CS3222 Computer Networks and Internets

Wireless Networks

Prof Weifa Liang

Weifa.liang@cityu-dg.edu.cn

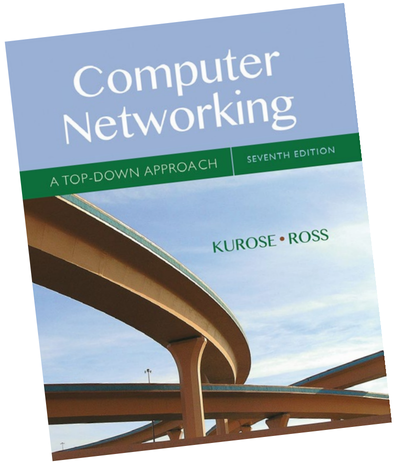
Slides based on book *<u>Computer Networking: A Top-Down Approach.</u>*

Wireless Networks - Roadmap

- Introduction

Wireless

- Wireless Links and network characteristics
- IEEE 802.11 wireless LANs: e.g., MAC protocols, WiFi
- 4G/5G and beyond



Chapter 7

Mobility

- Mobility management: principles
- Mobility: impact on higher-layer protocols

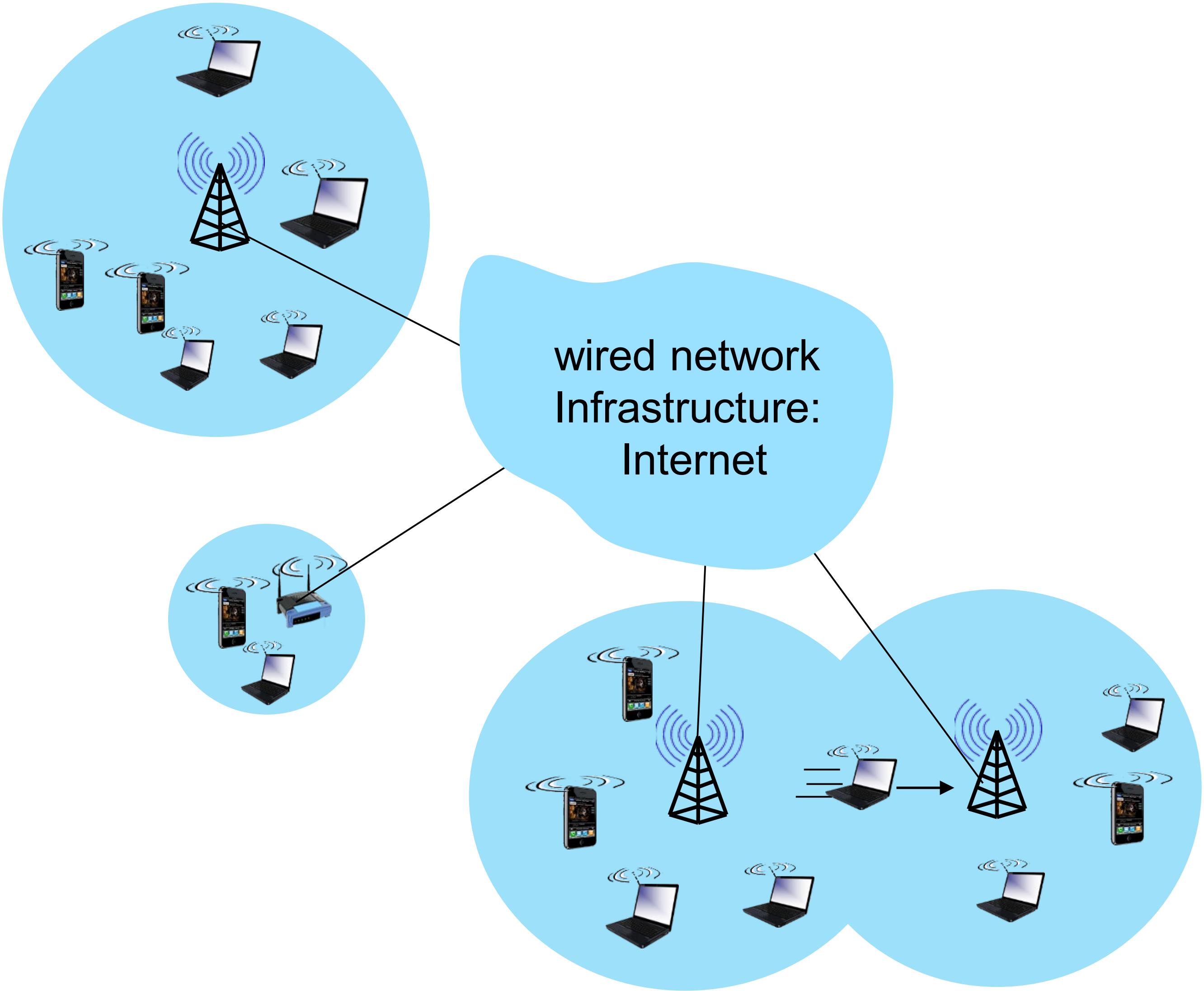
Multi-access Edge Computing (MEC)

- Design Rationale
- Challenges and Solutions

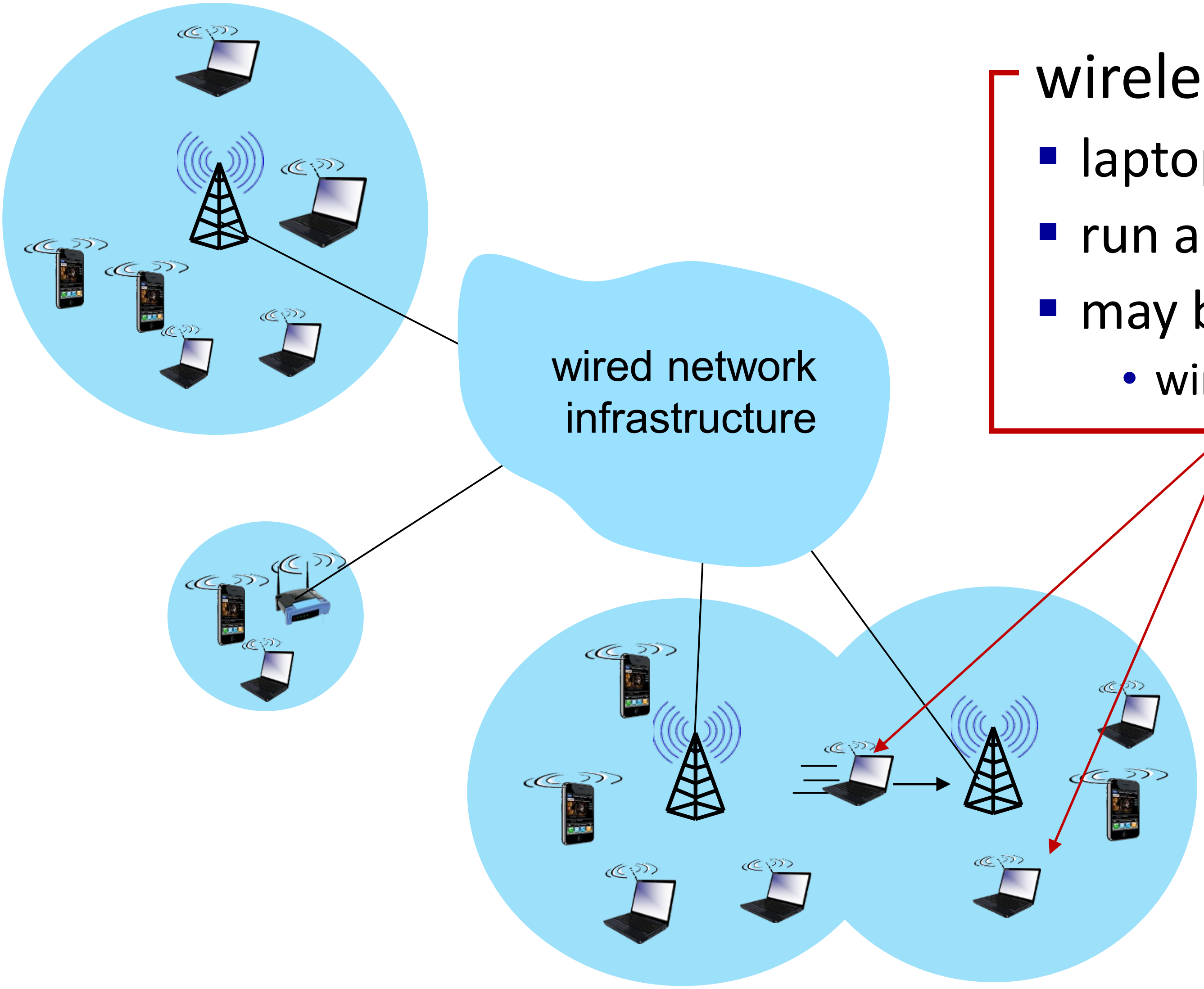
Wireless and Mobile Networks: context

- more wireless (mobile) phone subscribers than fixed (wired) phone subscribers (10-to-1 in 2019)!
- more mobile-broadband-connected devices than fixed-broadband-connected devices devices (5-1 in 2019)!
  - 4G/5G/6G cellular networks are now embracing Internet protocol stack, including SDN
- two important (but different) challenges
  - wireless: communications over wireless links, e.g., last hop provides freedom for end users
  - mobility: handling the mobile user who changes point of attachment to network

Elements of a wireless network



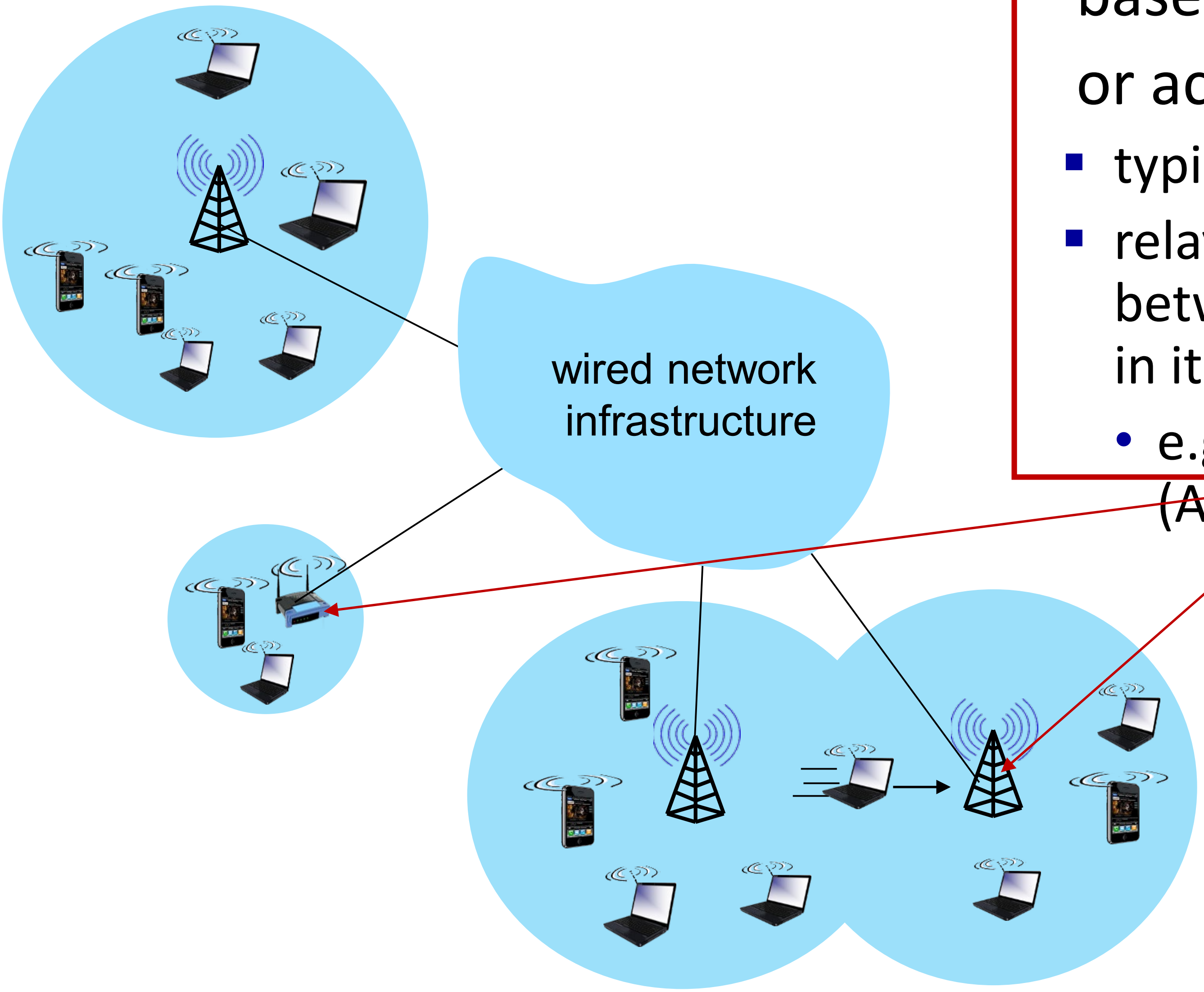
Elements of a wireless network



wireless hosts

- laptop, smartphone, IoT
- run applications
- may be stationary (non-mobile) or mobile
  - wireless does *not* always mean mobility!

Elements of a wireless network

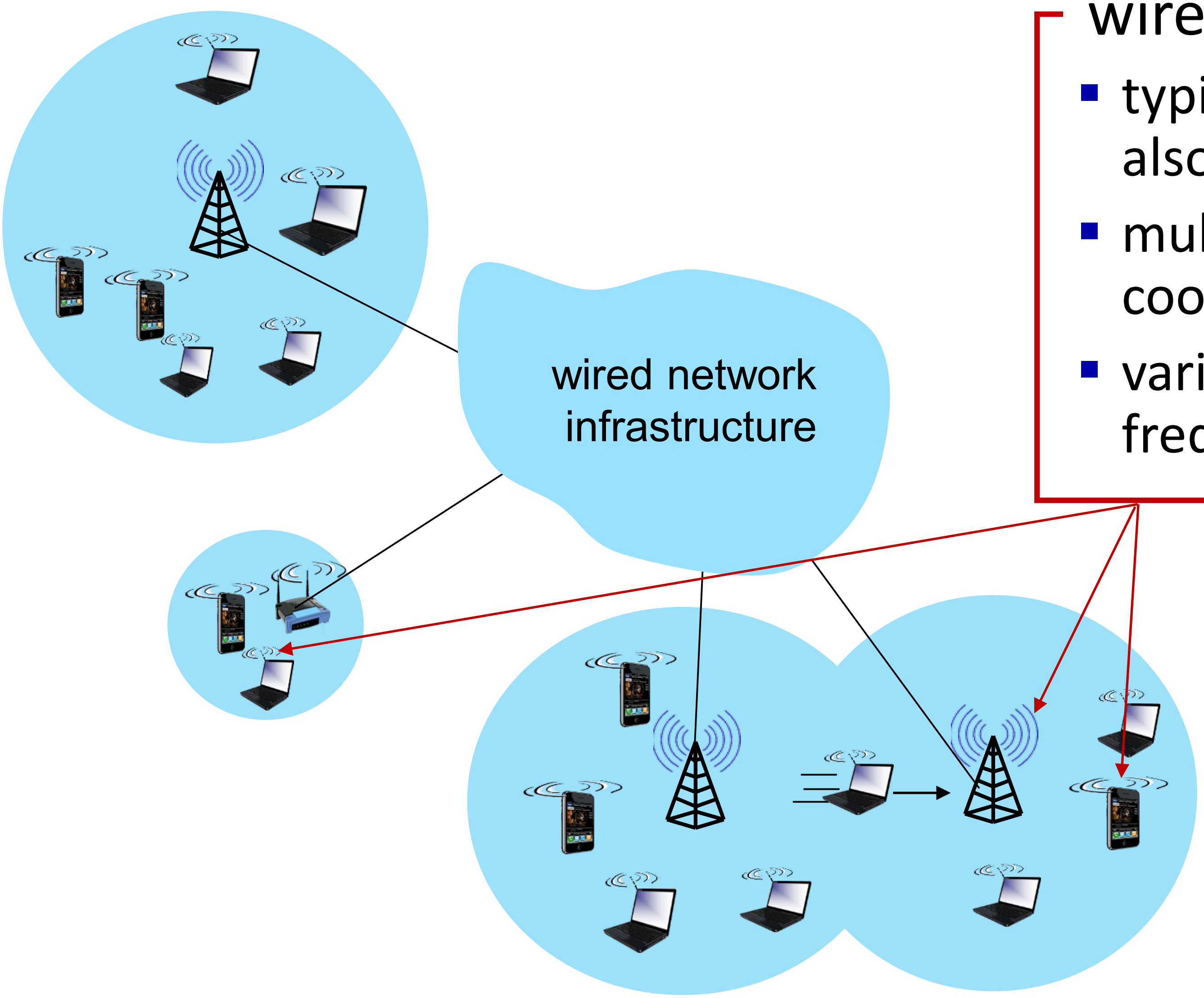


base stations (BSs)

or access points (Aps)

- typically connected to wired networks
- relay - responsible for sending packets between wired network and wireless host(s) in its "area"
  - e.g., cell towers (BSs), 802.11 access points (APs)

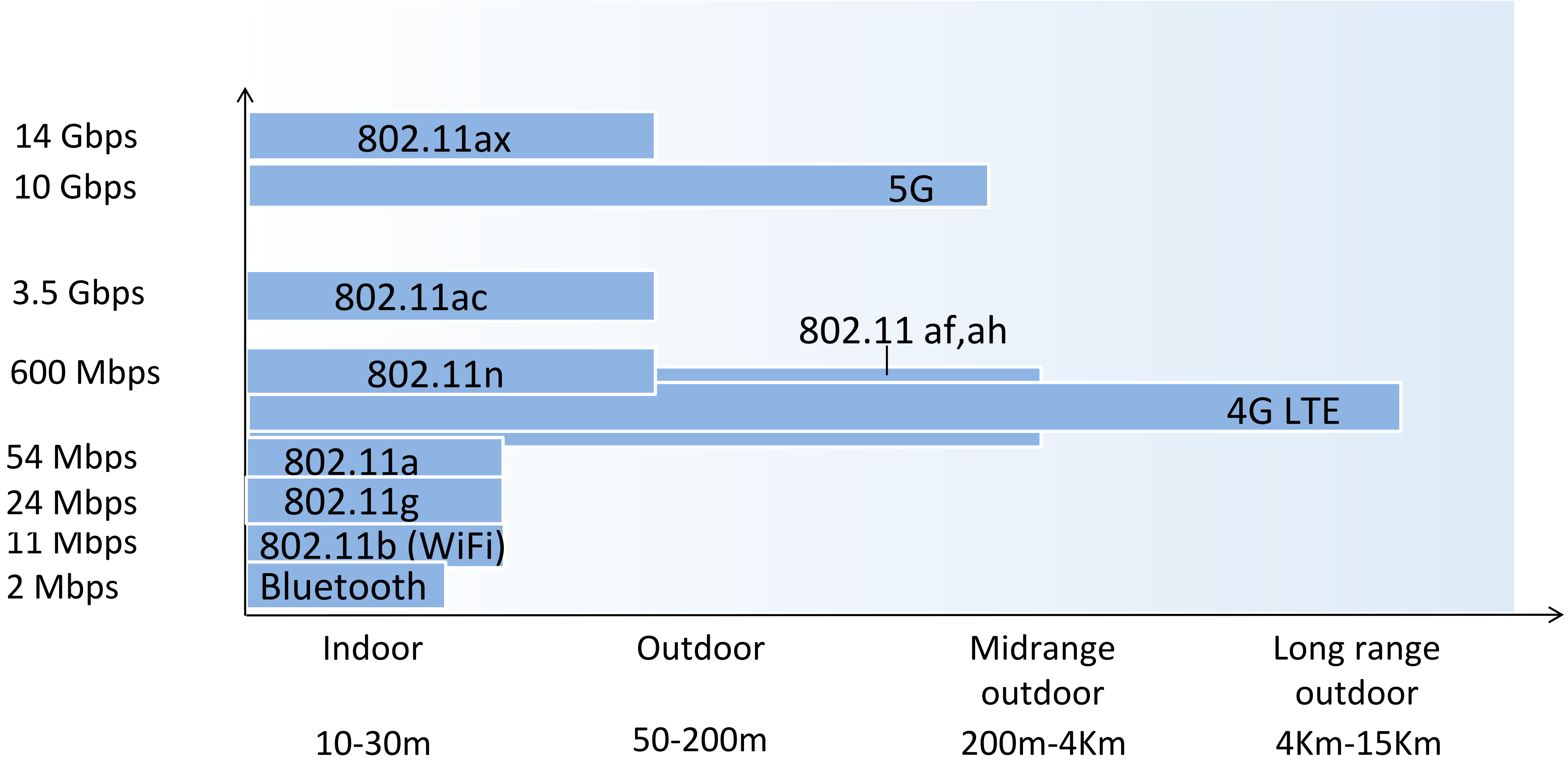
Elements of a wireless network



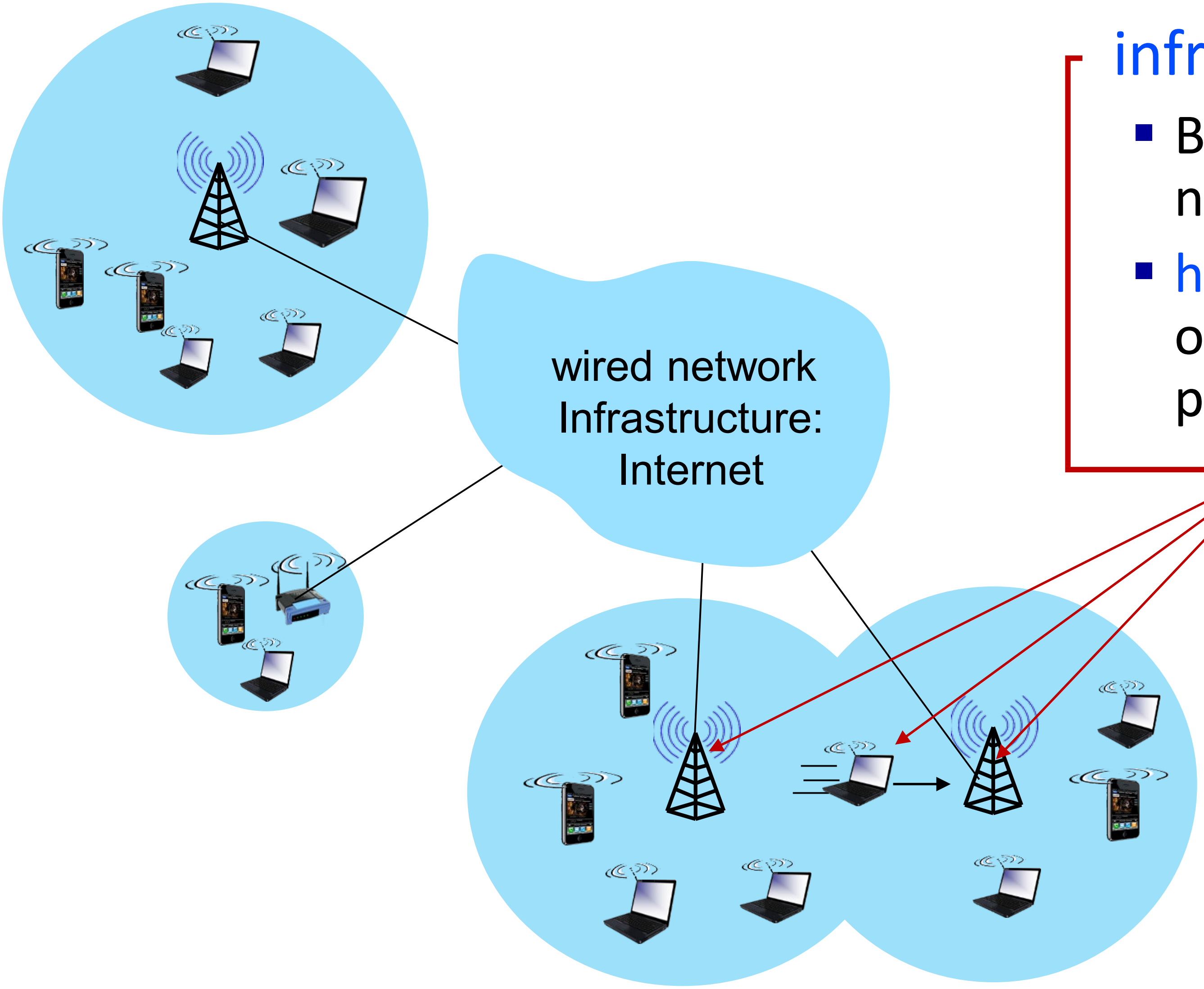
wireless link

- typically used to connect mobile(s) to BS, also used as backbone link
- multiple access protocol (MAC): coordinates link access
- various transmission rates and distances, frequency bands

Characteristics of selected wireless links



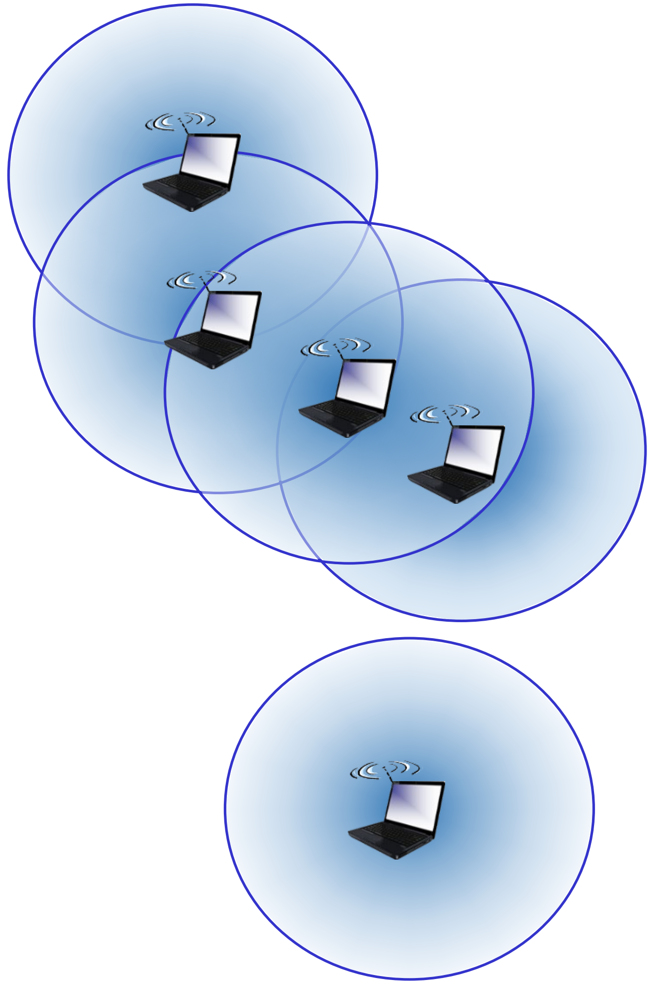
Elements of a wireless network



infrastructure mode

- BS connects mobiles into wired network
- handoff: mobile changes base station or access point, i.e., the connecting point to the wired network

Elements of a wireless network



ad hoc mode

- no base stations nor access points
- nodes can only transmit to other nodes within direct link coverage
- nodes organize themselves into a network: route among themselves

Mobile ad hoc networks, wireless sensor networks, or IoT networks

Wireless network taxonomy

	single hop	multiple hops
infrastructure (e.g., APs)	host connects to base station (WiFi, cellular) which connects to larger Internet	host may have to relay through several wireless nodes to connect to larger Internet: *mesh net or ad hoc mode in 4G/5G+ (D2D, sidelink)*
no infrastructure	no base station, no connection to larger Internet (Bluetooth, ad hoc nets, sensor nets, IoT)	no base station, no connection to larger Internet. May have to relay to reach others in a given wireless node: MANETs, VANETs

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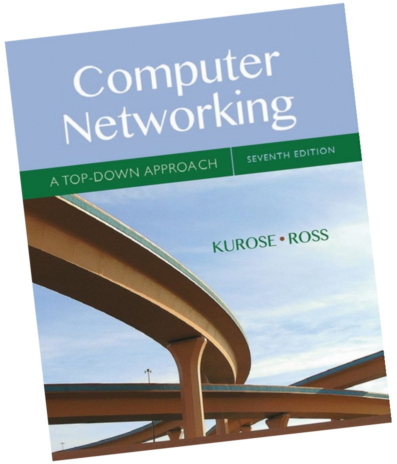
- 4G/5G and beyond

Mobility

- Mobility management: principles
- Mobility: impact on higher-layer protocols



Chapter 7

Multi-access Edge Computing (MEC)

- Design Rationale
- Challenges and Solutions

Wireless link characteristics (1)

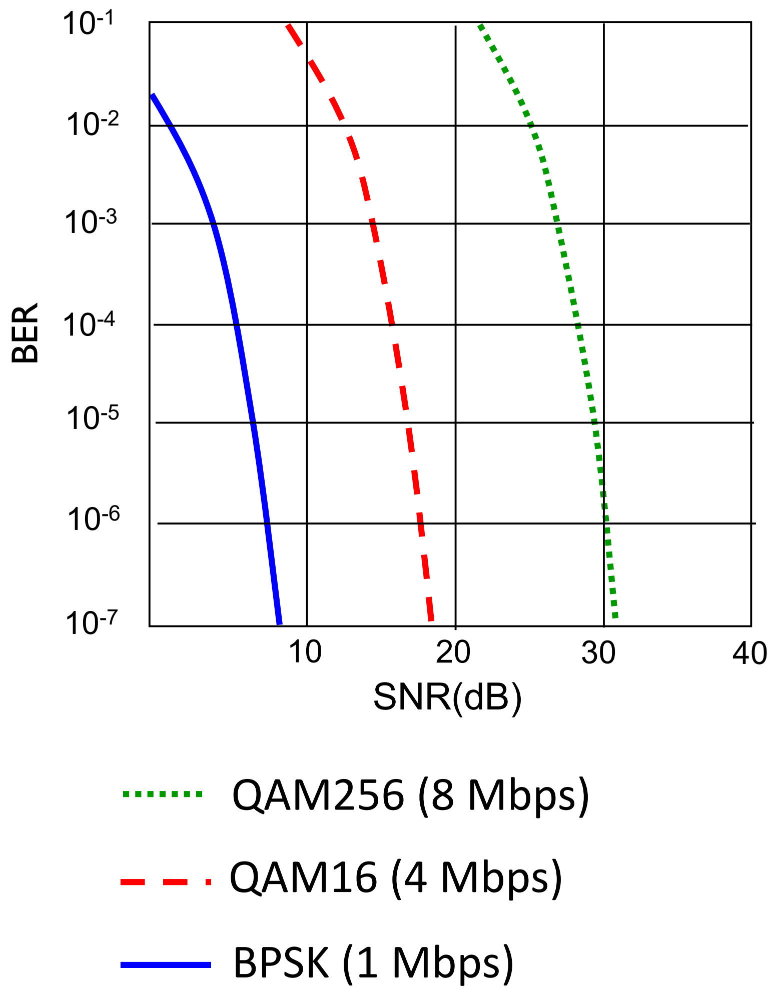
important differences from wired link ….

- decreased signal strength: radio signal attenuates as it propagates through a medium (path loss)
- interference from other nodes: wireless network frequencies (e.g., 2.4 GHz) shared by many devices (e.g., WiFi, cellular, motors): interference
- multipath propagation (e.g., echo): radio signal reflects off objects, ground, arriving at destination at slightly different times

…. make communication across (even a point to point) wireless link much more "difficult"

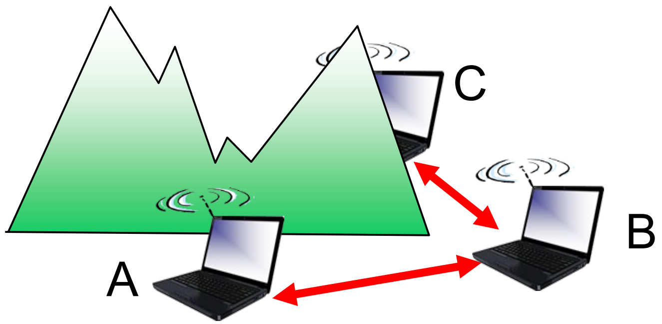
Wireless link characteristics (2)

- SNR: signal-to-noise ratio
  - larger SNR – easier to extract signal from noise (a "good thing")
    - "Shout louder!"
- SNR versus BER tradeoffs
  - *given physical layer:* increase power -> increase SNR->decrease BER
  - *given SNR:* choose physical layer that meets BER requirement, giving highest throughput
    - SNR may change with mobility (you can hear clearer when walking closer): dynamically adapt physical layer (adaptive modulation, rate adaptation)



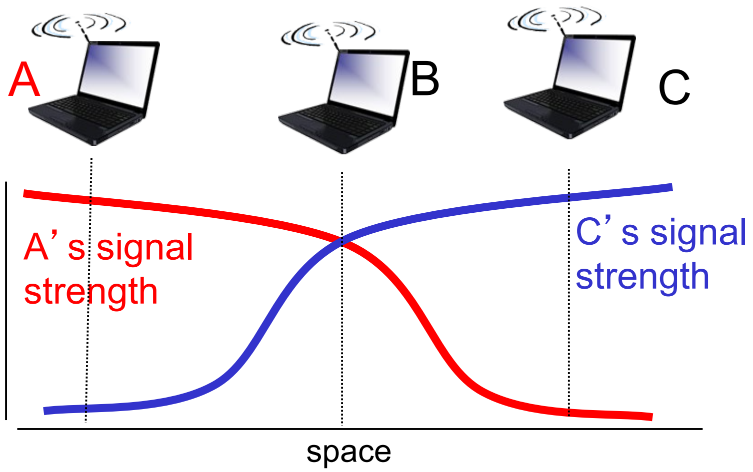
Wireless link characteristics (3)

Multiple wireless senders, receivers create additional problems (beyond multiple access):



Hidden terminal problem

- B, A hear each other
- B, C hear each other
- A, C that cannot hear each other means A, C are unaware of their existence, hence interference at B



Signal attenuation:

- B, A hear each other
- B, C hear each other
- A, C cannot hear each other interfering at B

A hidden terminal is in the receiver’s sensing range, but outside of the transmitter’s sensing range

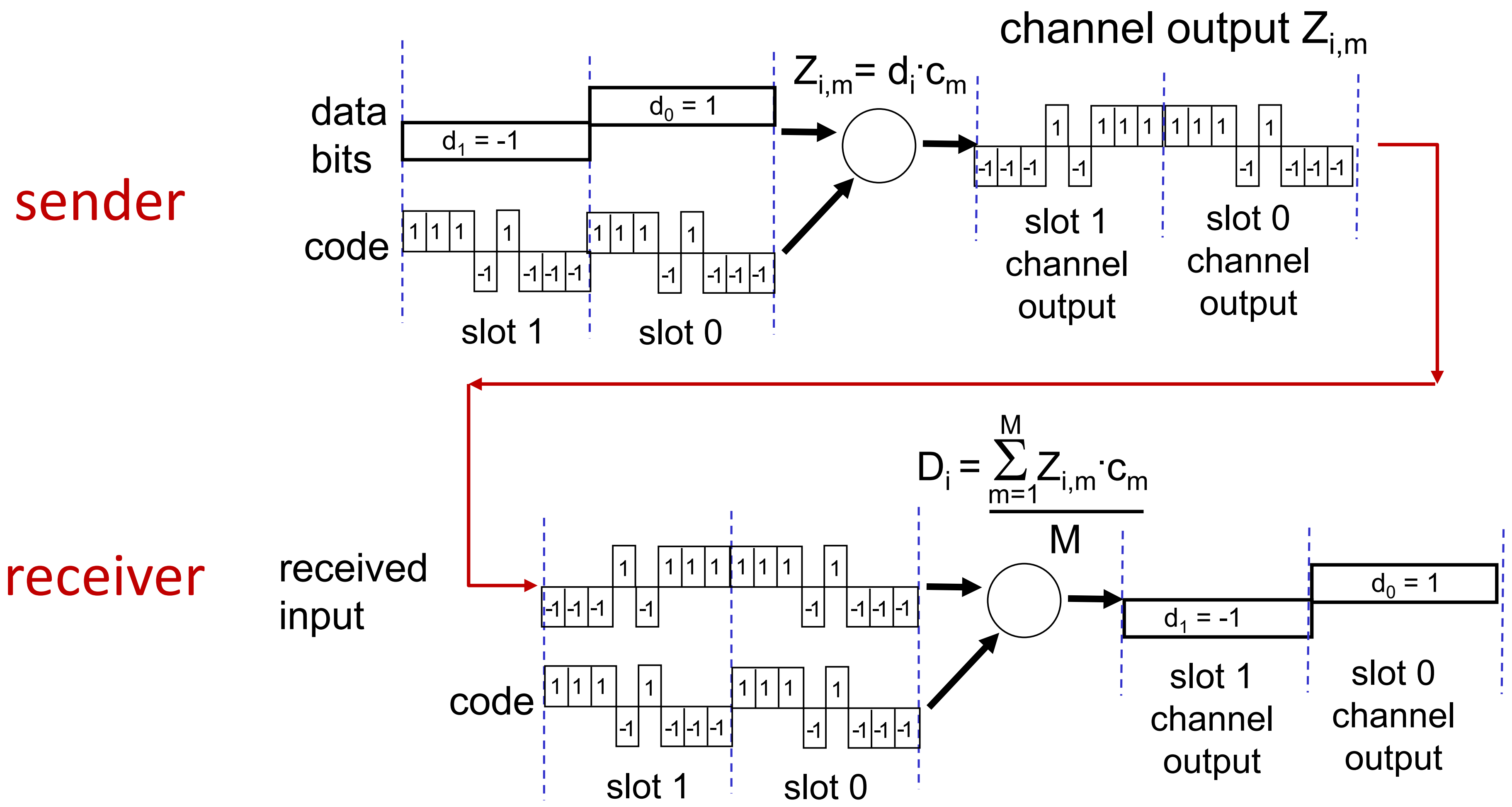
How to overcome interference

- Try to avoid using the same frequency in time, space, and code
  - Deterministic scheduling: TDMA, FDMA, CDMA
- Cooperative when using the same resource: MAC design
  - To avoid overlapping "interference" too much
  - To control the transmit power
- MAC protocols

Code Division Multiple Access (CDMA)

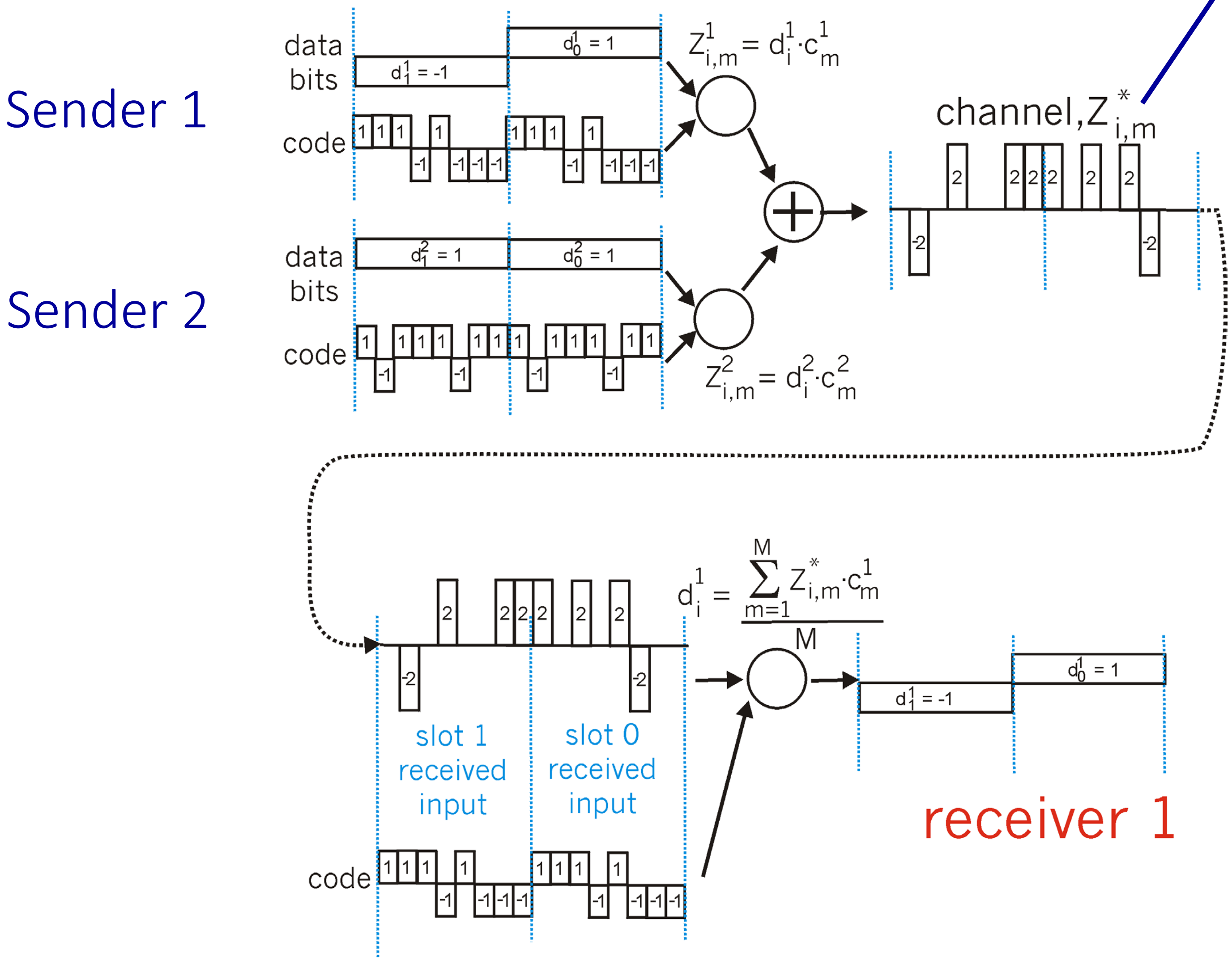
- unique "code" assigned to each user; i.e., code set partitioning
  - all users share the same frequency, but each user has its own "chipping" sequence (i.e., code) to encode data
  - allows multiple users to "coexist" and transmit simultaneously with minimum interference (if codes are almost "orthogonal")
- encoding: inner product: (original data) X (chipping sequence)
  - Modulation or multiplication
- decoding: summed inner-product: (encoded data) X (chipping sequence)
  - Correlator or correlation detection

CDMA encode/decode



... but this isn’t really useful yet!

CDMA: two-sender interference



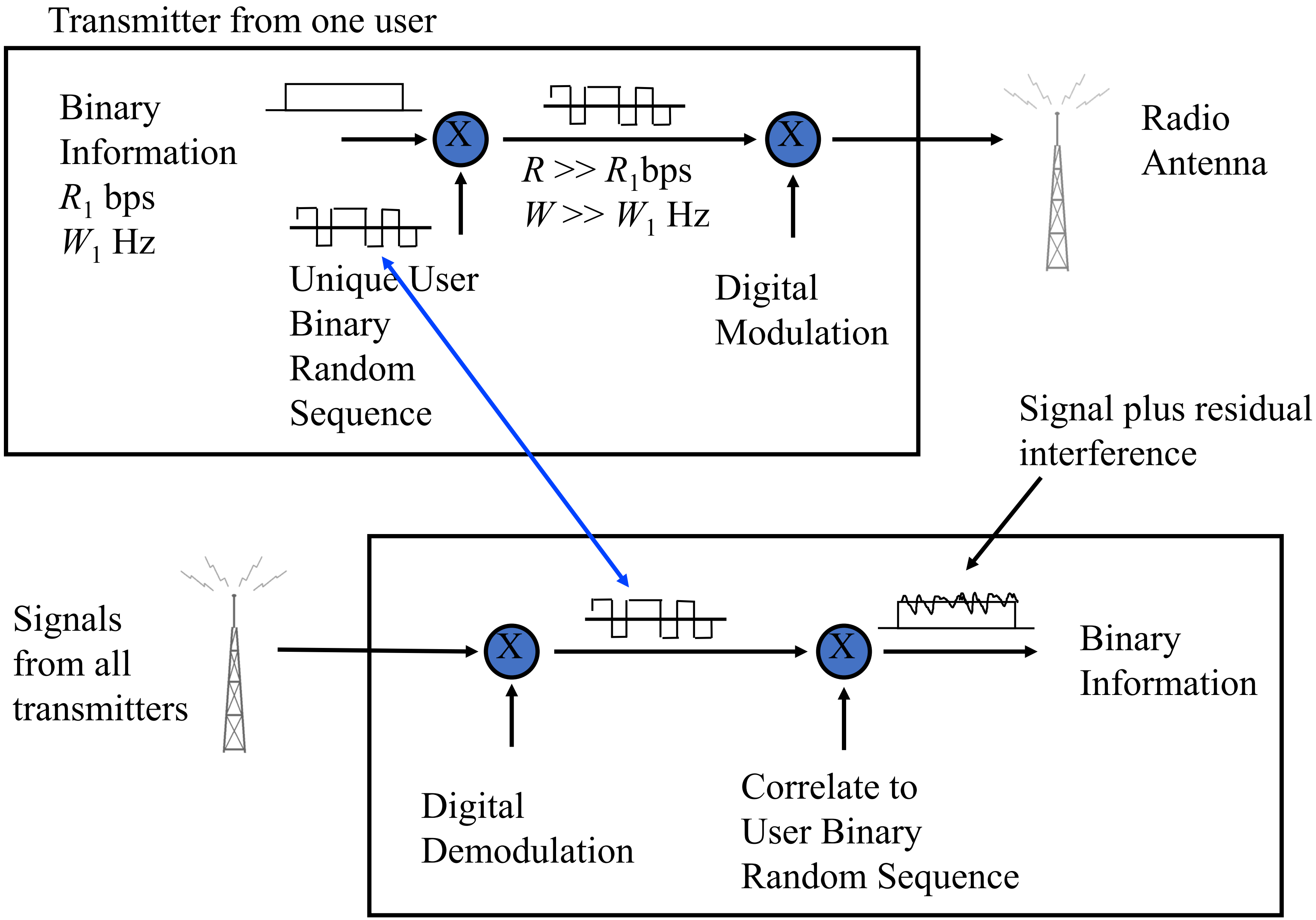
channel sums together transmissions by sender 1 and 2

using same code as sender 1, receiver recovers sender 1's original data from summed channel data!

... now *that's* useful!

CDMA

- Rough mathematical illustration
- MS to BS
  - Transmitted signal mobile i, $s_i(t)$, with code $c_i(t)$, which are orthogonal to each other: $\int c_i(t)c_j(t)dt = 0, \forall i \neq j$
  - At BS, it receives
    $$\mathrm{r(t)} = c_1(t)s_1(t) + c_2(t)s_2(t) + \cdots + c_k(t)s_k(t)$$
  - BS can recover user i's signal using correlation detector wit code $c_i(t)$ as follows:
    $$\int c_i(t)r(t)dt = \int c_i(t)c_i(t)s_i(t)dt + \sum_{j\neq i} \int c_i(t)c_j(t)s_j(t)dt$$
    $$= s_i(t) \int c_i(t)c_i(t)dt + \sum_{j\neq i} s_j(t) \int c_i(t)c_j(t)dt = s_i(t)$$
- BS to MS
  - BS uses user i's code $c_i(t)$ and generates the mixed signal $\mathrm{s(t)} = c_1(t)s_1(t) + c_2(t)s_2(t) + \cdots + c_k(t)s_k(t)$ and transmits to all users
  - MS i uses its own PN code $c_i(t)$ to decode its own signal $s_i(t)$



Transmitter from one user
Binary Information
R_1 bps
W_1 Hz
X
$R >> R_1$bps
$W >> W_1$ Hz
X
Radio Antenna
Unique User Binary Random Sequence
Digital Modulation
Signal plus residual interference
Signals from all transmitters
X
X
Binary Information
Digital Demodulation
Correlate to User Binary Random Sequence

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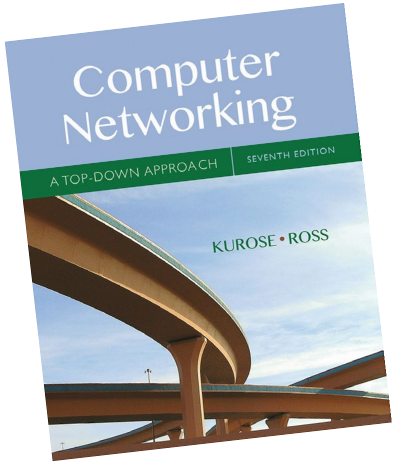


Chapter 7

IEEE 802.11 Wireless LANs

IEEE 802.11 standard	Year	Max data rate	Range	Frequency
802.11b	1999	11 Mbps	30m	2.4 Ghz
802.11a	1999	54 Mbps	30	5.8 GHz
802.11g	2003	54 Mbps	30m	2.4 Ghz
802.11n (WiFi 4)	2009	600Mbps	70m	2.4, 5 Ghz
802.11ac (WiFi 5)	2013	3.47Gpbs	70m	5 Ghz
802.11ax (WiFi 6)	2020 (exp.)	14 Gbps	70m	2.4, 5 Ghz
802.11af	2014	35 – 560 Mbps	1 Km	unused TV bands (54-790 MHz)
802.11ah	2017	347Mbps	1 Km	900 Mhz

- all use CSMA/CA for multiple access, and have base-station and ad-hoc network versions

802.11x: early development

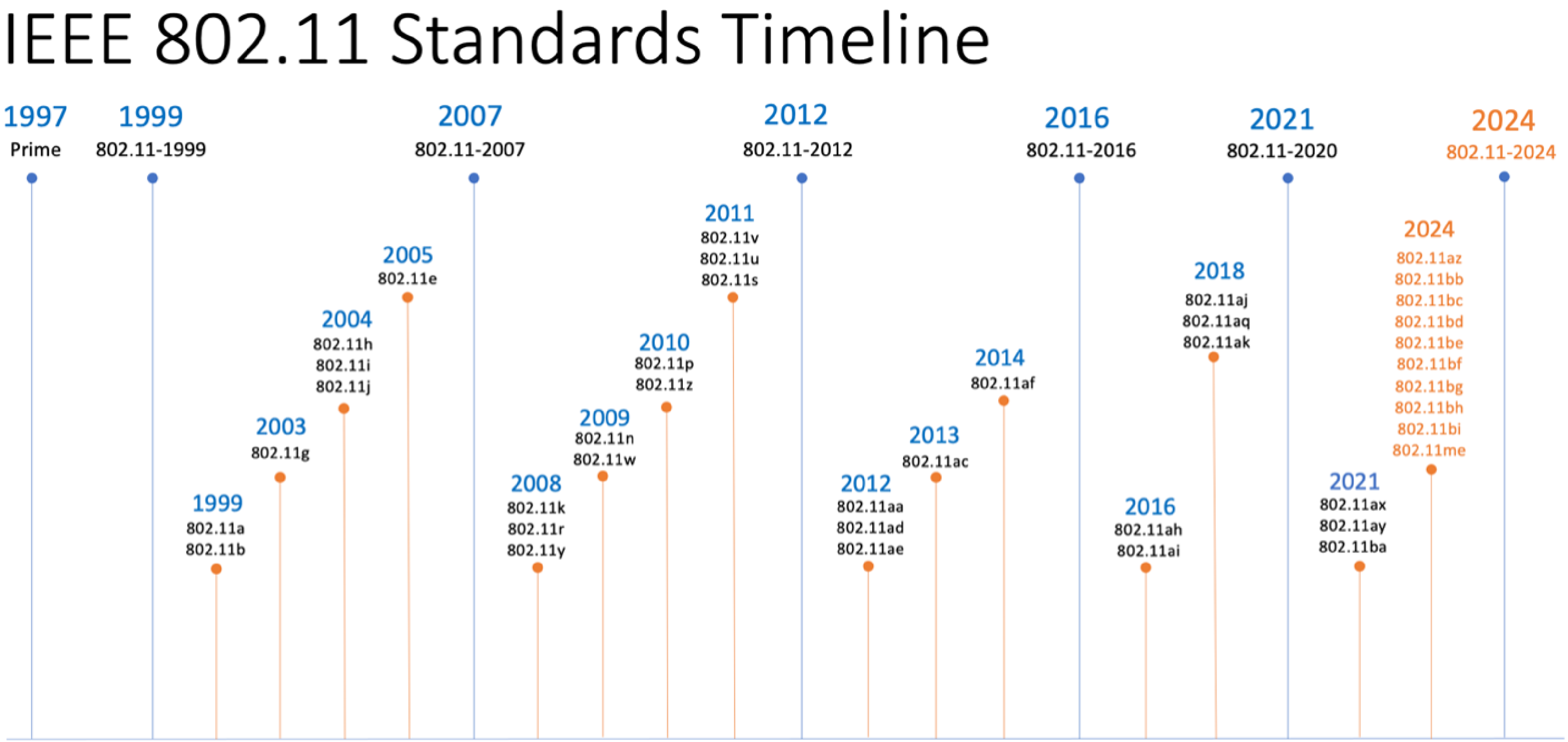
- 802.11-1997: The original standard released in 1997 provided 1-2 Mbps transmission speed in the 2.4 GHz band using Frequency Hoping Spread Spectrum (FHSS) or Direct Sequence Spread Spectrum (DSSS). It is currently obsolete.
- 802.11a: Provides a transmission speed of up to 54 Mbps in the 5 GHz band using Orthogonal Frequency-Division Multiplexing (OFDM).
- 802.11b: Works in the 2.4 GHz band and can provide up to 11 Mbps speed with a fallback rate to 5.5, 2 and 1 Mbps. 802.11b only uses DSSS.
- 802.11g: Provides a maximum speed of 54 Mbps in the 2.4 GHz band. It uses OFDM and DSSS and is backward compatible with 802.11b.
- 802.11n: Provides up to 150 Mbps throughput using spatial multiplexing. It uses the both 2.4 and 5 GHz band.

802.11x (cont)

Wireless Transmission 802.11 Protocols					
Standards	**Year Established**	**Band Frequency**	**Maximum Data Transfer**	**Channel Bandwidth**	**Antenna Configuration**
802.11a	1999	5 GHz	54 Mbps	20 MHz	1 x1 SISO
802.11b	1999	2.4 GHz	11 Mbps	20 MHz	1 x1 SISO
802.11g	2003	2.4 GHz	54 Mbps	20 MHz	1 x1 SISO
802.11n	2009	2.4 & 5 GHz	600 Mbps	20 & 40 MHz	Up to 4x4 MIMO
802.11ac	2013	5 GHz	1.3 Gbps	20, 60, 80, 160 MHz	Up to 3x3 SU-MIMO
802.11ac Wave 2	2015	5 GHz	3.47 Gbps	20, 60, 80, 80+80, 160 MHz	Up to 4x4 SU-MIMO & MU-MIMO

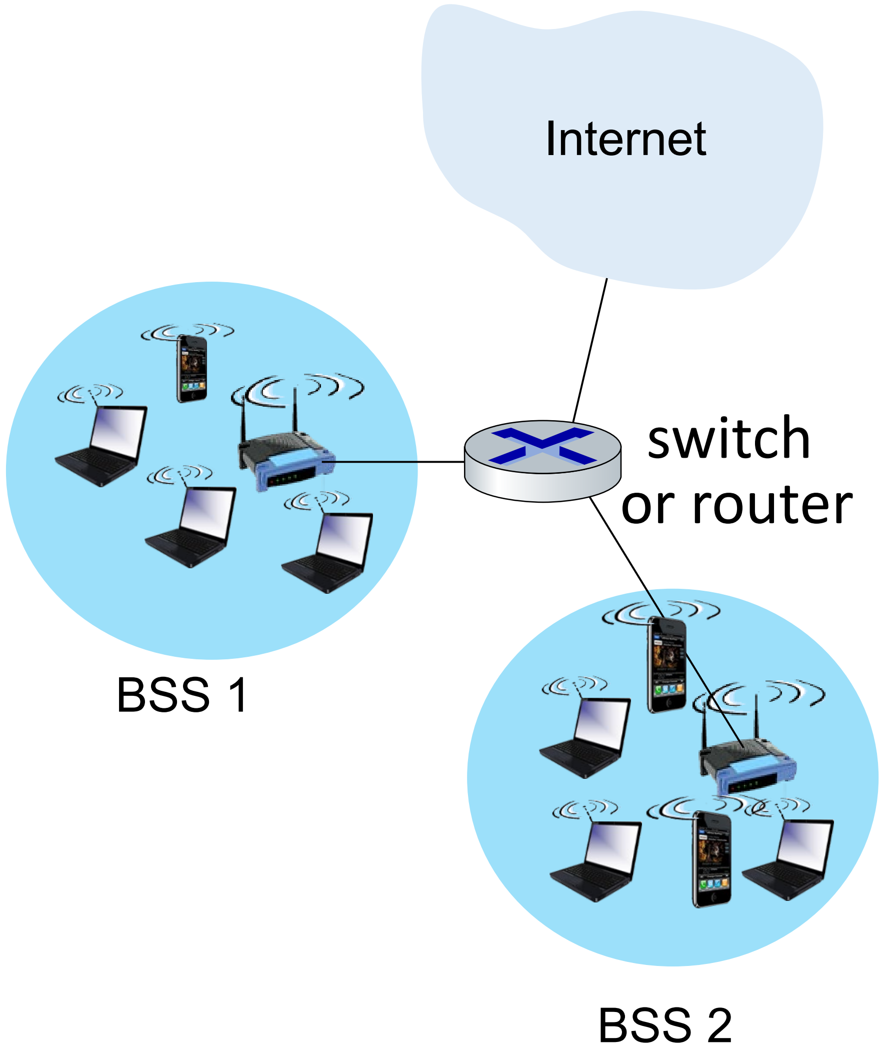
https://www.pinterest.com/pin/670614819306471037/

802.11x (cont)



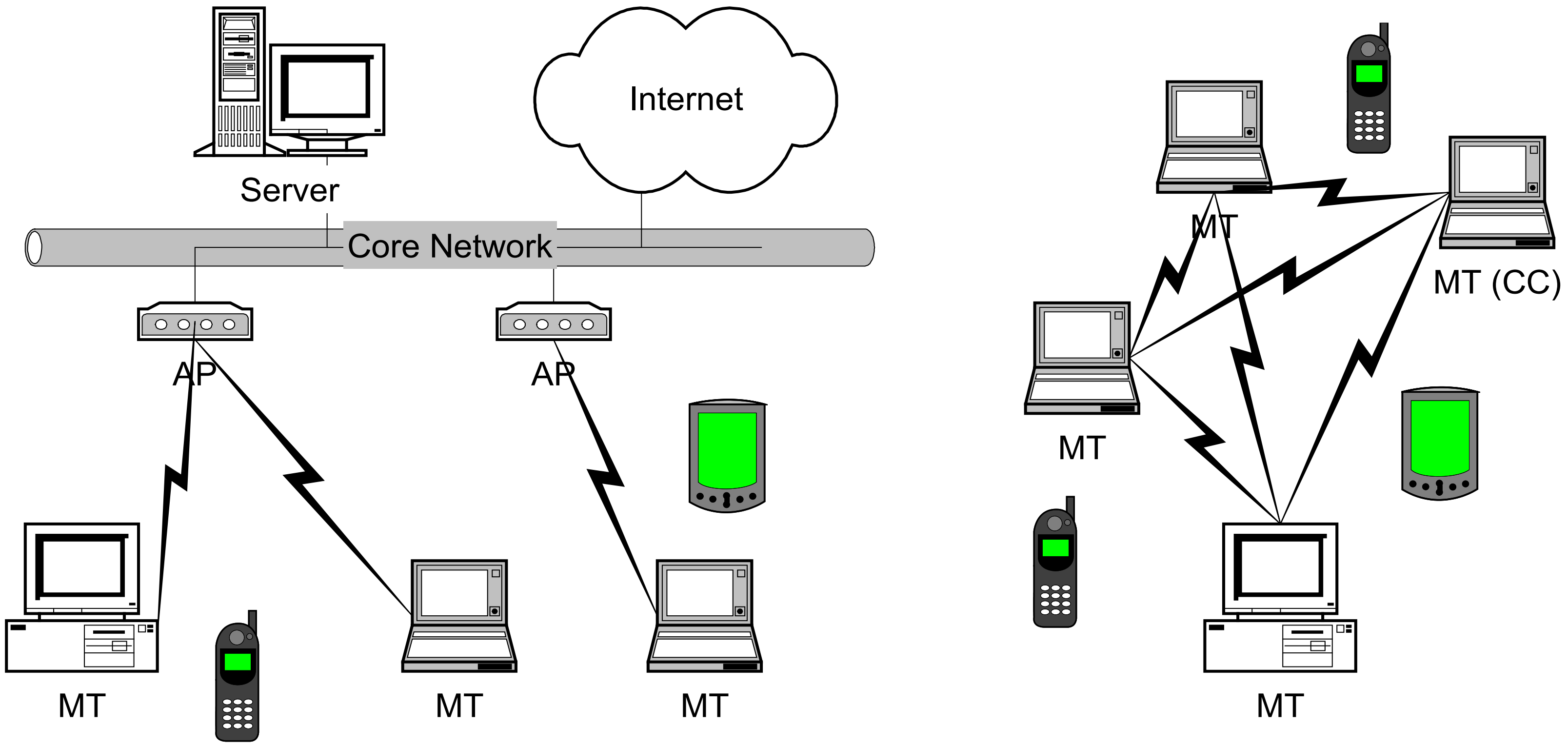
Source: https://grouper.ieee.org/groups/802/11/Reports/802.11_Timelines.htm

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): base station
  - ad hoc mode: hosts only, even AP is regarded as one of the hosts

802.11 LAN architecture



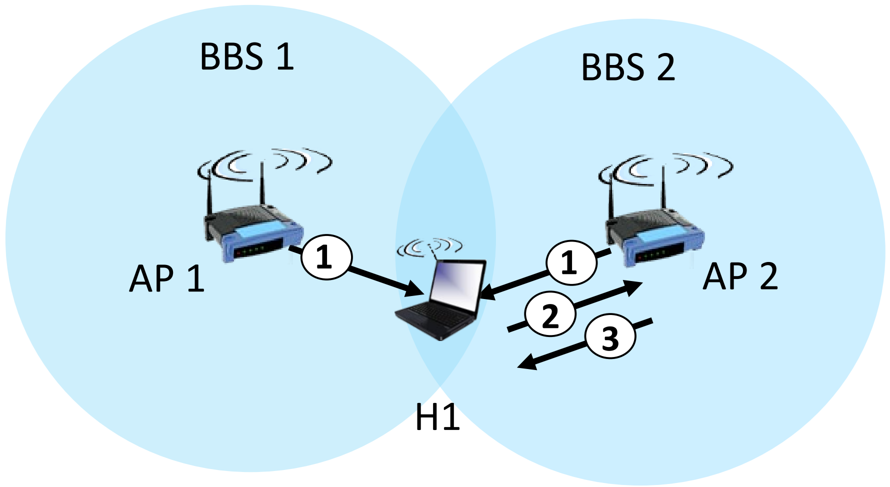
802.11: Channels, association

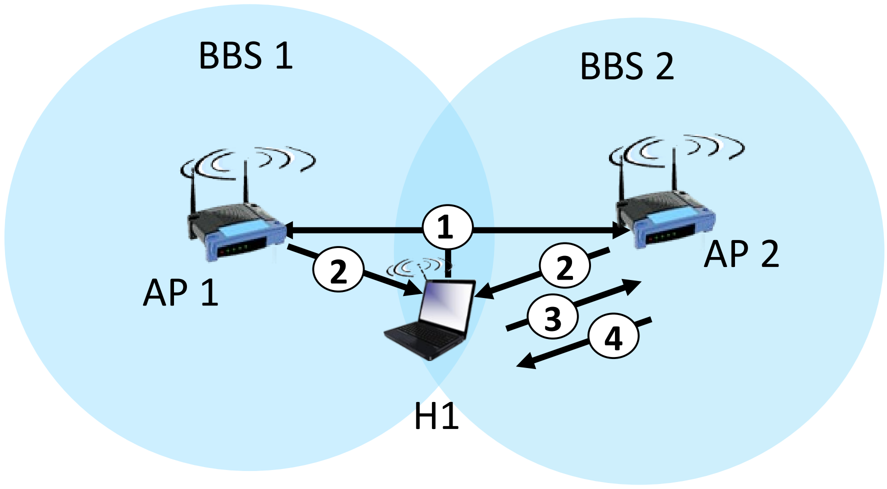
- spectrum is divided into channels at different frequency band
  - AP admin chooses frequency for AP
  - interference is possible: channel can be the same as that chosen by neighboring AP!

- arriving host: must associate with an AP
  - scans channels, listening for *beacon frames* containing AP's name SSID (service set identifier) and MAC address
    - A list of APs shown on your iPhone when you open wireless
  - selects AP to associate with
  - then may perform authentication [Chapter 8]
  - then typically run DHCP to get IP address in AP's subnet

BSS

802.11: passive/active scanning





passive scanning:

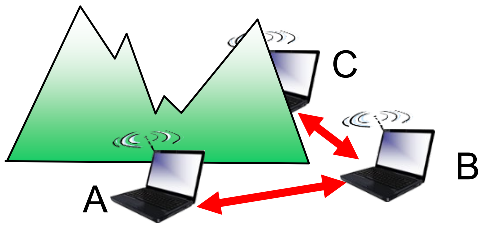
(1) beacon frames sent from APs
(2) association Request frame sent: H1 to selected AP
(3) association Response frame sent from selected AP to H1

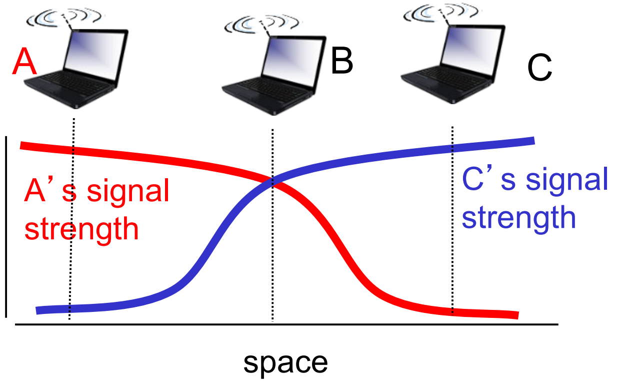
active scanning:

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

IEEE 802.11: multiple access control or medium access control (MAC)

- avoid collisions: 2+ nodes transmitting at the same time
- 802.11: CSMA - sense before transmitting
  - don't collide with detected ongoing transmission by another node
- 802.11: *no collision detection*!
  - difficult to sense collisions: high transmitting signal, weak received signal due to fading
  - can't sense all collisions in any case: hidden terminal, fading
  - goal: *avoid collisions:* CSMA/<u>C</u>ollision<u>A</u>voidance



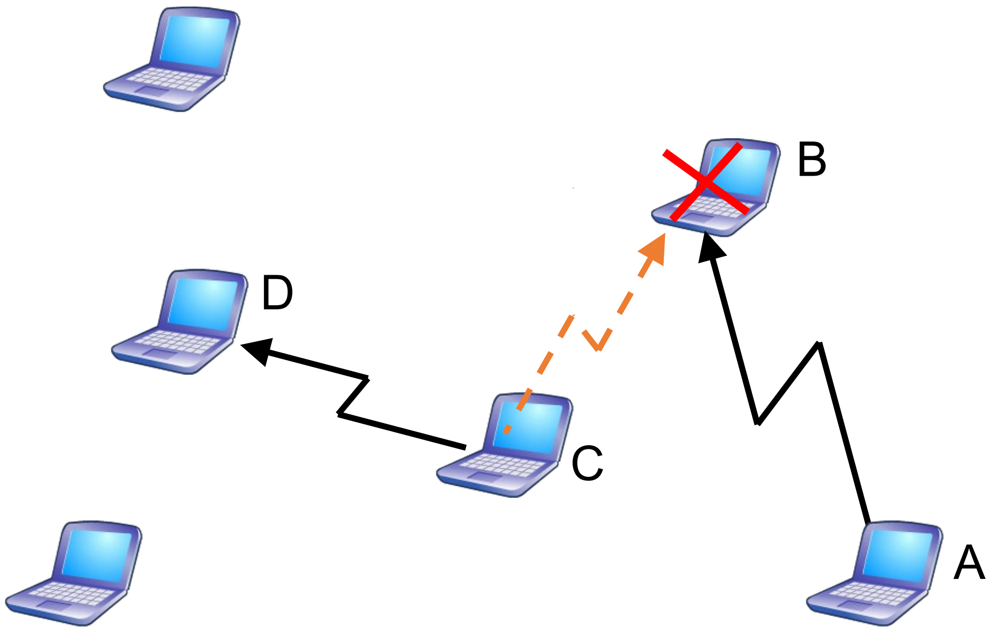


CSMA/CA

- Carrier sensing mechanism
  - Physical layer carrier sensing: physical layer carries out the medium sensing (power sensing)
  - Virtual carrier sensing: each node monitors the Duration field in all MAC frames and places this information in the station's Network Allocation Vector (NAV) if the value is greater than the current NAV value. The NAV acts like a timer to indicate that the medium is busy with transmissions from other nodes
- Two operating modes
  - PCF mode: Point Coordination Function mode, access point (AP) coordinates the transmission
  - DCF mode: Distributed Coordination Function mode, also known as peer-to-peer mode, a contention-based operational mode

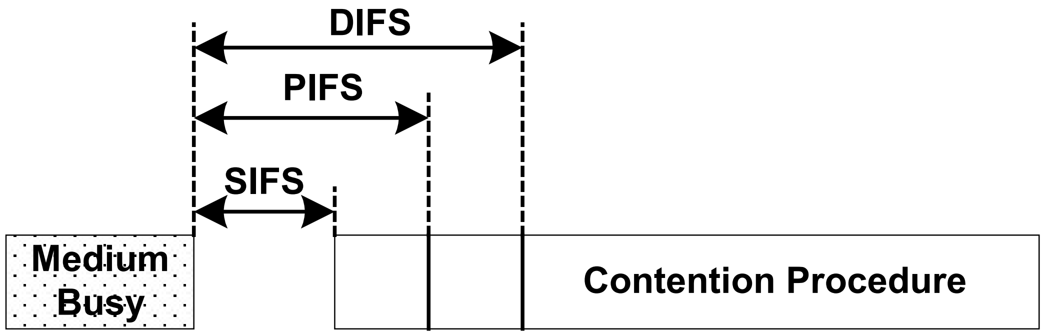
DCF

- Coordinate the usage of the shared medium
  - mitigate collision
  - minimize the idle time



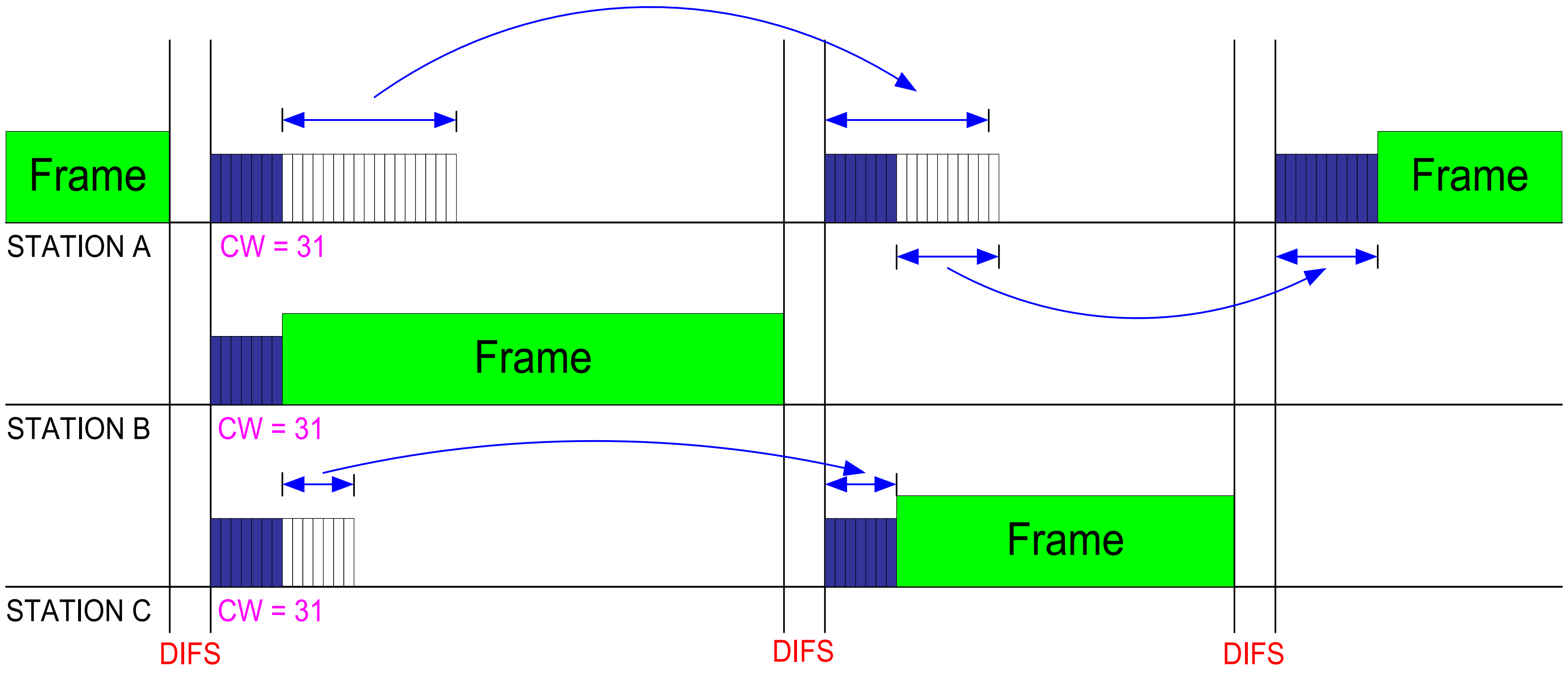
DCF

- Time-spacing
  - IFS: inter-frame space
  - SIFS: short IFS– providing highest priority level to access channel, e.g., for ACK, CTS, the 2nd or subsequent MSDU of a fragment burst
  - PIFS: PCF IFS, allowing PCF mode to take over
  - DIFS: DCF IFS, allowing DCF mode to operate

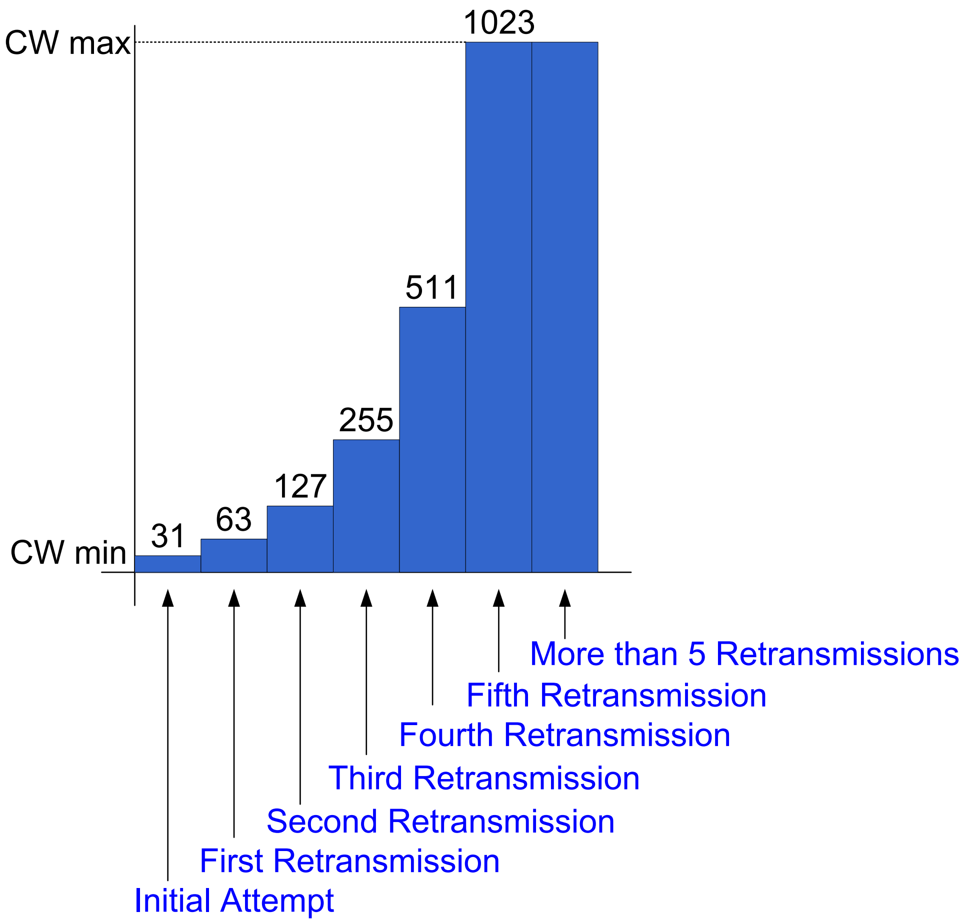


DCF: Fundamental mode

- DCF mode operation



Binary Exponential Backoff



Binary Exponential Backoff

- Algorithm for delayed transmission: a random delayed time period
- Binary Exponential backoff (BEB)
  - Whenever a node has data to transmit, pick up a number between 0 and CW_{min} , the minimum contention window size
  - Whenever an idle slot is detected, all timers are reduced by 1
  - If its transmission failure is detected, it doubles the contention window size, $CW_k = 2*CW_{k-1}$, then pick a number between 0 and CW_k, and set it to the new timer, starting count-down
  - Whenever the channel is sensed busy, all timers are frozen until another DIFS is detected
  - Whenever a timer is run to zero, it starts transmission until its transmission is successful or is given up (in 802.11x, 7 round of tries will lead to fatal failure!)

Avoiding collisions between bigs and smalls

idea: sender "reserves" channel usage first for data frames using small reservation packets

- sender first transmits *small* request-to-send (RTS) packet to BS using CSMA
  - RTSs may still collide with each other (but they're short)
- BS broadcasts clear-to-send CTS in response to RTS
- CTS heard by all nodes
  - sender transmits data frame
  - other stations defer transmissions
- Virtual carrier sensing is carried out by RTS/CTS

Multiple Access with Collision Avoidance (MACA)

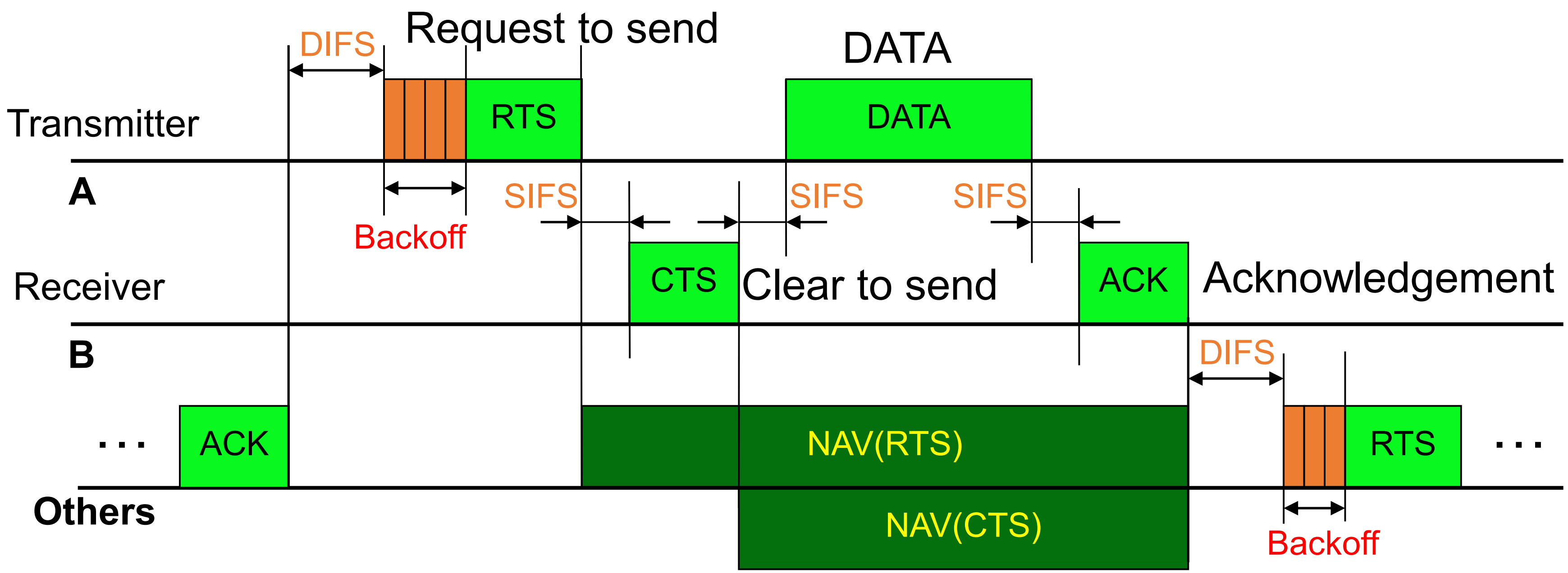
- Operations
  - sender sends RTS to receiver, any node hearing RTS will not transmit
  - receiver, upon the correct reception of RTS, will send CTS to the sender, any node hearing the CTS will refrain from transmission
  - regular data exchange starts after successful RTS-CTS exchange

Distributed Foundation Wireless MAC (DFWMAC)

- IEEE 802.11 wireless LAN standard
- RTS-CTS-DATA-ACK four-way handshake protocol (an option for 802.11 family)
- Operations
  - sender sensing the channel idle will wait for DIFS and then transmit RTS
  - receiver, upon receiving the RTS correctly, will wait for SIFS and then reply with CTS
  - sender, upon receiving CTS correctly, will wait for SIFS and transmit data
  - receiver will send ACK SIFS later after correct data
  - time spacing (DIFS>SIFS) provides priority to certain message
  - backoff algorithm will be used if collision

IEEE 802.11 MAC Protocol (Distributed)

- CSMA/CA
  - Carrier sensing
    - Physical Carrier Sensing
    - Virtual Carrier Sensing
  - Interframe Spacing (IFS)
    - Short IFS (SIFS) < DCF IFS (DIFS)
  - Binary Exponential Backoff
    - Randomly chosen from [0, CW]
    - CW doubles in case of collision



Distributed Foundation Wireless MAC (DFWMAC)

- Collision resolution: backoff algorithm
  - IEEE 802.11: binary exponential backoff
    - Any node involving in collisions (when the node does not receive the desired CTS for the transmitted RTS) will double the contention window size up to its maximum: i.e., the node picks a random number between 0 and double of the previous window size for the next attempt
  - Fast collision resolution (FCR) algorithm (WINET approach)
    - Upon collision, all nodes with data ready to transmit will expand their contention window size: i.e., even the already deferred nodes will act again to actively avoid future collisions

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

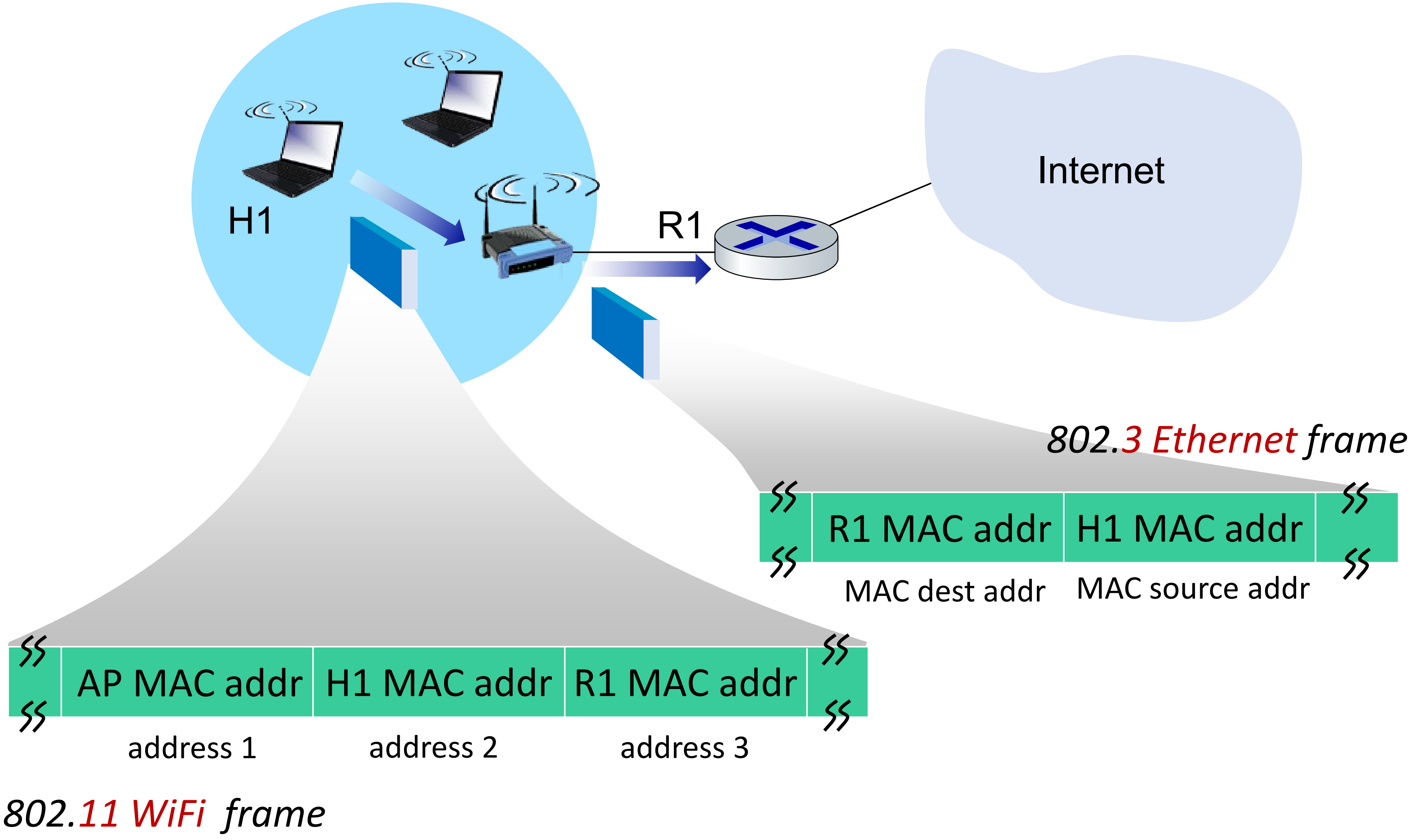
Address 1: MAC address of wireless host or AP to receive this frame

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



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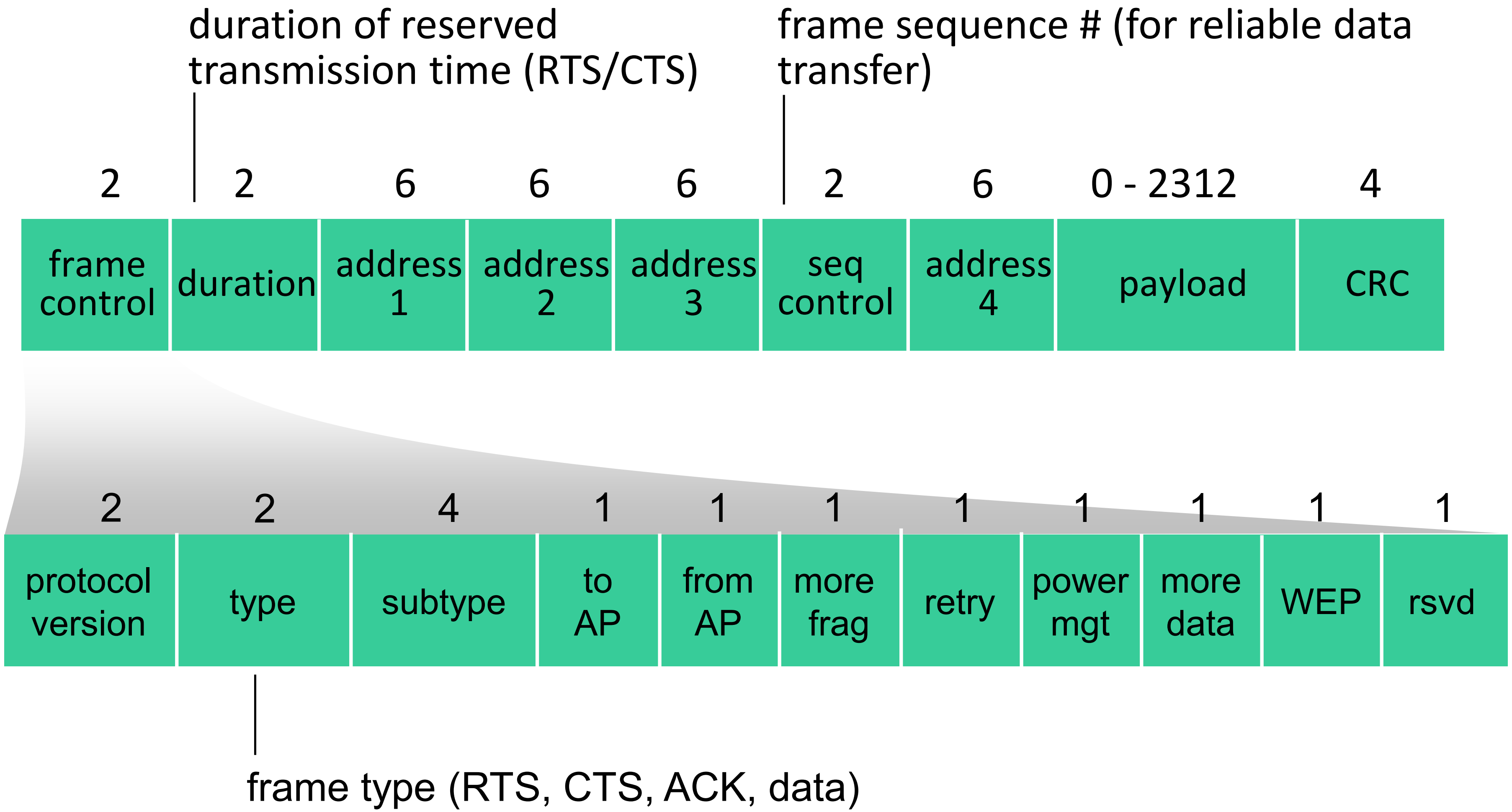
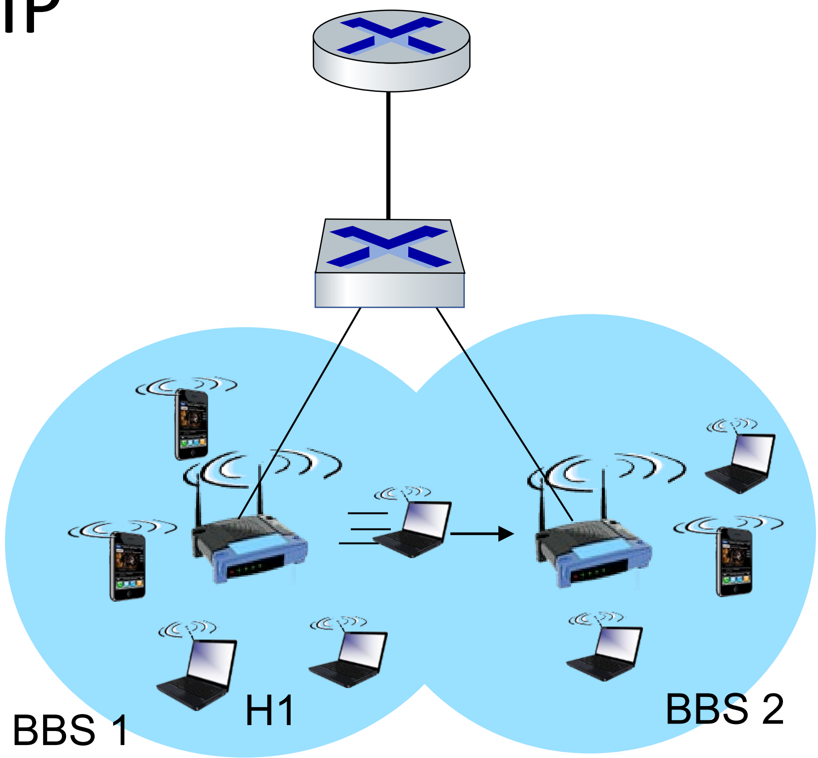


802.11: mobility within same subnet

- H1 remains in same IP subnet: IP address can remain same
- switch: which AP is associated with H1?
  - self-learning (Ch. 6): switch will see frame from H1 and "remember" which switch port can be used to reach H1



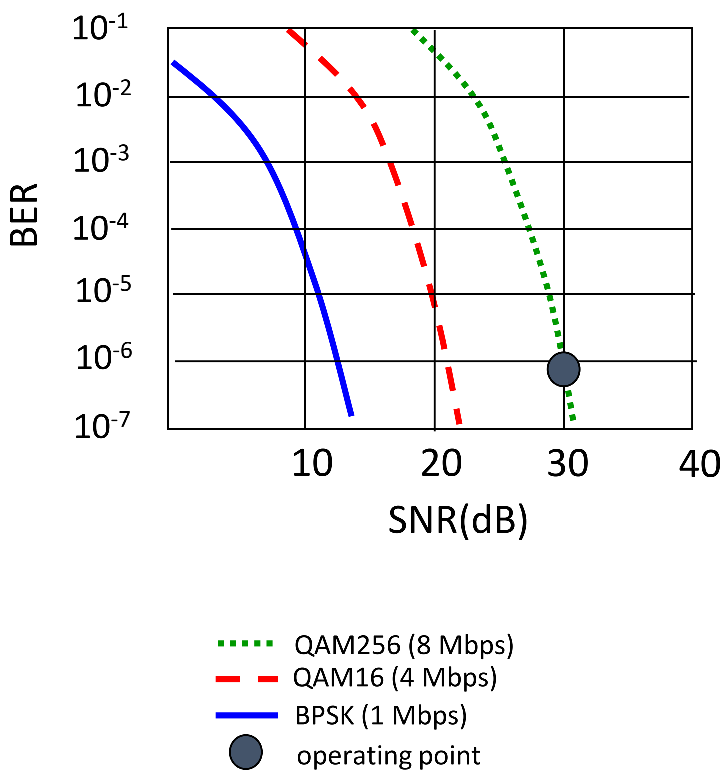
802.11: advanced capabilities

Rate adaptation: modulation and coding system (MCS)

- 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



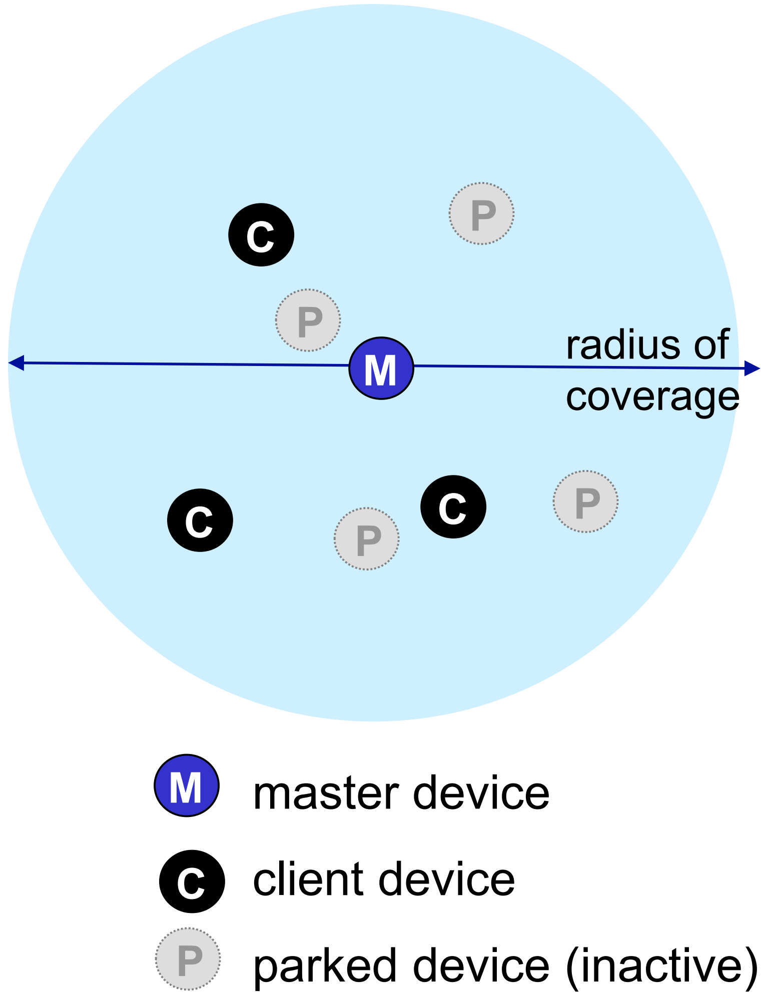
802.11: advanced capabilities

power management (sleeping schedule)

- 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
  - node will stay awake if AP-to-mobile frames to be sent; otherwise sleep again until next beacon frame

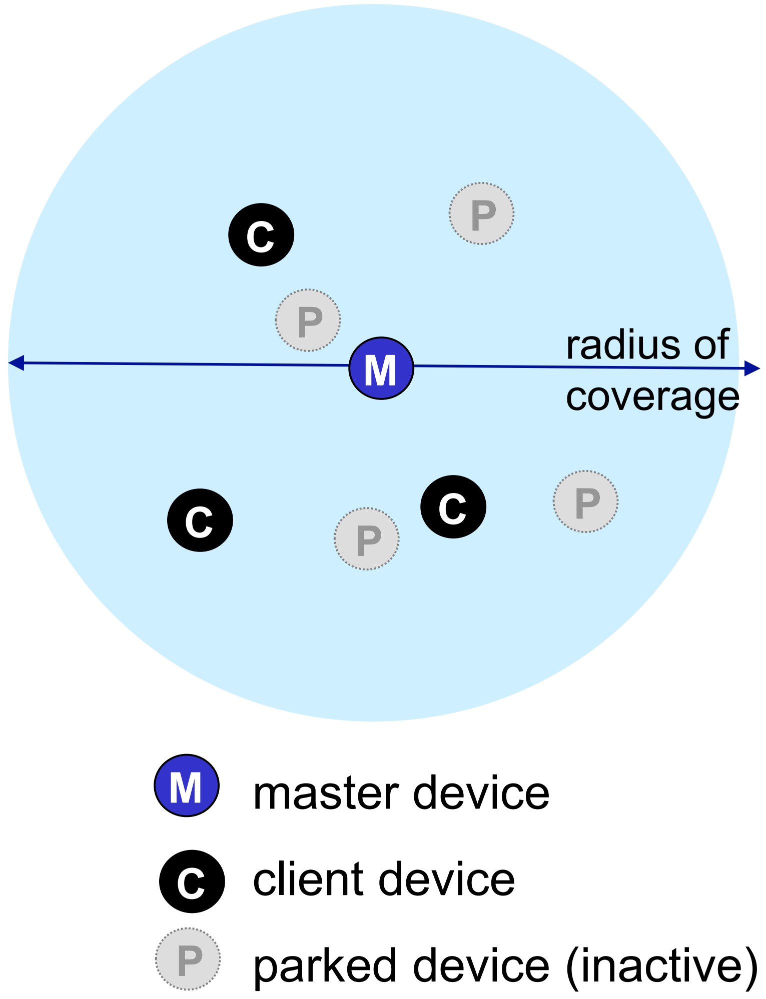
Personal area networks: Bluetooth

- less than 10m diameter
- replacement for cables (mouse, keyboard, headphones)
- ad hoc: no infrastructure
- 2.4-2.5 GHz ISM radio band, up to 3 Mbps
- master controller / client devices:
  - master polls clients, grants requests for client transmissions



Personal area networks (PANs): Bluetooth

- TDM, 625 μsec sec. slot
- FDM: sender uses 79 frequency channels in known, pseudo-random order slot-to-slot (spread spectrum)
  - other devices/equipment not in piconet only interfere in some slots
- parked mode: clients can "go to sleep" (park) and later wakeup (to preserve battery)
- bootstrapping: nodes self-assemble (plug and play) into piconets



Wireless Networks - Roadmap

- Introduction

Wireless

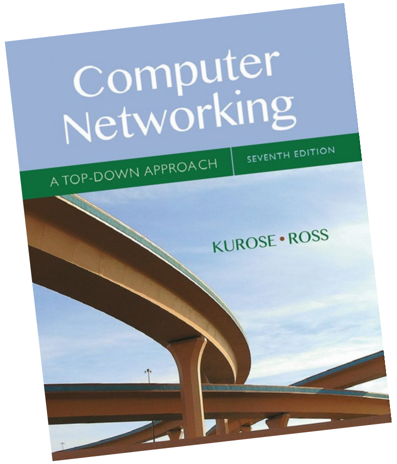
- Wireless Links and network characteristics
- IEEE 802.11 wireless LANs: e.g., MAC protocols, WiFi
- 4G/5G and beyond

Mobility

- Mobility management: principles
- Mobility: impact on higher-layer protocols

Multi-access Edge Computing (MEC)

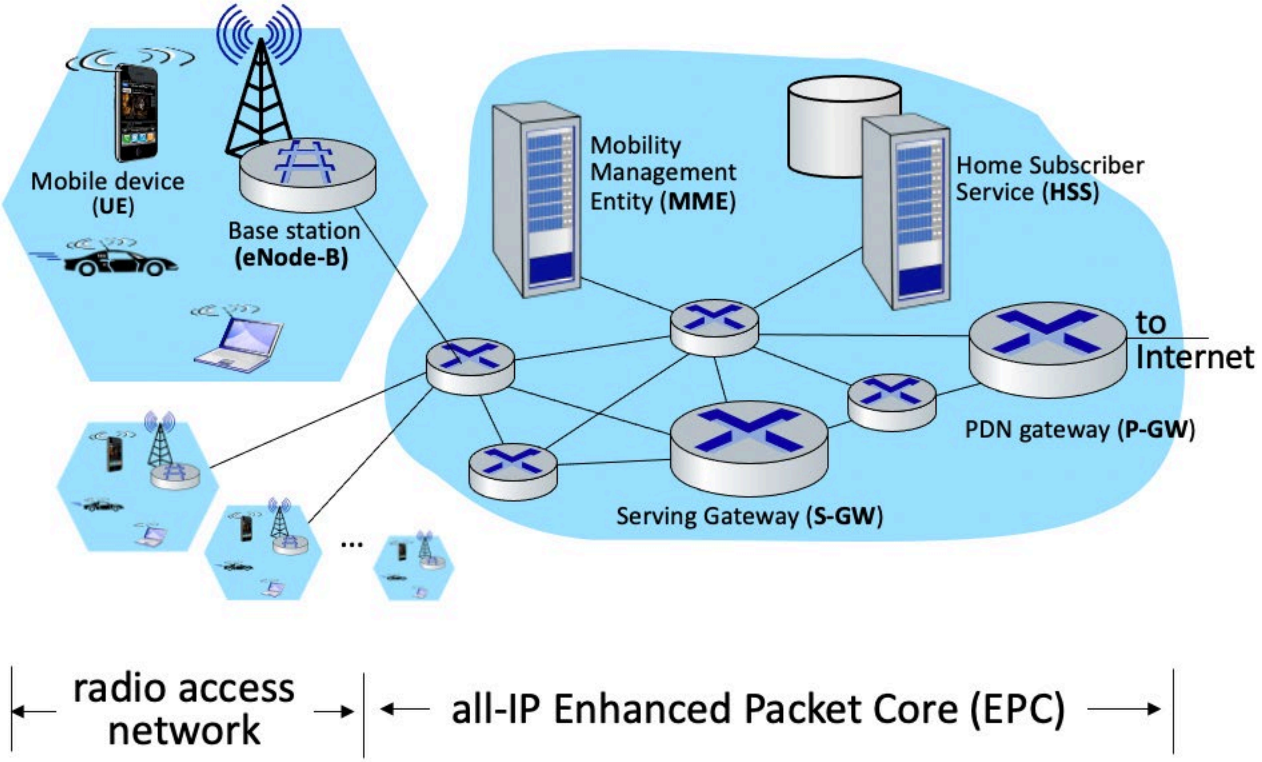
- Design Rationale
- Challenges and Solutions



Chapter 7

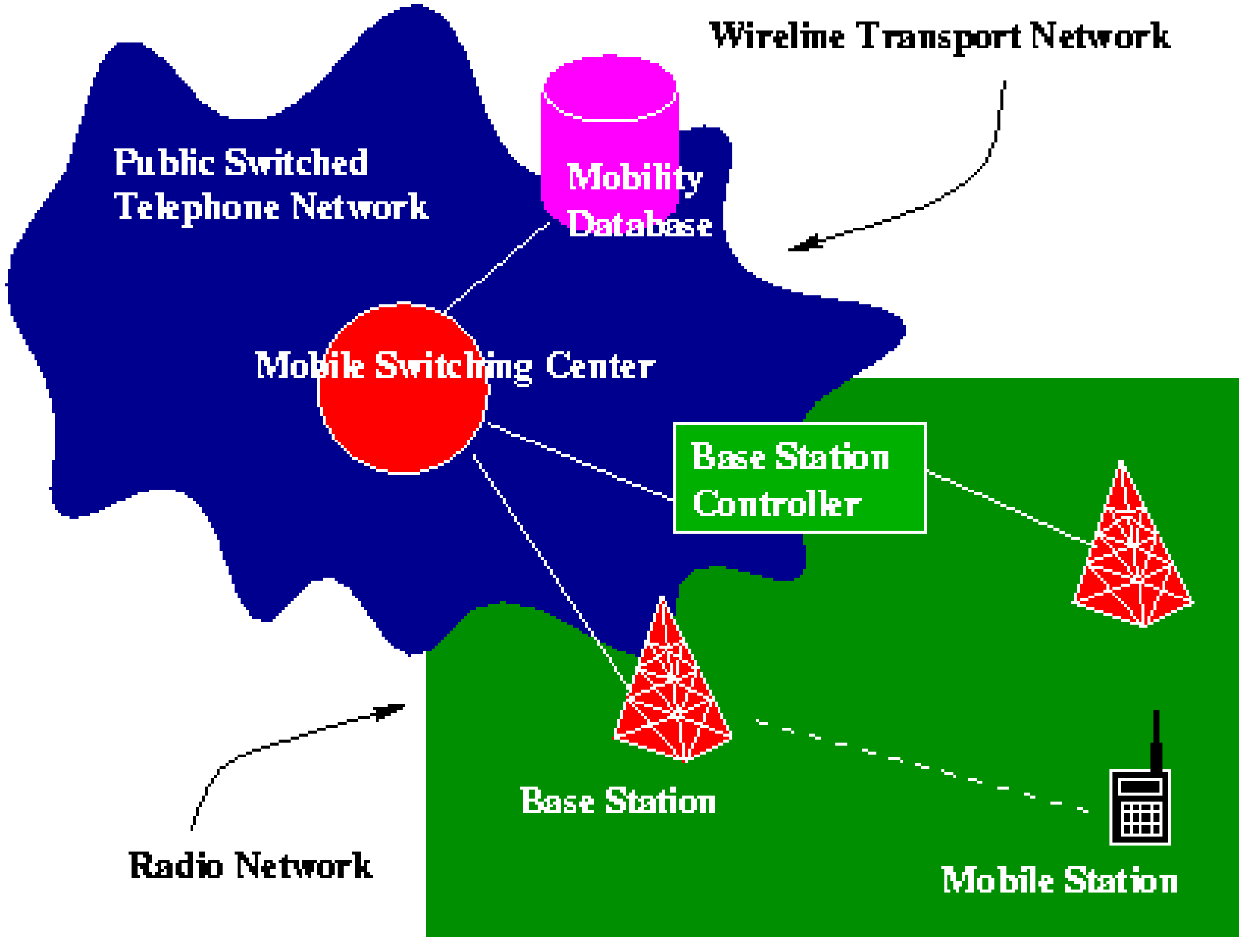
4G Cellular Networks: Architecture and Elements

- Mobile device (MD): smartphone, tablet, laptop, or IoT devices
  - ✓ IMSI, User Equipment (UE)
- Base Station (BS): the physically connecting “edge” point to all mobile
  - ✓ BS, SBS, eNode-B, NG, …
- Home Subscriber Service (HSS): home hosting user profile info
- Serving Gateway (S-GW): gateway router connecting cellular operators' networks
- PDN-Gateway (P-GW): gateway router connecting cellular services to Internet (packet data network)
- Mobility Management Entity (MME): handler of user mobility
- Ran Access Networks (RANs): wireless link between MD and BS



1G/2G: Cellular fundamentals

- Voice-centric design
  - ✓ Limited
- 3G+ still preserves the same logical design architecture
- BS is the mobile “access” point
- MSC (mobile switching center) is the “edge” router
- Mobility database
  - ✓ Home location register (HLR)
  - ✓ Visiting location register (VLR)
- Public Switching Telephone Network (PSTN) as the backbone
- Mostly for voice service



(Courtesy from Professor Yi-Bing Lin)

Call Origination (Call Out)

- A mobile station (MS) contact a BS which is strongest in power (serving base station)
- MS transmits its Mobile Identification Number (MIN), its Electronic Serial Number (ESN) and the called phone number
- BS sends these data to the MSC via wireline connection
- MSC finds the terminating switch (EO for wired or MSC for wireless) of the called party via connection finding operation in PSTN
- Terminating switch finds the called party via paging
- Connection is established

Call Termination (Call In)

- Caller's terminating switch finds the MSC of the callee using MIN,ESN,callee's phone number
- Upon receiving these numbers, MSC will page its charging area (send paging message to all BSs) and BSs will send a message on their paging channels for the callee
- The MS being paged will respond to BS, then MSC
- Connection is then established

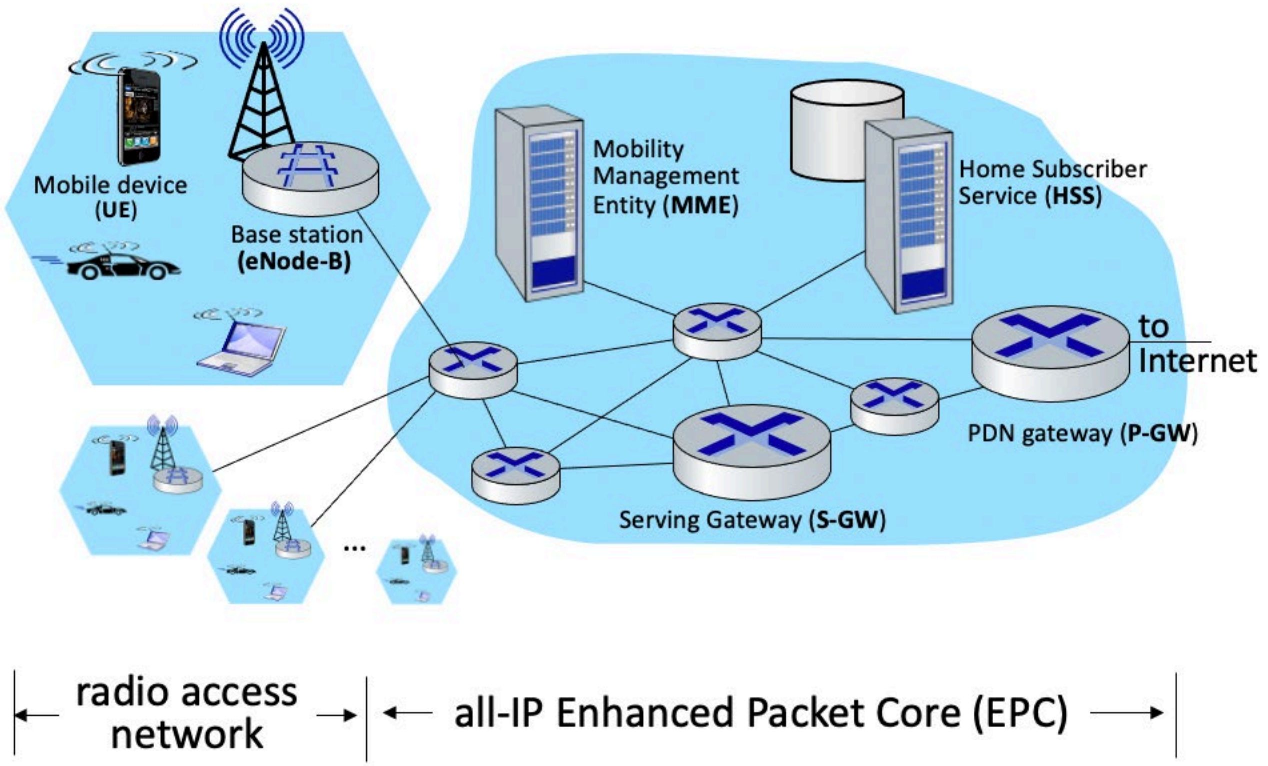
Design Issues for 2G

- Channel assignment
- Mobility management
  - Location management
  - Handoff strategies
- Call admission control (Resource allocation)
- Interference and system capacity
  - Power control
- Trunking and grade of service (GoS)
- Capacity improvement
  - Cell splitting
  - Sectorization
  - Power control

3G/4G/LTE System Architecture

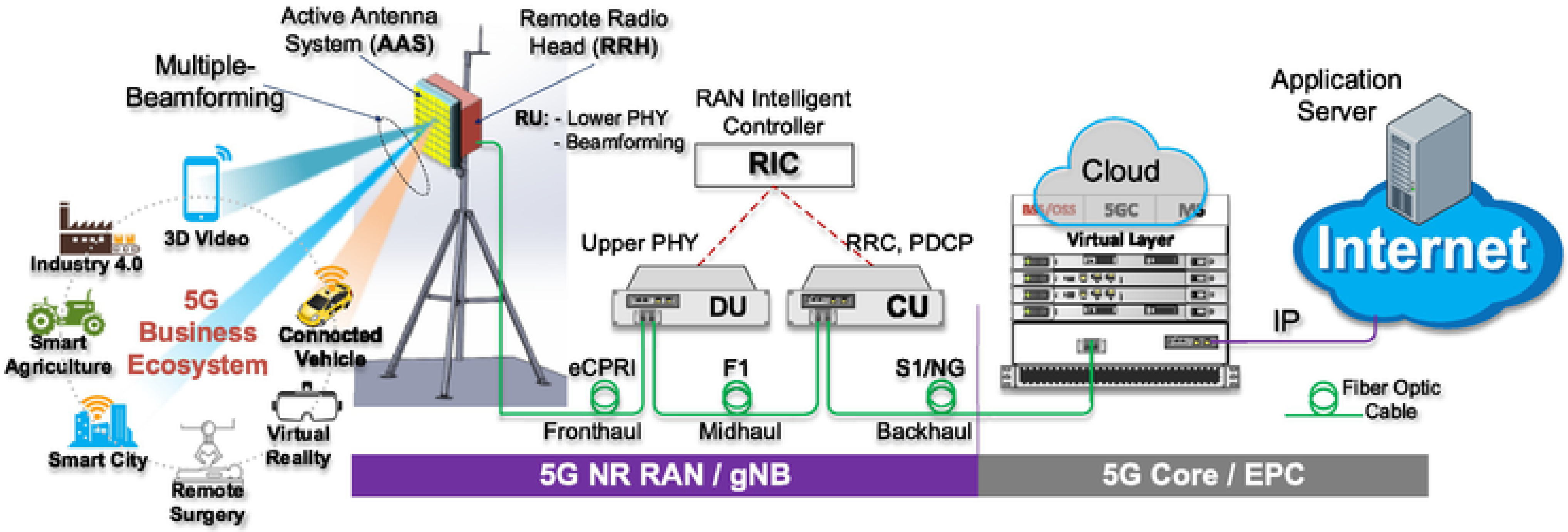
Some salient features

- Data-centric design
  - ✓ Voice is one type of data
- Grand integration
  - ✓ 3G: integrating with WiFi, separating circuit-switched voice service and packet-switched data services with the carrier's core network
  - ✓ 4G: harmonization of heterogeneous wireless systems
  - ✓ Shifting to all-data (all-IP) networks



5G+

http://www.omniblonde.com



- Typical technologies: OFDM, MIMO, hyper densification, mmWave, Reconfigurable Intelligent Surface, …
- Features: enhanced mobile broadband (eMBB), Ultra Reliable Low Latency Communication (URLLC), massive Machine Type Communication (mMTC), and Time-Critical Communication (TCC).
- 6G = 5G + AI/ML

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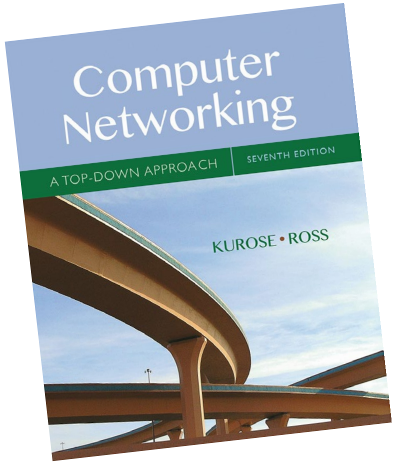


Chapter 7

Mobility

- Mobility management: principles
- Mobility: impact on higher-layer protocols

Multi-access Edge Computing (MEC)

- Design Rationale
- Challenges and Solutions

What is mobility?

- spectrum of mobility, from the network perspective:

no mobility — high mobility

- device moves between networks, but powers down while moving
- device moves within same AP/BS in one provider network
- device moves among APs/BSs in one provider network
- device moves among multiple provider networks, while maintaining ongoing connections

We're interested in these!

Mobility approaches

- let network (routers) handle it:
  - routers advertise well-known name, address (e.g., permanent 32-bit IP address), or number (e.g., cell #) of visiting mobile node via usual routing table exchange
  - Internet routing could do this already *with no* changes! Routing tables indicate where each mobile located via longest prefix match!
  - DHCP provides another way
  - Mobility management is key component of cellular systems
  - Mobile IP could be used to manage routing areas for Internet

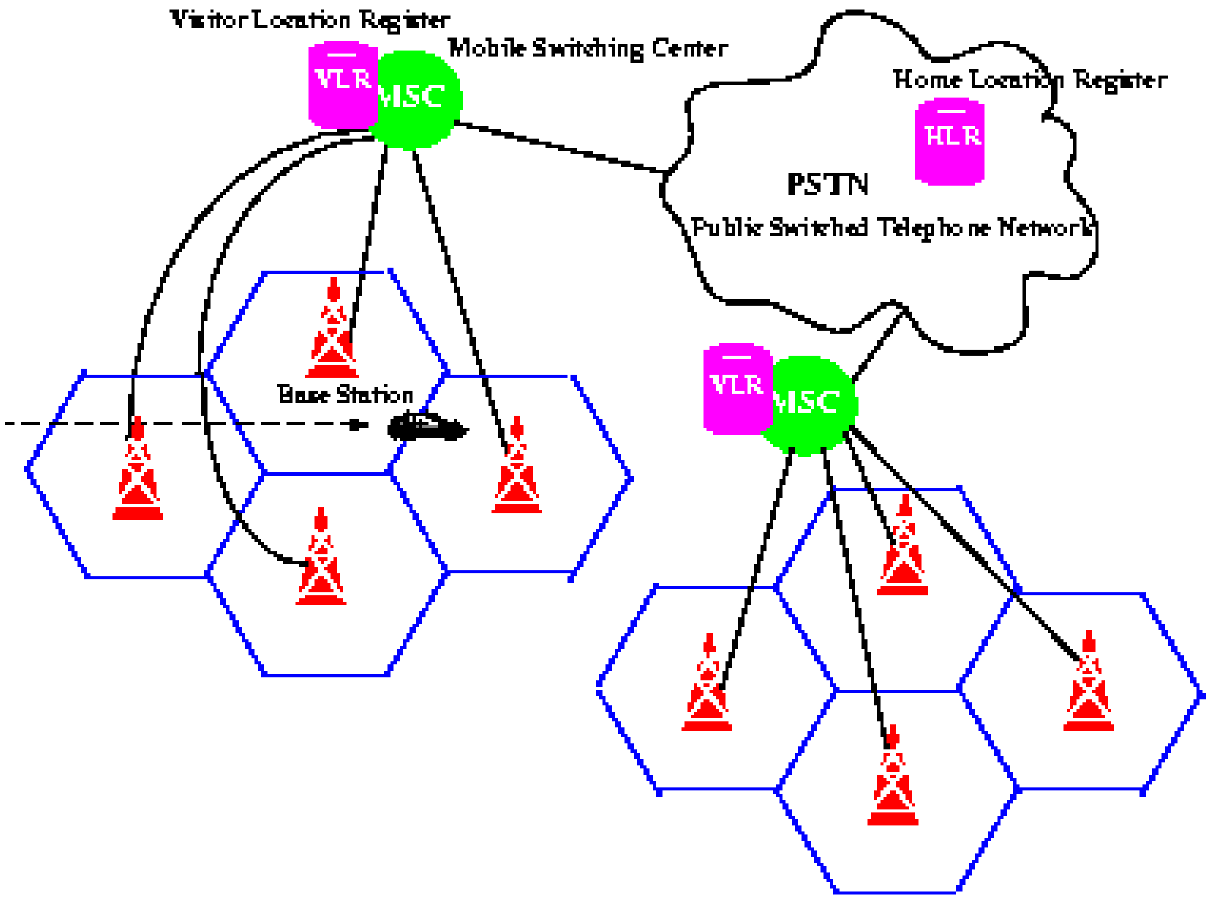
Mobility approaches

- let network (routers) handle it:
  - routers advertise well-kn ... address (e.g., permanent 32-bit IP address), or numb ...) of visiting mobile node via usual routing table exch...
  - Internet routing could do ... dy *with no* changes! Routing tables indicate where each mobile located via longest prefix match!

not scalable to billions of mobiles

- let end-systems handle it: functionality at the "edge"
  - *indirect routing:* communication from correspondent to mobile goes through home network, then forwarded to remote mobile
  - *direct routing:* correspondent gets foreign address of mobile, send directly to mobile

Basic Mobility Management (2G Cellular)



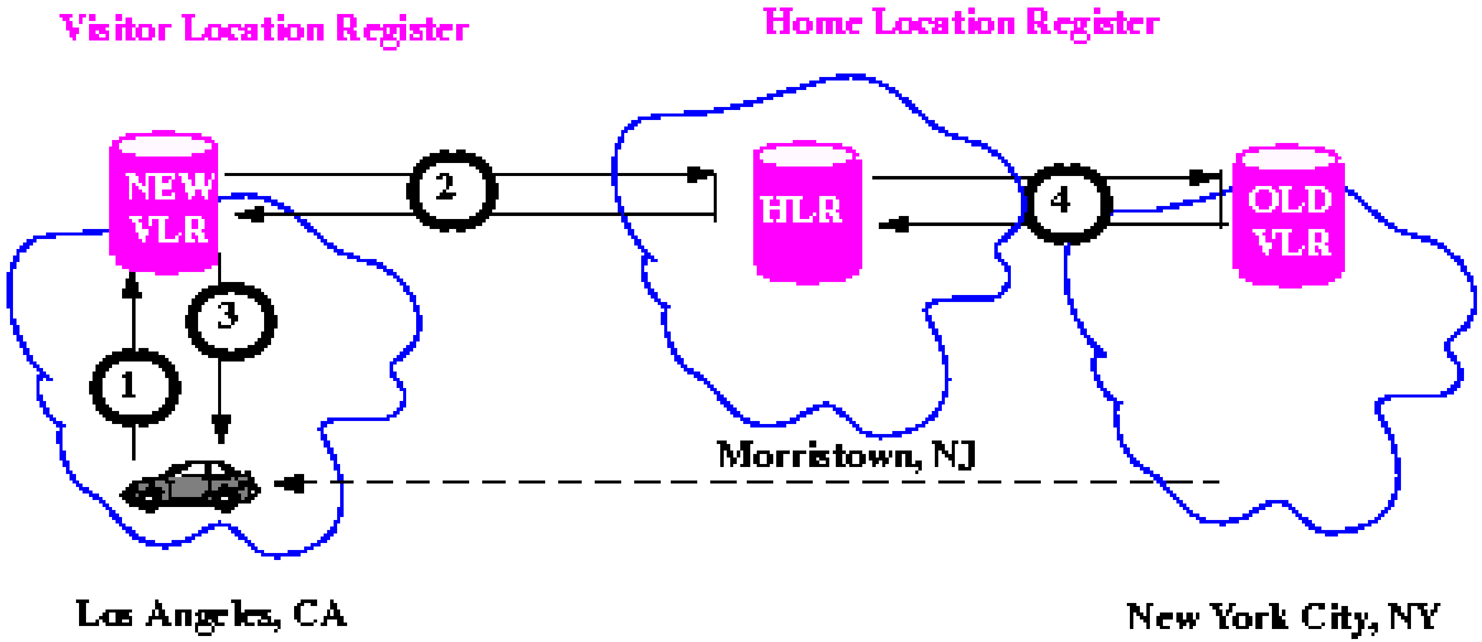
(Courtesy from Professor Yi-Bing Lin)

Mobility Management

- Two basic operations
  - Registration (location update): a process that a mobile user informs the system about its location
    - update the location information in HLR
    - location info: the VLR's ID the MS is currently visiting
  - Paging (location tracking): a process that the system locates the MS
    - MSC associated with the VLR for the MS directs all BSs to broadcast a message for the MS
    - Paging procedure
      - sequential paging
      - parallel paging
      - selective paging

Registration Process (2G Location Update)

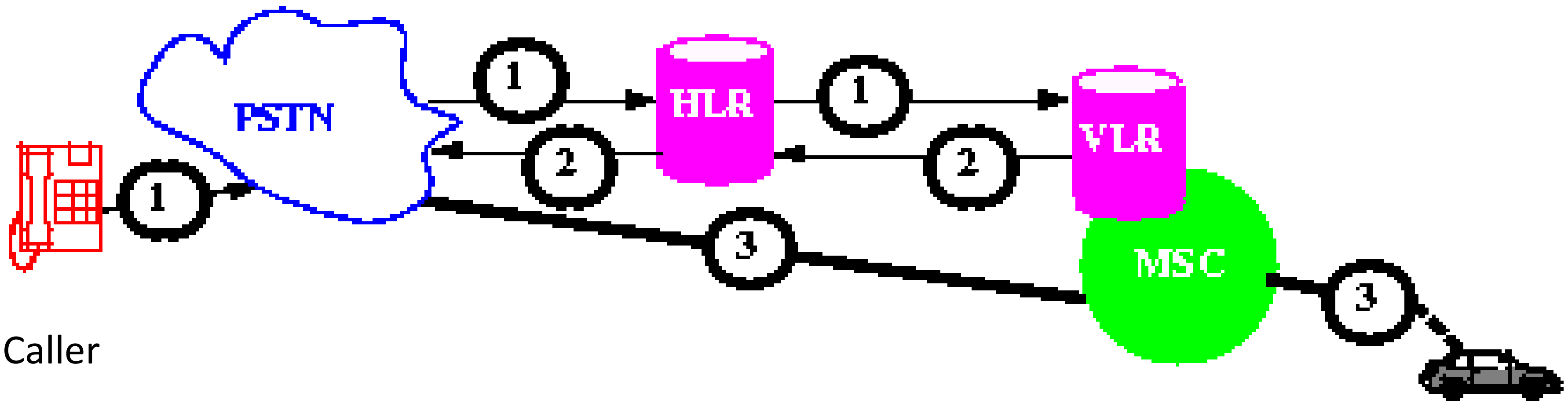
- VLR-HLR-VLR signaling



(Courtesy from Professor Yi-Bing Lin)

Call Delivery Procedure

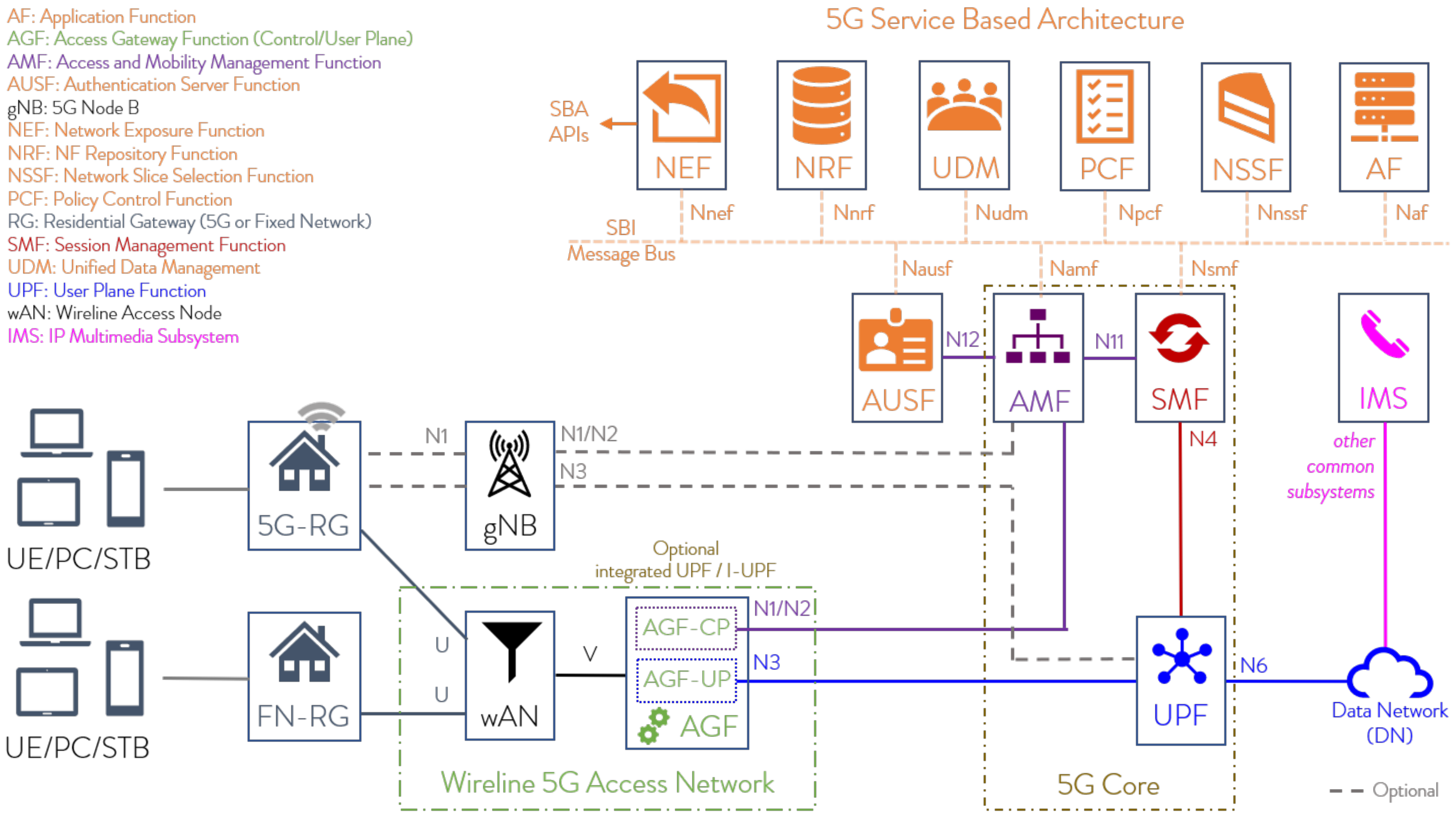
- Call delivery or call termination



(Courtesy from Professor Yi-Bing Lin)

Mobility for 5G+

- 5G and beyond will have some changes



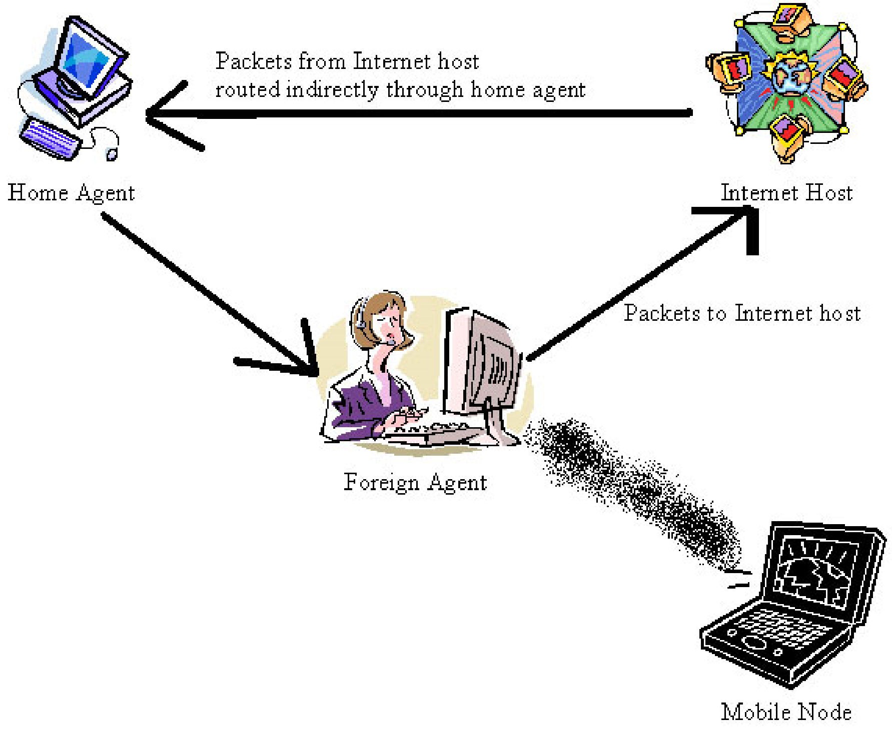
https://www.metaswitch.com/knowledge-center/reference/what-is-a-5g-access-gateway-function-agf

IP Mobility (indirect routing)

- Mobile IP: maintain IP capability and add mobility support
  - each mobile node will be assigned a permanent IP address
  - *home agent* (HA): an agent at home system (to which an MN subscribe service) handling the service for the MN
  - *foreign agent* (FA): an agent at visiting system handling the service of the MN
  - *care-of-address*: an IP address in the visiting system assigned to the MN (binding)
  - can handle all mobility types (micro-mobility, macro-mobility and global-mobility)
  - interworking functionality has been added
  - however, too much overheads are induced

IP Mobility

- Mobile IP operation
  - Triangular routing
    - a packet for an MN is first directed to the MN's HA
    - HA contacts current FA and forward the packet to FA
    - FA, using the binding IP address, forwards the packet to the MN
    - tunneling is used: all packets are encapsulated from HA to FA
  - Mobility handling: when an MN moves from one FA to another, the new FA will update HA about the change
  - IPv6 has added the mobility support
  - Mobile-IP is standardized by IETF



https://ipsit.bu.edu/sc546/sc441Spring2003/mobileIP/concerns.html

Wireless, mobility: impact on higher layer protocols

- logically, impact *should* be minimal …
  - best effort service model remains unchanged
  - TCP and UDP can (and do) run over wireless, mobile
- … but performance-wise:
  - packet loss/delay due to bit-errors (discarded packets, delays for link-layer retransmissions), and handover loss
  - TCP interprets loss as congestion, will decrease congestion window un-necessarily
  - delay impairments for real-time traffic
  - Wireless bandwidth is a scarce resource for wireless links

Applications with high mobility

- Mobility is the norm other than the exception and must be addressed!
  - Satellite communications (e.g., LEOs, SpaceX)
  - High-speed rails (HSR)
  - Vehicular communications (e.g., V2X)
  - Subways
  - Ferries or maritime communications
  - Walks

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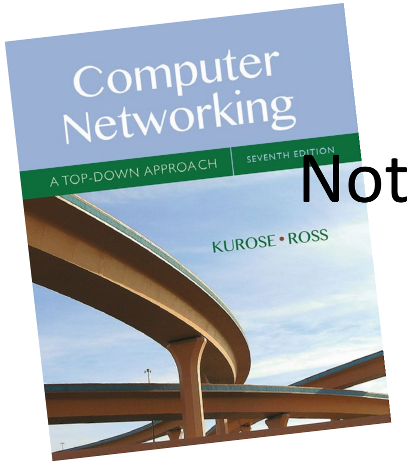


Not in Textbook

Multi-access Edge Computing (MEC)

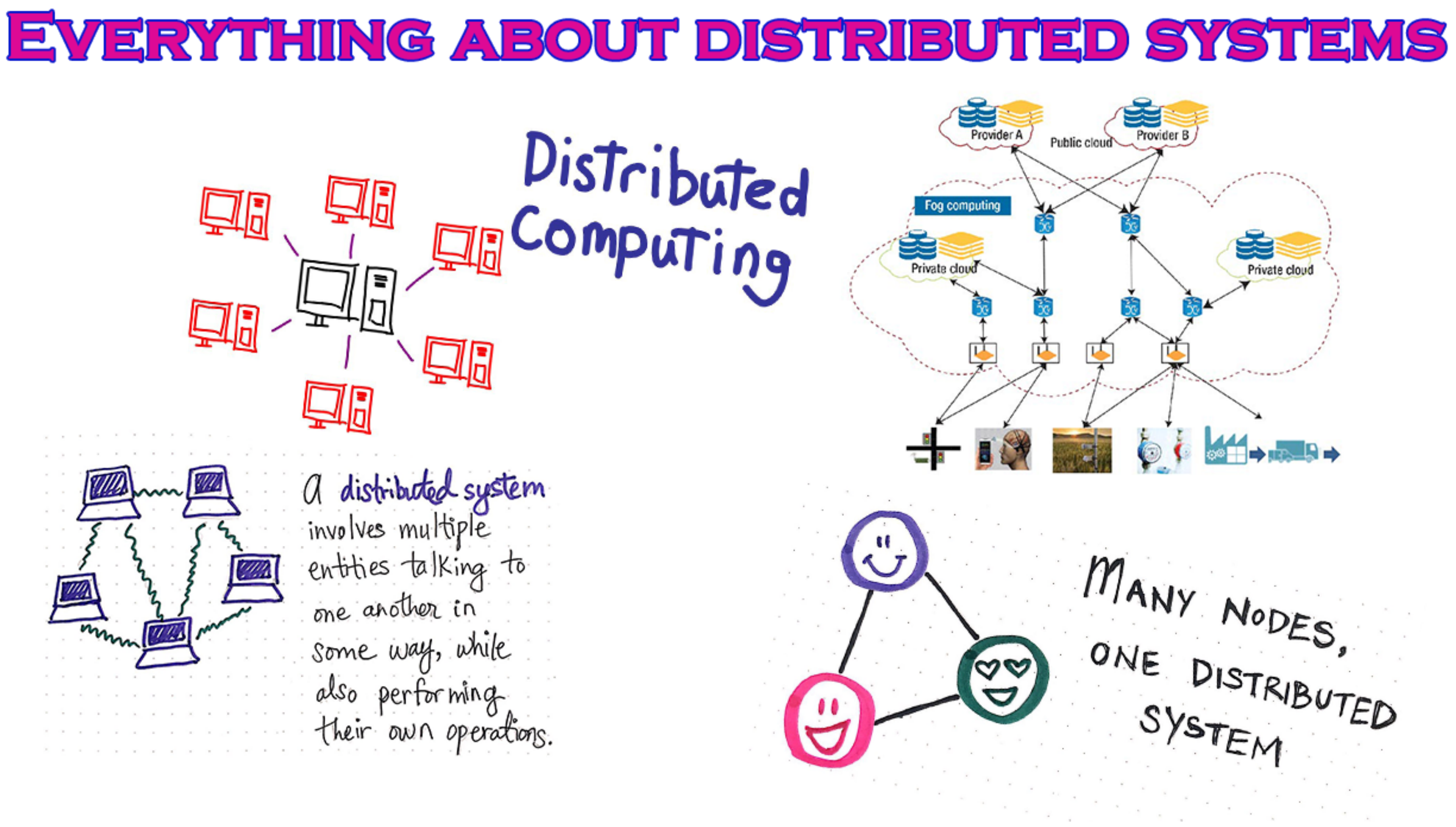
- Design Rationale
- Challenges and Solutions

When communication meets computing

- (IoT) sensing + communication + computing ≈ AI/ML
- Communication/networking is no longer just for communications, but a tool to intelligentize everything!
  - Internet business
  - Internet gaming
  - Intelligent transportation systems or smart mobility
  - Smart and connected health
  - Smart grid
  - Smart city
  - …

Revisit to Distributed Systems

- Distributed systems vs distributed computing



(blog: Nuwan Chamikara, 2019)

Revisit to Distributed Systems

- Technologies
  - Middleware: linking operating systems and apps
  - Grid computing: integrate distributed resources (hardware/software) to share
  - Mobile agents: help end users to search for resources and complete computing
  - P2P (peer-to-peer computing): end users share their resources or contents out: content distribution networks
  - Web service/computing: computing service platforms
    - Hadoop (Apache): MapReduce (mapping tasks and schedule)
    - Spark (Berkeley): resilient distributed dataset or RDD to reduce R&W I/Os
    - Apache Storm (Twitter): stream data processing and computing

Interesting observations

- Grid computing (GC) → cloud computing (CC): fully distributed → centralized
  - ✓ GC: resources on PCs are wasted when not used, GC provides a platform to share them out when idle (kind of crowdsourcing)
  - ✓ CC: systematically customize resources and make them available!
- Cloud computing → Multi-access Edge Computing (MEC): centralized → partially distributed
  - ✓ Crowdsourcing: loosely distributed resources are used opportunistically
  - ✓ MEC: systematically customized "small" resources and distribute them to the premise that can be used conveniently!
  - ✓ MEC/FOG: edge servers/fog nodes are still loosely distributed and used opportunistically

What is the edge?

- “The customer is God!” (East) “The customer is King!” (West): last mile solution → first mile service
  - ✓ Action is where the money is ☺
- Edge is the premise that closer to the action or end users
  - ✓ Communications (C): the proximity of end users
  - ✓ Computing (C): the premise of the actions to be taken
  - ✓ Sensing: the location of source data
  - ✓ Storage (S): buffering space
  - ✓ Intelligence (I): AI/ML tools
- Generally speaking
  - ✓ The spot where the resource (CCSI) is needed for some actions to be taken timely

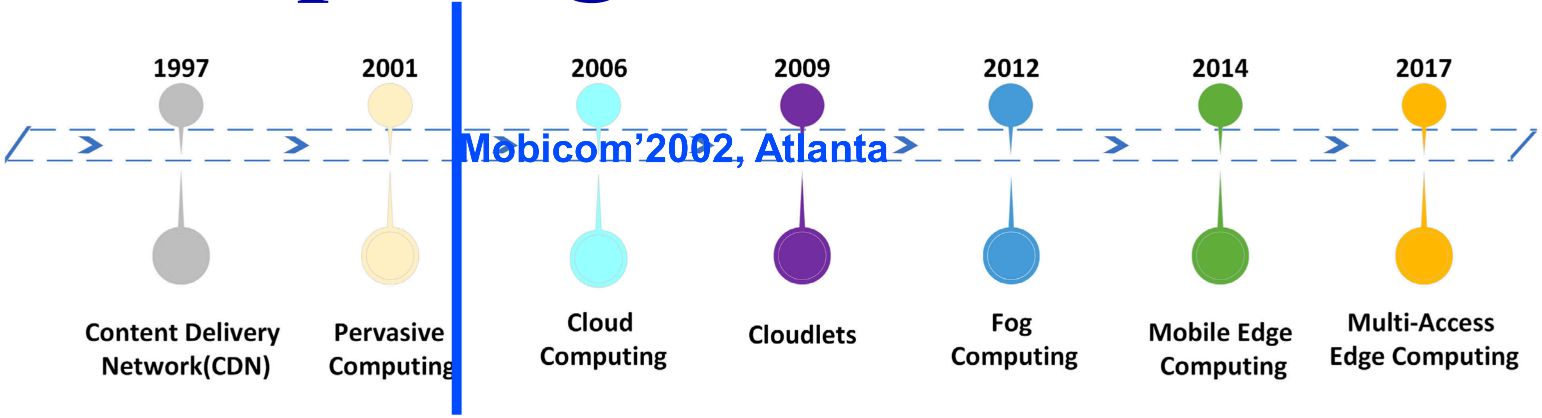
Cloud vs Edge

- Cloud: centralized, located at “remote” specific places (“cool” locations)
  - ✓ Does have much more powerful computing capability, but demands long-haul connection (Internet connection)
  - ✓ Tends to be “congested” at the cloud in both communications and computing
  - ✓ Long latency and high jitter, not suitable for real-time actions
- Edge: “Push” resource closer to where the actions are
  - ✓ Less powerful resource, but enough
  - ✓ Distributed in nature, potentially reducing the long-haul latency
  - ✓ More suitable for real-time actions

Why edge?

- Reinforcing the motivation
  - Latency requirement: IoT apps collect tons of data, which may have to be processed tight on spots and may become useless after a short time
  - Traffic volume: Too much Internet data contain too much useless info, not worth transporting to the cloud for processing
  - Control: timely actions may be needed so the latency for the actions to be taken should be within the limit
  - Security & privacy: S&P may be of serious concern and should be limited to the confine as much as possible
  - Last mile service → first mile service

Edge computing

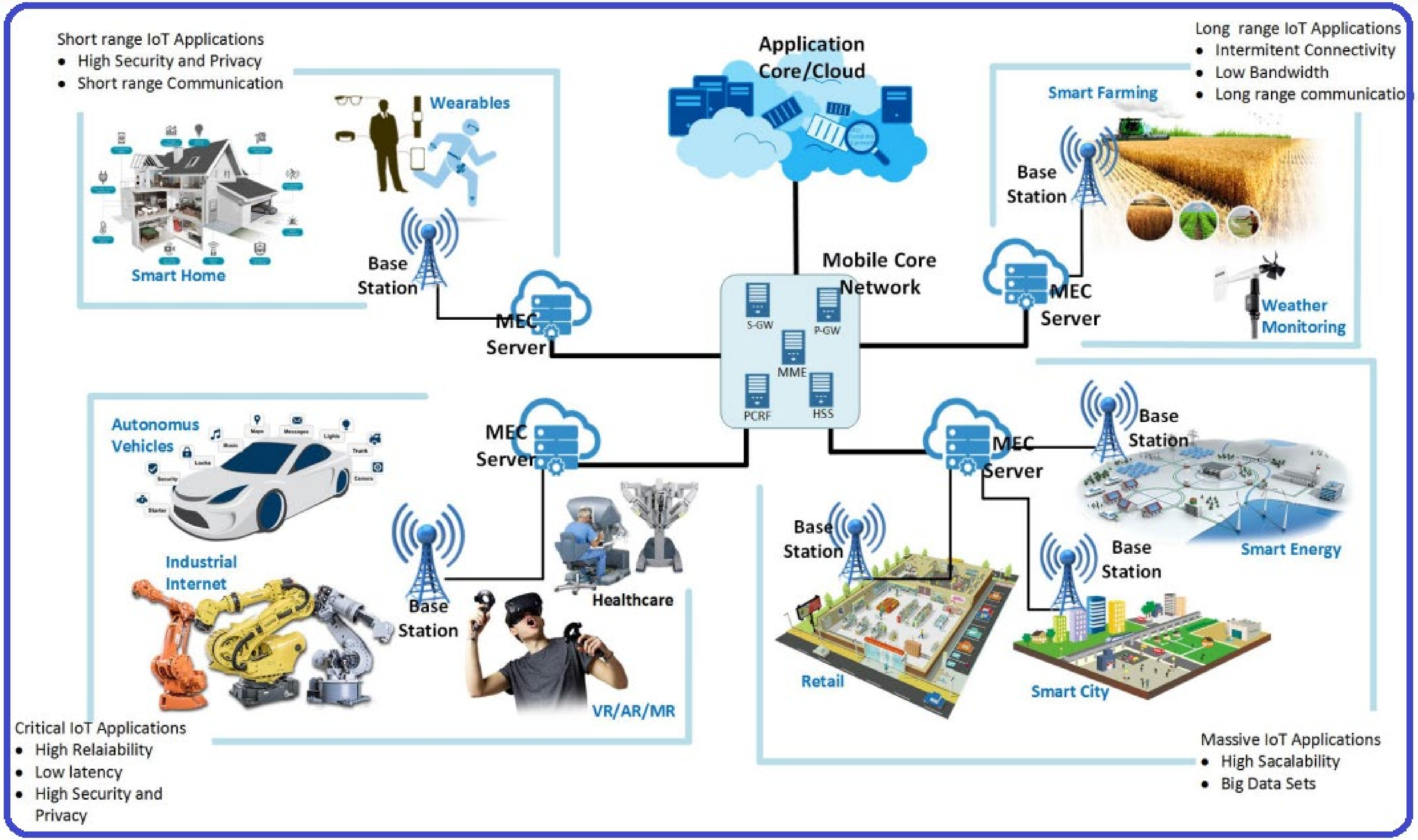


- Peer-to-peer computing/CDN/web caching: earliest concept for content sharing, relying on crowdsourcing
- ACM Mobicom'2002: a paper on grid computing presented → "mobiles help mobiles" ("wireless grid computing"!)
  - ✓ "Integrating Mobile Wireless Devices Into the Computational Grid"
- Cloudlets/mobile cloud computing: mobile devices are self-organized for resource/capability sharing, mostly not relying on infrastructure (mobile ad hoc networks or MANETs)
- Fog computing (CISCO, 2012): edge servers are deployed to interact with end nodes and infrastructure (Internet) networks/cloud, mostly computing "relaying" points (fog nodes)
- Multi-access Edge Computing (MEC) (ETSI, 2017): a general edge computing system connecting end users (people/things/sensors/actuators)

Interesting Applications (1)

- Public safety and security monitoring
  - ✓ Video surveillance camera: analytics on the spot to detect
- Smart mobility and traffic safety (e.g., smart and connected driving)
  - ✓ Collision avoidance, debris warning, congestion control: timely detection
- Smart and connected health
  - ✓ Wearable devices or home monitoring: 24/7 health watch
- Smart manufacturing
  - ✓ Industrial Internet of Things (IIoT), Industrial revolution 4.0: real-time analytics and control
- Smart city: digitalization and intelligentization

Interesting Applications (2)



https://www.linkedin.com/pulse/iot-mobile-edge-computing-mec-5g-network-sudarshan-warale

Problems & Challenges (1)

- MEC placement and management
  - Similar to BS/AP placement, but need to have the coverage of CCSI
  - Collocated with or embedded in BS/AP/Lamppost/RSU
  - Placement at strategic locations for coverage
- Computation offloading
  - Where to offload (other devices, edge, or cloud)
  - How much: partially or wholly offload computing tasks to edge servers
  - Tradeoff and/or optimization among constraints on resources and energy

Problems & Challenges (2)

- Resource provisioning & management
  - ✓ Provisioning and customization of spectrum, computing power, memory/storage
  - ✓ Resource pooling (recruitment of edge servers for specific tasks)
  - ✓ Resource allocation and optimization under constraints
- Energy conservation
  - ✓ End/Mobile devices (Eds/MDs) are mostly battery-powered and need to conserve energy
  - ✓ Balancing the energy consumption in communications and computing (including processing)

Problems & Challenges (3)

- Mobility management and computing migration
  - Mobility management is handling communication service continuation while computing migration is dealing with VM (virtual machine) migration
  - Determine when and where to migrate
  - Need to consider load balancing and latency requirement (QoS)
  - Horizontally migrate (the same admin domain) or vertically migrate (different admin domain), security/privacy policy may be a factor
  - Tradeoff or optimization between relatively remote computing and relatively close interactions (communications)

Wireless landscape

- Wireless is still a fast-growing industry
  - Satellites
    - GEO/MEO/LEO (e.g., failed Iridium)
    - Elon Musk's vision: >3,000 small satellites for SpaceX to provide Internet services
  - Cellular systems: 1G→2G→3G→4G→ 5G→6G…
  - Wireless local area networks
    - 802.11x family
  - ZigBee, Lora (IoT apps)
  - Bluetooth (smart home or smart health)
  - V2X
- Convergence of sensing, communications, computing, storage, and intelligence
  - Wireless sensing, smart and connected health, smart mobility, smart grid, smart city, …
- Wireless future is in your hands!!!