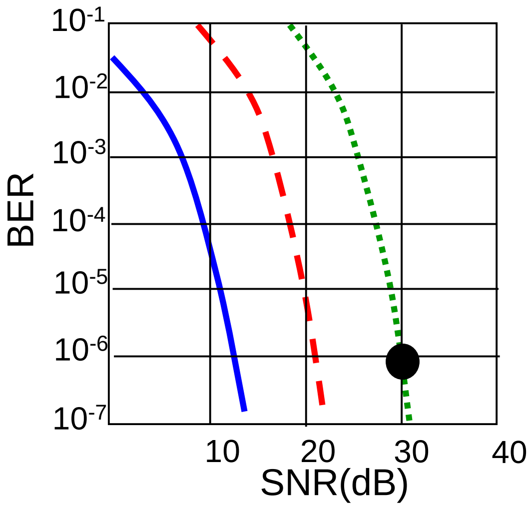
802.11 frame: addressing

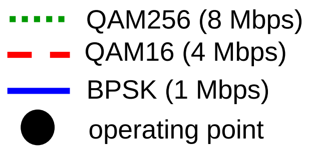


802.11: advanced capabilities

Rate Adaptation

- base station, mobile dynamically change transmission rate (physical layer modulation technique) as mobile moves, SNR varies





1. SNR decreases, BER increase as node moves away from base station

2. When BER becomes too high, switch to lower transmission rate but with lower BER

802.11: advanced capabilities

Power Management

- node-to-AP: "I am going to sleep until next beacon frame"
  - AP knows not to transmit frames to this node
  - node wakes up before next beacon frame
- beacon frame: contains list of mobiles with AP-to-mobile frames waiting to be sent
  - Every 100ms (250μs wakeup time)
  - node will stay awake if AP-to-mobile frames to be sent; otherwise sleep again until next beacon frame
  - Explicit pull request

Note: Nodes with nothing to send/receive can save 99% of energy

Bluetooth (BT) overview

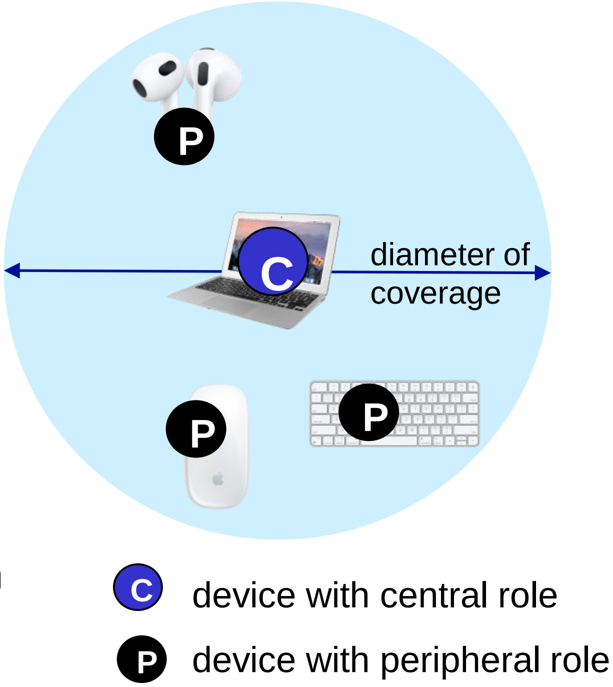
example of *wireless ad hoc network*: devices have no "infrastructure" (e.g., access point, base station) to connect to

- BT devices must find other BT devices, *organize themselves* into a network from scratch!
  -
  -
  -
  -
  -

An entirely new architecture and protocol stack (different from Internet) is needed!

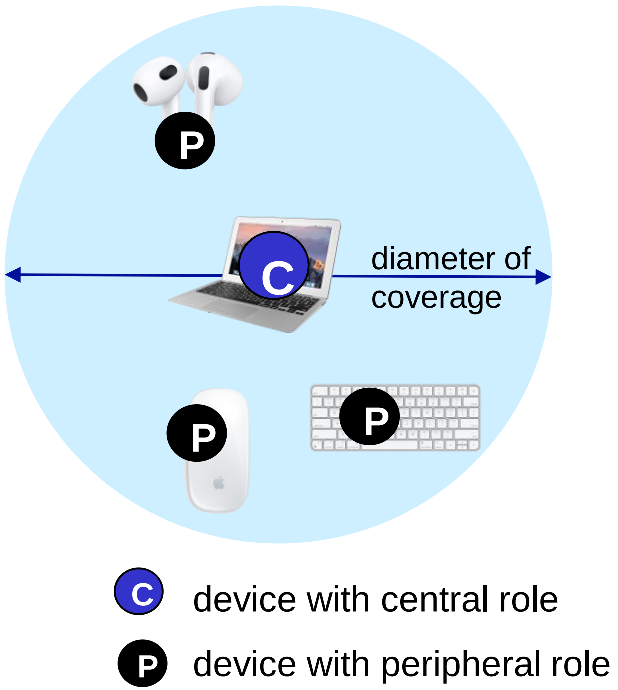
Bluetooth: overview

- Bluetooth network: piconet
- coverage: generally <10 m diameter
- no more than 8 devices per piconet
  - device initially forming network: *central* role
  - up to 7 more devices: *peripheral* role
- *communication only between central and peripheral node*
  - no direct peripheral-to-peripheral communication
- BT device has unique 48-bit address
- Operate in unlicensed ISM band: 2.4 GHz



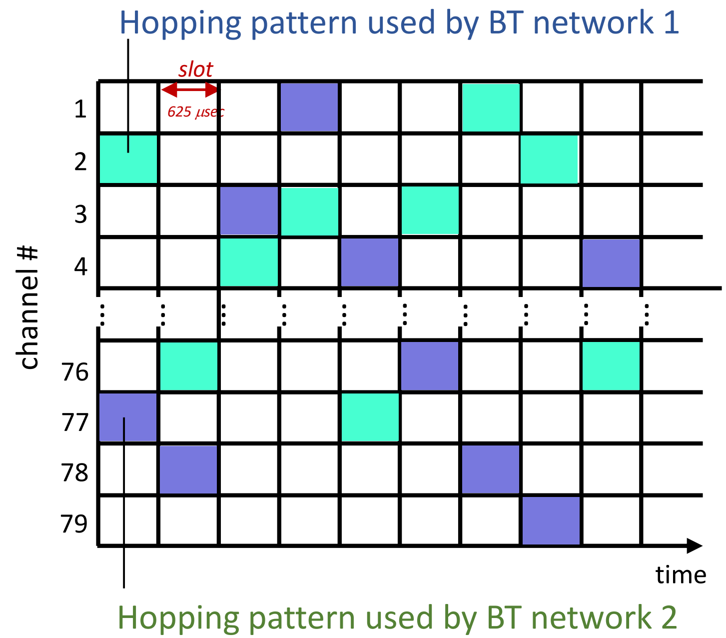
Bullet basics: wireless channel

- BT channel: TDM, 625 μsec slot length
- channel access via polling: central device advertises, grants channel access to peripherals in its BT network
- uses frequency hopping (form of "spread spectrum") transmissions



Bluetooth channel: frequency hopping

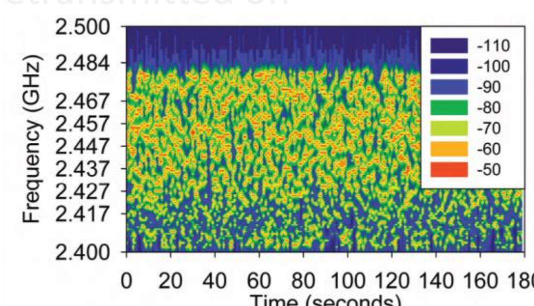
- senders in BT network “hop” among 79 frequencies/channels
  - transmit on different frequency after each slot
  - hopping pattern known by all BT devices in same piconet
- different BT piconets (with different hop patterns) can exist in same space



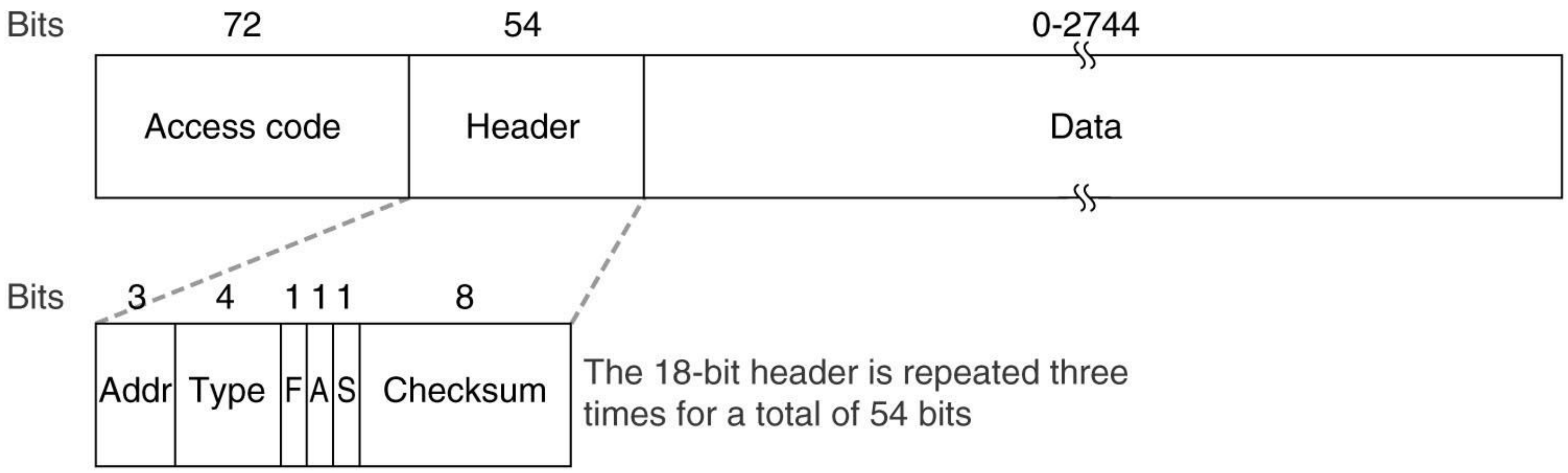
Q: Why hop?

A: minimize effects of interference:

- potentially many interfering transmitters in ISM
- If interfering device uses channel *x*, *x* occurs only occasionally in sequence
- BT frame sent on *x* (not received at receive due to interference), retransmitted on different frequency in next slot



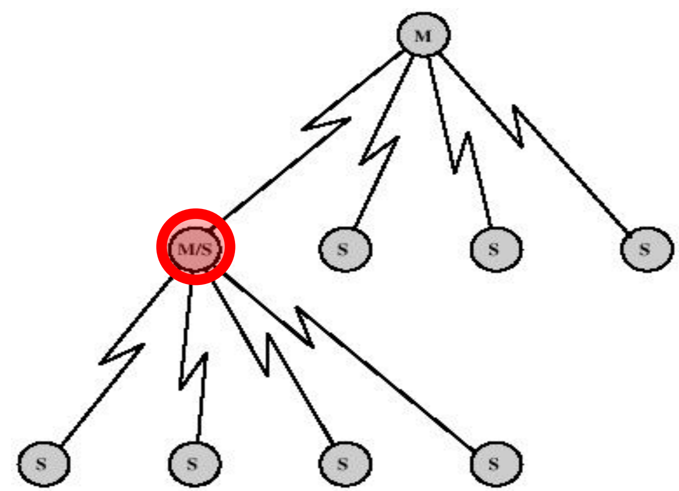
A typical Bluetooth data frame



Bluetooth Networking

Scatternets: Network formed by several connected piconets

- A device may belong to different piconets and may have a central role in one and a peripheral role in other piconets



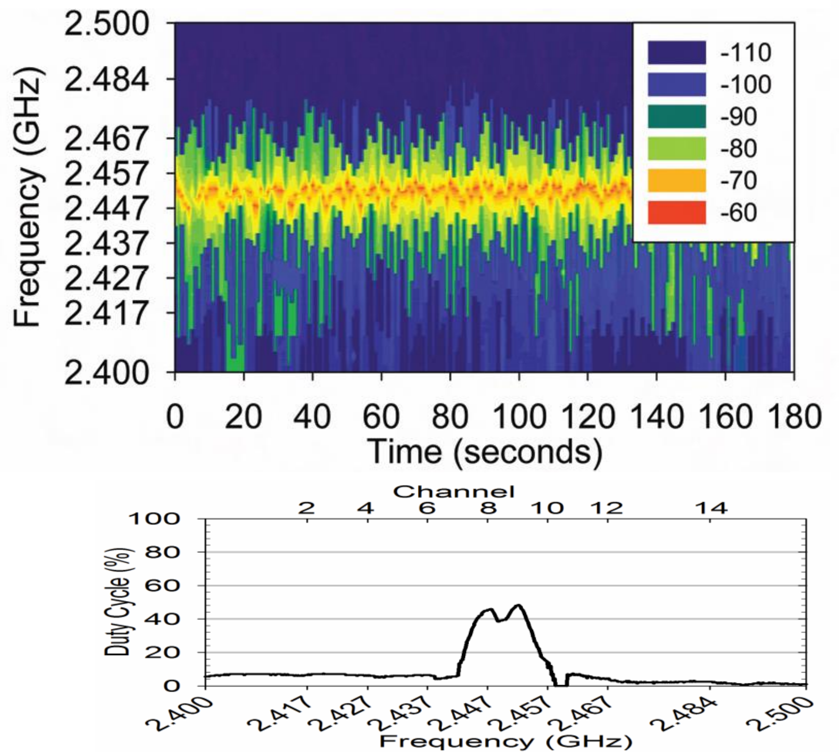
Two Popular 2.4 GHz Standards:

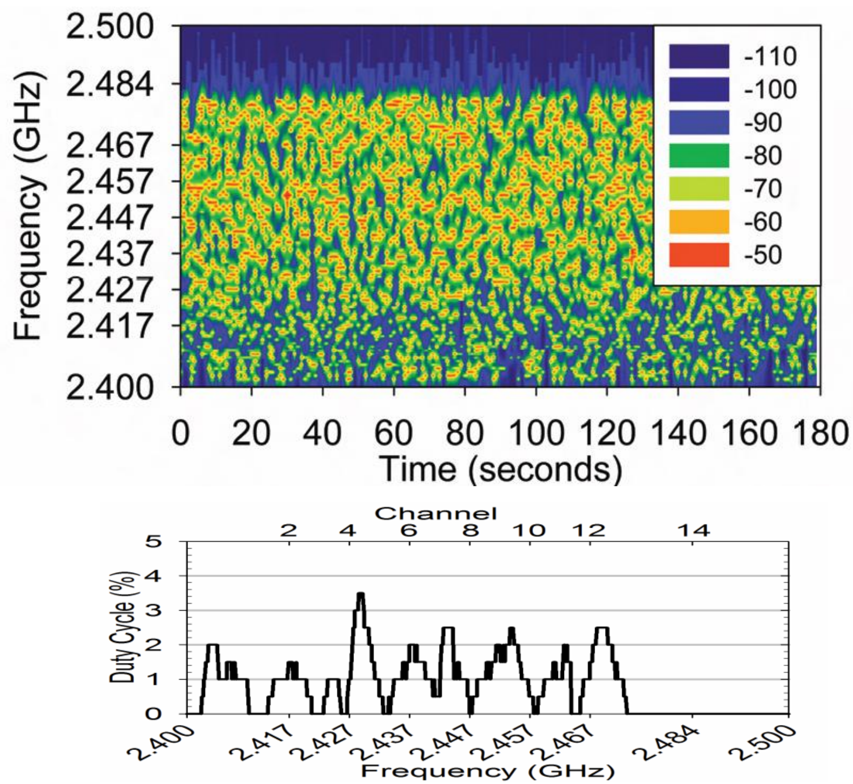
- IEEE 802.11 (WiFi)
  - Fast (11 Mbps)
  - High power
  - Long range
  - Single-purpose
  - Typically channel 1, 6, or 11
  - Ethernet replacement
  - Easily available

- Bluetooth
  - Slow (1 Mbps)
  - Low power
  - Short range
  - Flexible
  - Frequency hopping
  - Cable replacement (e.g., device-to-device)

Example

- What technology/device?

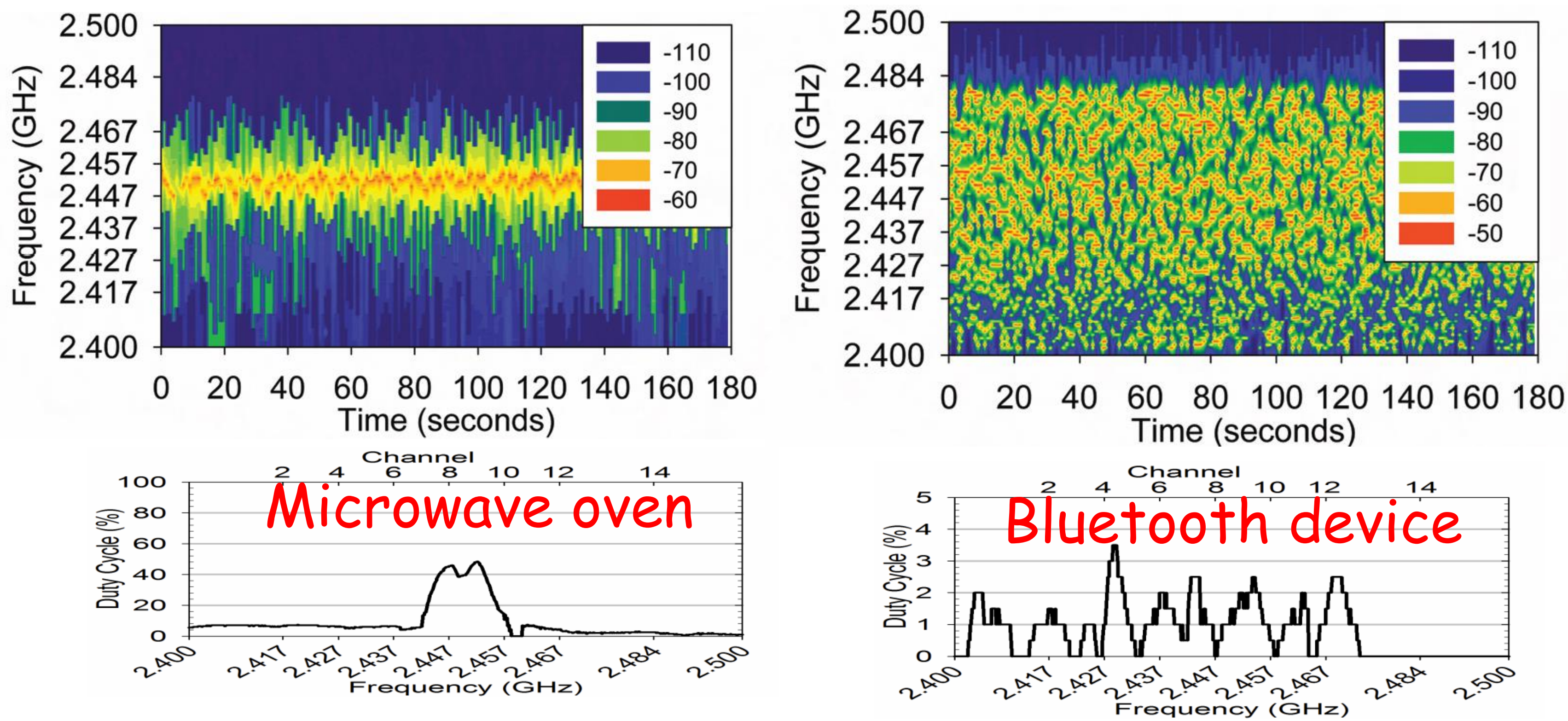




Example

Figures from:
A. Mahanti et al., "Ambient Interference Effects in Wi-Fi Networks", *Proc. IFIP Networking*, 2010.

- Many devices and technologies share the medium … results in time varying interference



Example: Channel Utilization

- Many devices and technologies share the medium … results in time varying interference

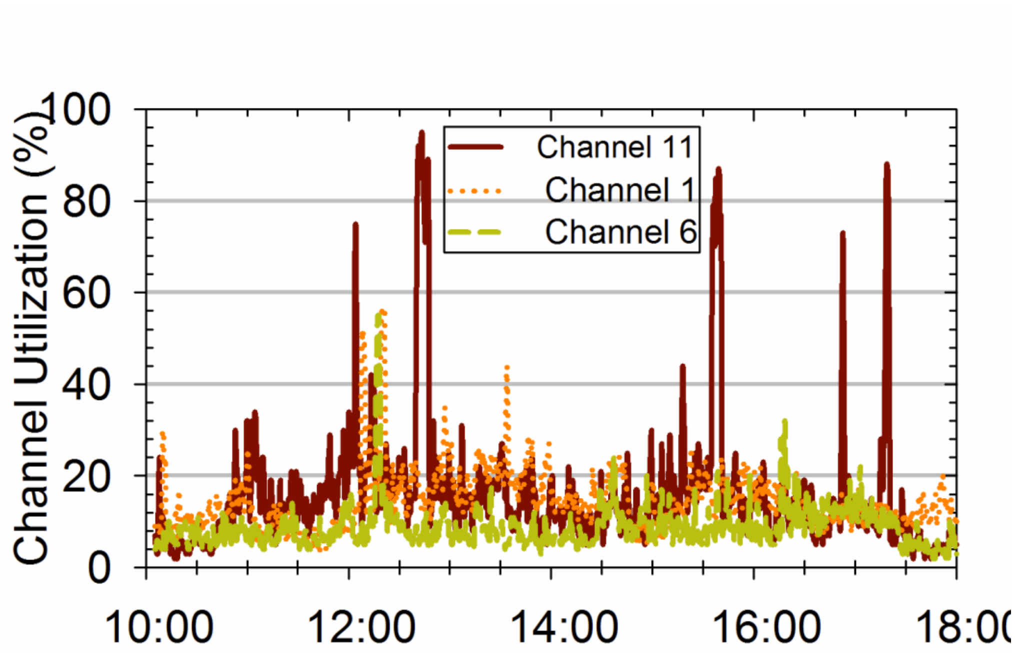
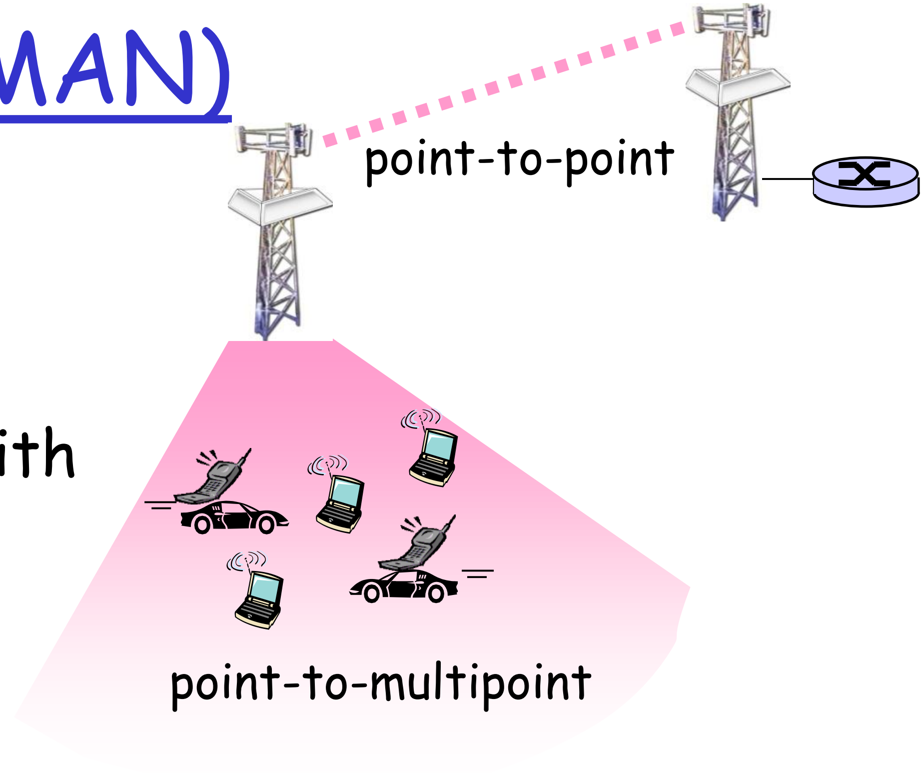


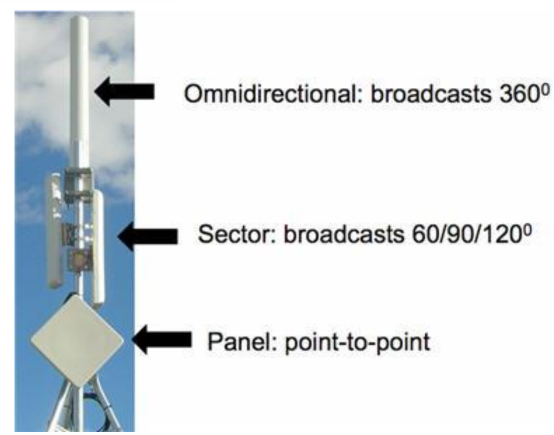
Figure from:
A. Mahanti et al., "Ambient Interference Effects in Wi-Fi Networks", *Proc. IFIP Networking*, 2010.

- **Channel utilization:** The % of time a transmission is present from a known RF source, in a given channel
- Channels 1 and 6, utilization peaked near 60%, while for channel 11 it was over 90%.
- Channel 11 spikes caused due to microwave ovens, cordless phones, and other fixed-frequency devices.

802.16: WiMAX (MAN)



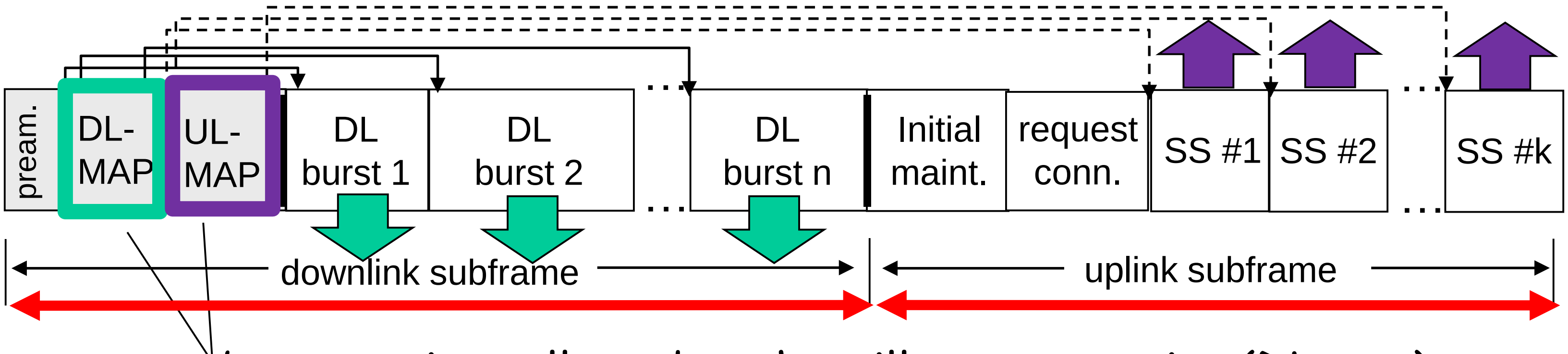
- like 802.11 & cellular: base station model
  - transmissions to/from base station by hosts with omnidirectional antenna
  - base station-to-base station backhaul with point-to-point antenna



- unlike 802.11:
  - range ~ 6 miles ("city rather than coffee shop")

802.16: WiMAX: downlink, uplink scheduling

- transmission frame
  - down-link subframe: base station to node
  - uplink subframe: node to base station



base station tells nodes who will get to receive (DL map) and who will get to send (UL map), and when

Repeat …

- WiMAX standard provide mechanism for scheduling, but not scheduling algorithm
  - Note: This separation between standardized mechanisms and scheduling/optimization common

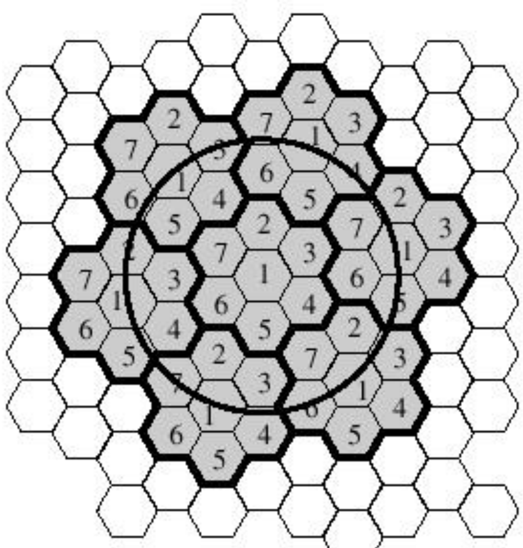
Components of a 3G network

cell

- covers geographical region
- *base station* (BS) analogous to 802.11 AP
- *mobile users* attach to network through BS
- *air-interface:* physical and link layer protocol between mobile and BS

MSC

- connects cells to wide area net
- manages call setup (more later!)
- handles mobility (more later!)



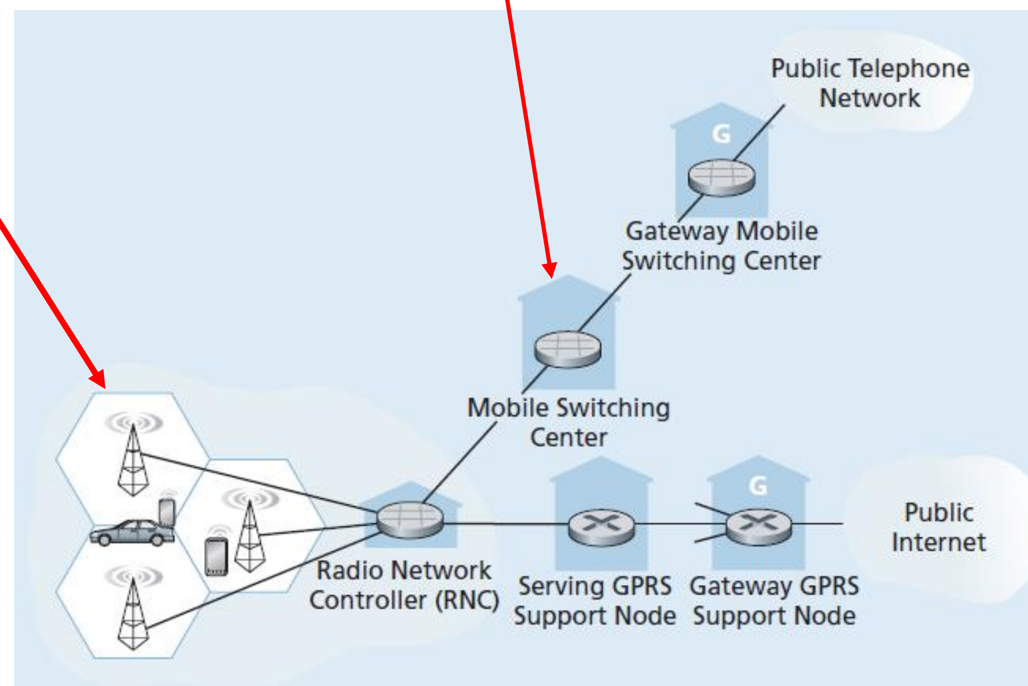


Figure 7.20 ♦ 3G system architecture: supporting separate circuit-switched voice service and packet-switched data service with the carrier's core network

Components of a 4G network

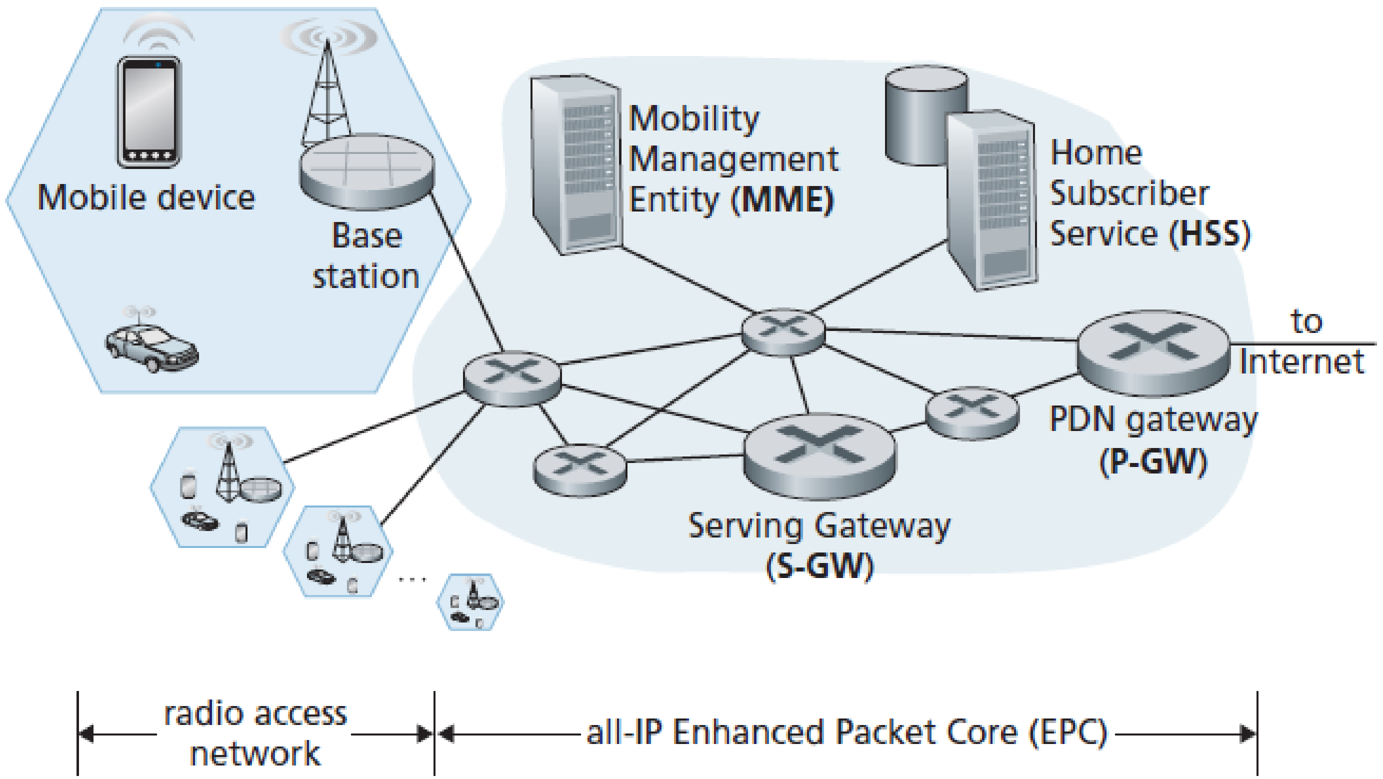
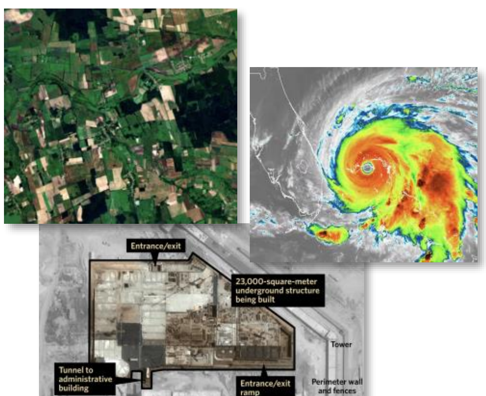


Figure 7.17 ♦ Elements of the 4G LTE architecture

Satellite applications

Sensing:

- environment: weather, land use, various human activity
- resolution: ~m/pixel



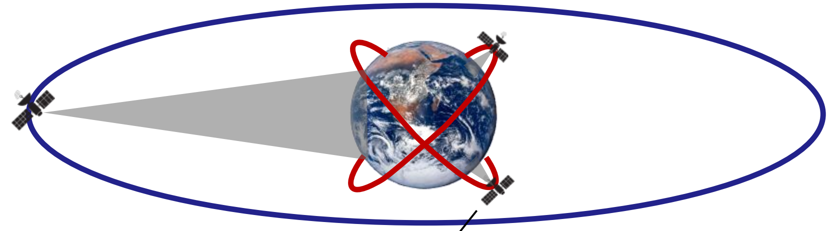
Broadcast:

- consumer: Direct to Home TV/video, radio (Dish, SiriusXM)
- business: content to many cable head ends
- GPS
- leverage broadcast: one send reaches many users

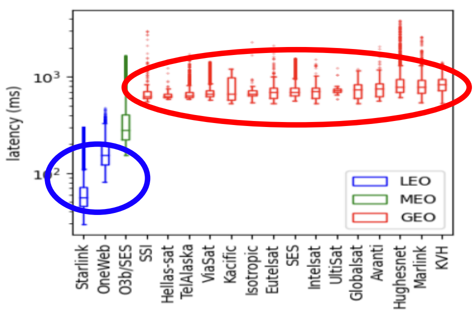
Internet:

- connectivity to unserved regions, alternative to wired Internet
- low latency over long distances
- access i

GEO and LEO satellites

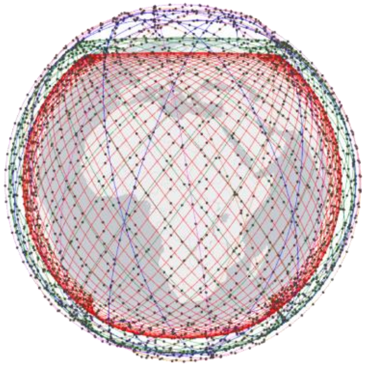


GEO:
- *geosynchonous:* stationary with respect to ground
- 35,768 km above earth
- ~800 msec RTT
- wide area coverage / satellite

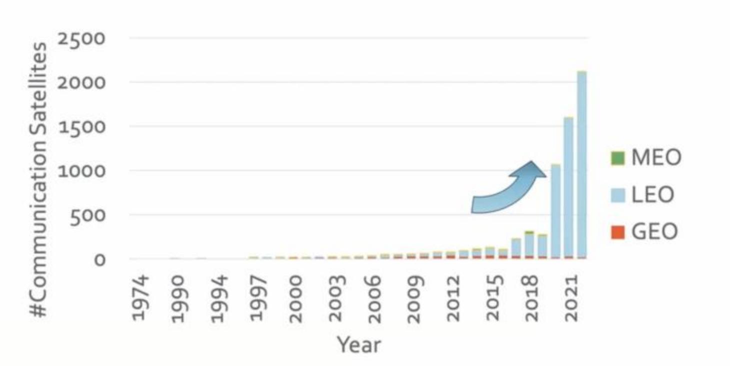


LEO:
- *Low Earth Orbit:* satellite moves with respect to ground: 27,000 km/hour
  - within line of sight (LOS) of ground station for 5-15 mins
- 550 - 1200 km above earth
- ~30 msec RTT in practice
- smaller area coverage / satellite
  - constellation (network) of multiple LEO satellites to cover wide area
  - inter-satellite links (ISL)

Satellites: why all the fuss?



Lots of (LEOS) satellites being launched

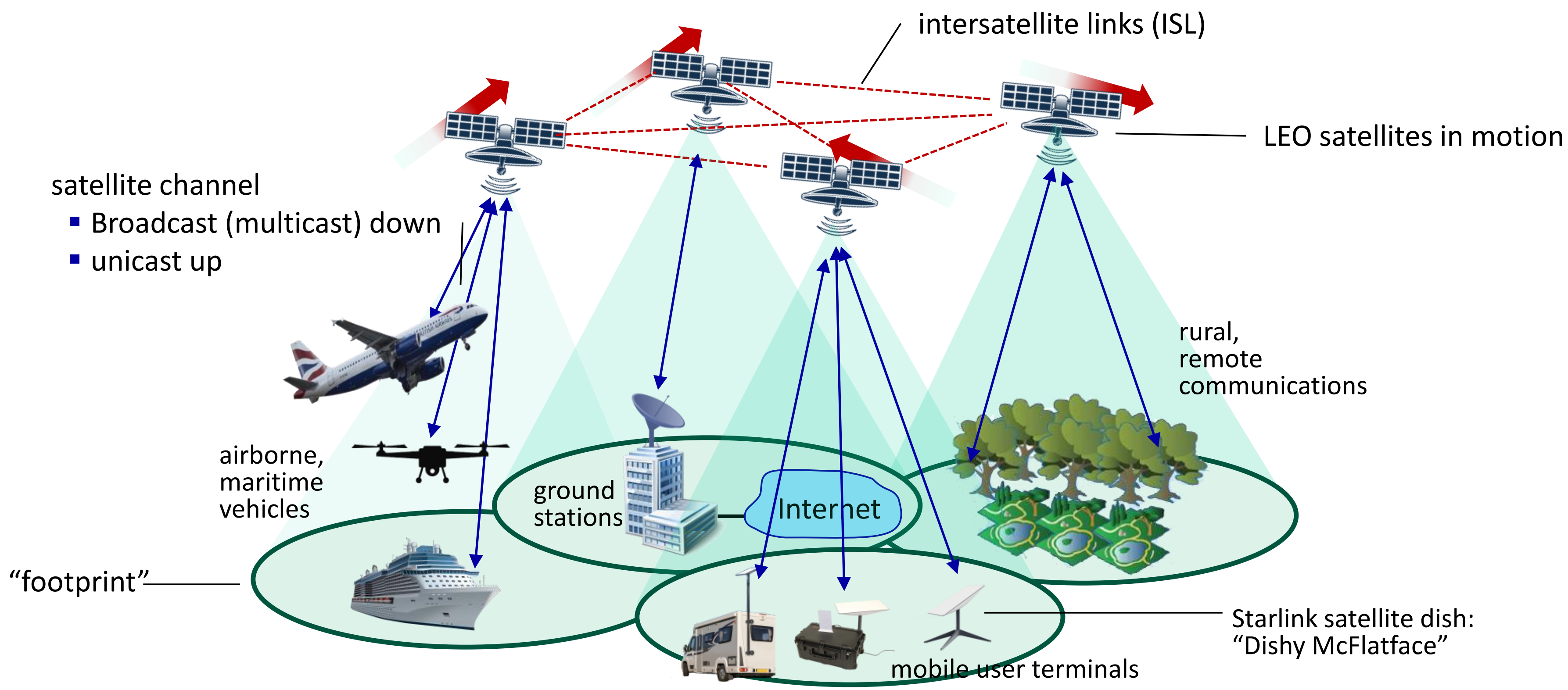


LEOS constellations

	# deployed (2025)	# planned	ISL planned?
Starlink	7,239	12,000 - 42,000	Yes
EutelSat Oneweb	648	716 – 6,372	No
Kuipers (Amazon)	27	3,236	?
Telesat	1	298 - 1671	Yes

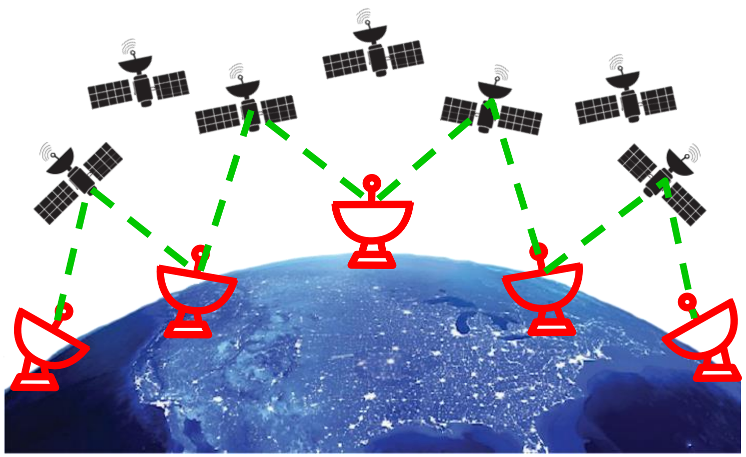
Sources: A. Raman, LEO Satellite Mega Constellations, networkingchannel.eu;
N.Pachler et al., An Updated Comparison of Four Low Earth Orbit Satellite Constellation Systems to Provide Global Broadband; company literature

Components of a LEO satellite network



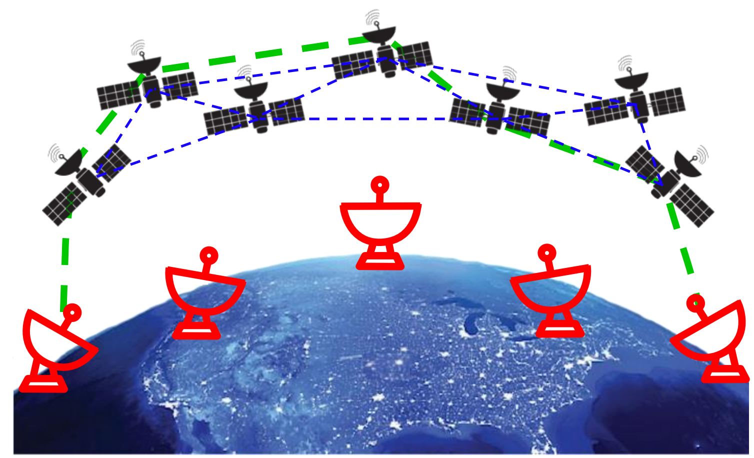
Satellite networking: a *link* or a *network?*

links in the sky



- single satellite hop between base stations
- AKA “bent pipe” architecture

network in the sky:



- multiple satellite hops between base stations
- routing among satellites

Starlink

- April 2025: ~7,239 operational LEO satellites (planned: 12K, requested: 30K)
  - first launches: 2019
  - three low-Earth-orbit orbital shells, at 525, 530, 535 km
  - satellites: 500 – 2700 lbs

60 Starlink satellites stacked together before deployment on 24 May 2019

- services:
  - Internet service: 4M subscribers in Sept 2024 (residential US: $120/mo)
  - service in Ukraine (terrestrial networks damaged)
  - 2024: testing direct-to-smartphone tests would use cellular spectrum from SpaceX's U.S. mobile partner T-Mobile

More slides (e.g., if time)

Other PAN example (even lower energy): The ANT protocol stack

- Wireless sensor communications protocol stack
  - 2.4 GHz RF spectrum (i.e., the ISM band)
  - Establishes rules for co-existence, data representation, signaling, authentication, and error detection
- Low computational overhead and high efficiency
  - Low power consumption by the radios
- Targeted at the sports sector, particularly fitness and cycling performance monitoring.
  - Transceivers are embedded in equipment such as heart rate belts, watches, cycle power and cadence meters, and distance and speed monitors