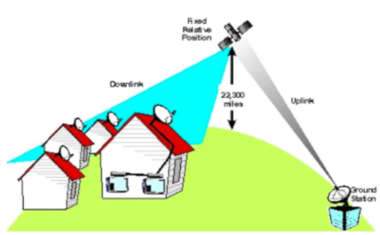
Chapter 1

Introduction to LTE / LTE-A Cellular Systems

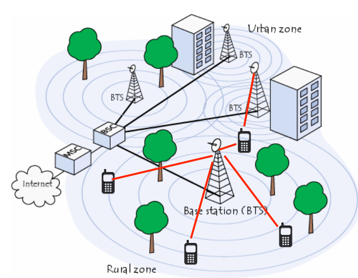
- I. F. Akyildiz, D. M. Gutierrez-Estevez, and E. Chavarria-Reyes, "The Evolution to 4G Cellular Systems: LTE-Advanced," Physical Communications (Elsevier) Journal, 2010.
- D. Tse and P. Viswanath, *Fundamentals of Wireless Communications*, Cambridge University Press.
- Gordon L. Stuber, *Principles of Mobile Communication*, Springer.
- J. Kurose, K. Ross: *Computer Networking: A Top Down Approach.*
- Zhi Sun, Lecture Slides

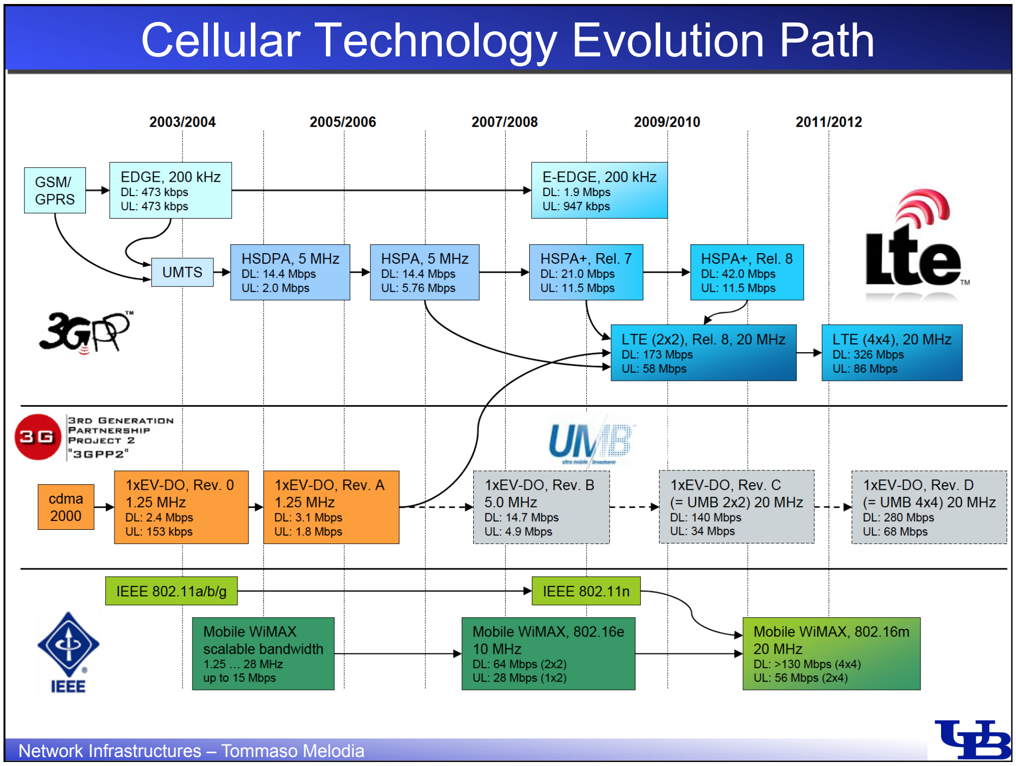
TV System vs Cellular System

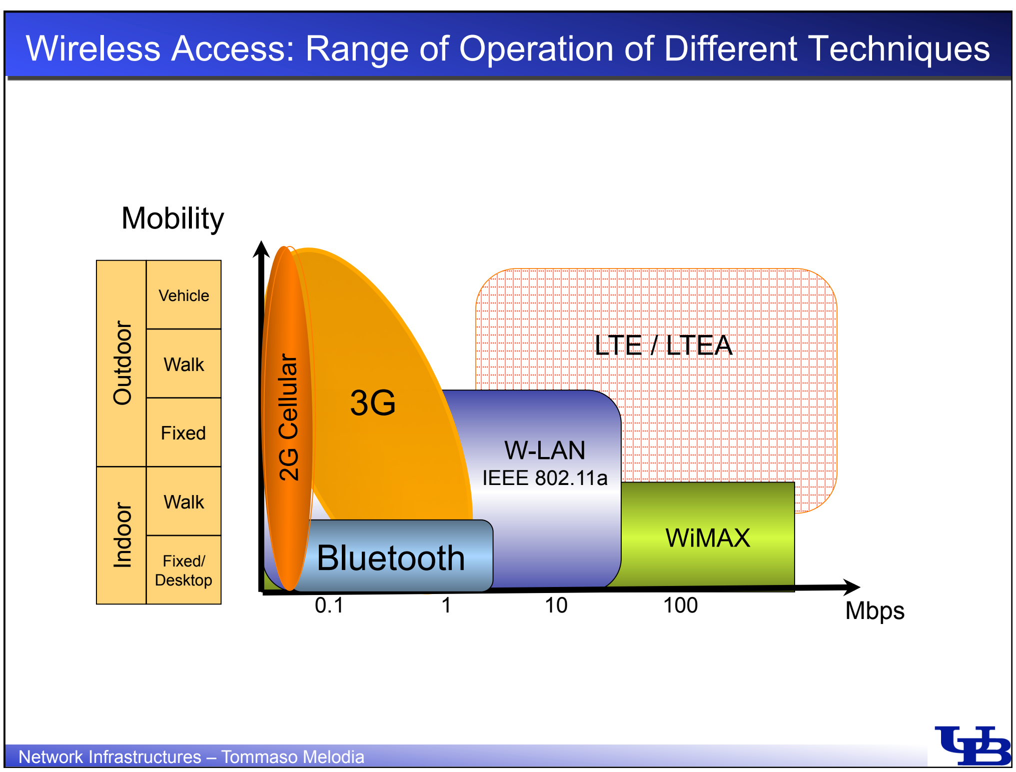
- TV System:
  - 1 to N,
    single direction broadcast
  - Channel access is well defined
  - Less amount of MPEG2 transmission stream
  - Less challenging channel



- Cellular System:
  - N to N,
    double direction transmission
  - Millions of users compete for wireless channel
  - Huge amount of diverse data (Voice, Data, Video, Message…).
  - Worst terrestrial wireless channel




Cellular Technology Evolution Path
2003/2004
2005/2006
2007/2008
2009/2010
2011/2012
GSM/ GPRS
EDGE, 200 kHz DL: 473 kbps UL: 473 kbps
E-EDGE, 200 kHz DL: 1.9 Mbps UL: 947 kbps
UMTS
HSDPA, 5 MHz DL: 14.4 Mbps UL: 2.0 Mbps
HSPA, 5 MHz DL: 14.4 Mbps UL: 5.76 Mbps
HSPA+, Rel. 7 DL: 21.0 Mbps UL: 11.5 Mbps
HSPA+, Rel. 8 DL: 42.0 Mbps UL: 11.5 Mbps
LTE (2x2), Rel. 8, 20 MHz DL: 173 Mbps UL: 58 Mbps
LTE (4x4), 20 MHz DL: 326 Mbps UL: 86 Mbps
3GPP
3G 3rd Generation Partnership Project 2 "3GPP2"
UMB
cdma 2000
1xEV-DO, Rev. 0 1.25 MHz DL: 2.4 Mbps UL: 153 kbps
1xEV-DO, Rev. A 1.25 MHz DL: 3.1 Mbps UL: 1.8 Mbps
1xEV-DO, Rev. B 5.0 MHz DL: 14.7 Mbps UL: 4.9 Mbps
1xEV-DO, Rev. C (= UMB 2x2) 20 MHz DL: 140 Mbps UL: 34 Mbps
1xEV-DO, Rev. D (= UMB 4x4) 20 MHz DL: 280 Mbps UL: 68 Mbps
IEEE 802.11a/b/g
IEEE 802.11n
Mobile WiMAX scalable bandwidth 1.25 … 28 MHz up to 15 Mbps
Mobile WiMAX, 802.16e 10 MHz DL: 64 Mbps (2x2) UL: 28 Mbps (1x2)
Mobile WiMAX, 802.16m 20 MHz DL: >130 Mbps (4x4) UL: 56 Mbps (2x4)
IEEE
Network Infrastructures – Tommaso Melodia


Wireless Access: Range of Operation of Different Techniques
Mobility
Outdoor
Vehicle
Walk
Fixed
Indoor
Walk
Fixed/ Desktop
2G Cellular
3G
LTE / LTEA
W-LAN IEEE 802.11a
WiMAX
Bluetooth
0.1
1
10
100
Mbps
Network Infrastructures – Tommaso Melodia

Contents

- Part1: Fundamentals of Cellular System

Wireless and Mobile Networks

Background:

- # wireless (mobile) phone subscribers now exceeds # wired phone subscribers (5-to-1)!
- # wireless Internet-connected devices equals # wireline Internet-connected devices
  - laptops, Internet-enabled phones promise anytime untethered Internet access
- two important (but different) challenges
  - *wireless:* communication over wireless link
  - *mobility:* handling the mobile user who changes point of attachment to network

Outline

[Wireless]

Wireless links, characteristics
- CDMA

IEEE 802.11 wireless LANs (“Wi-Fi”)

Cellular Internet Access
- architecture
- standards (e.g., GSM)

[Mobility]

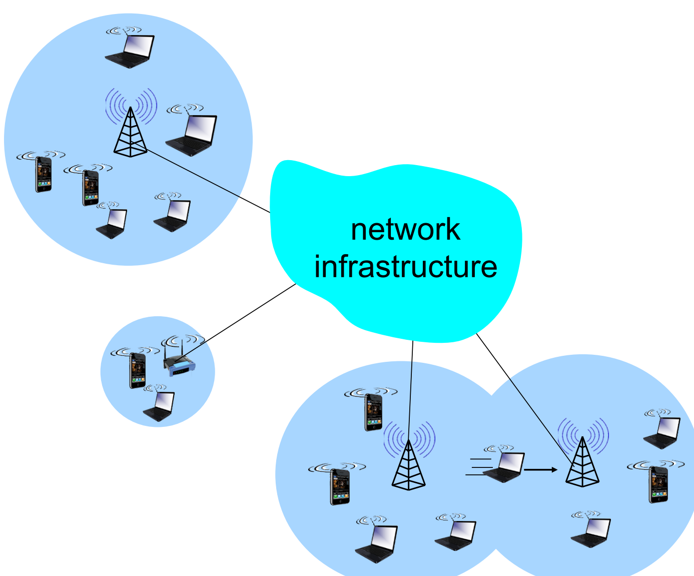
Principles: addressing and routing to mobile users

Mobile IP

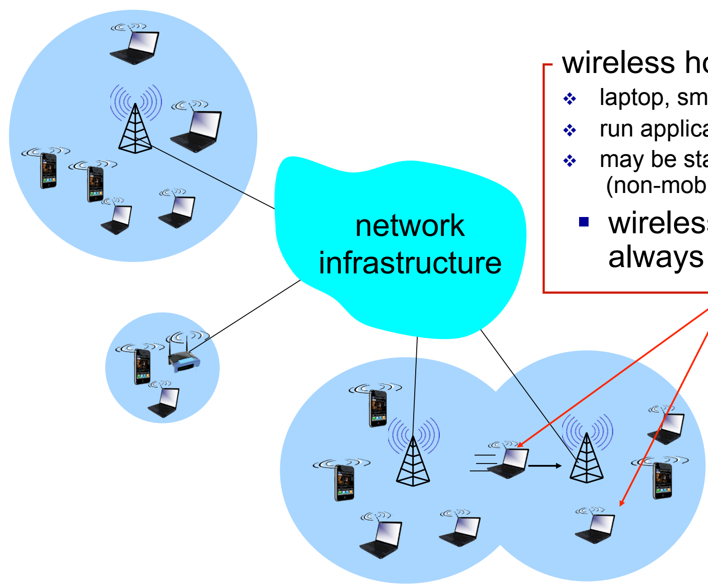
Handling mobility in cellular networks

Mobility and higher-layer protocols

Elements of a wireless network



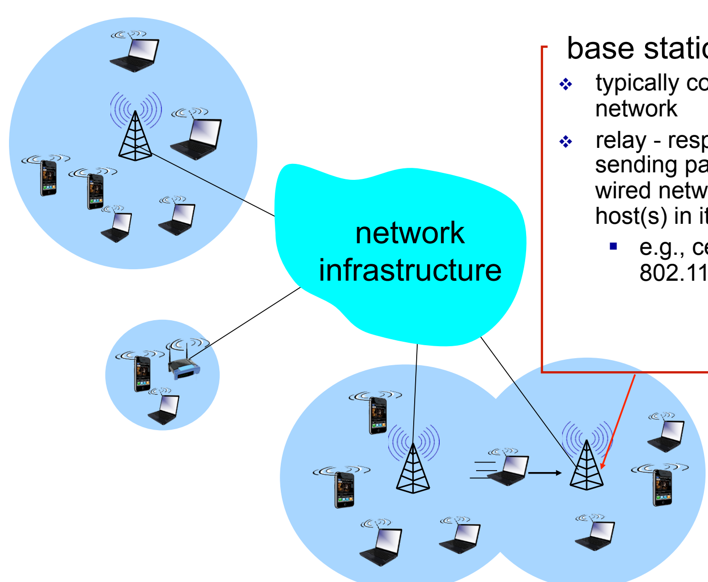
Elements of a wireless network



wireless hosts

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

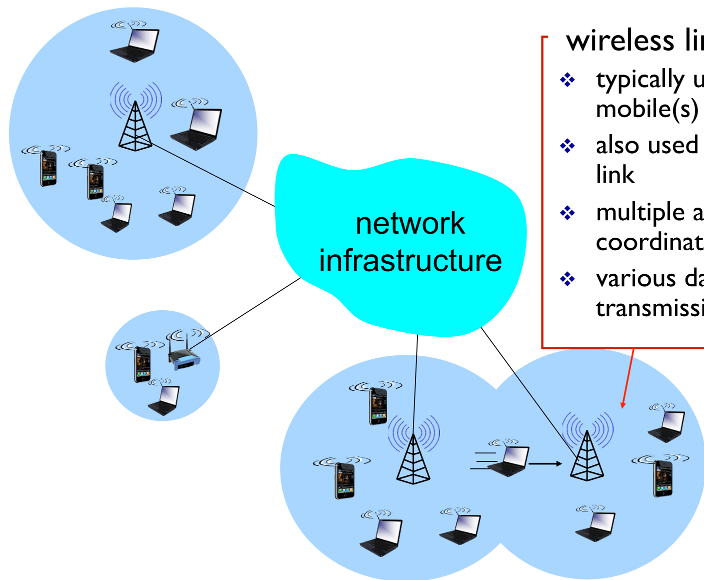
Elements of a wireless network



base station

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

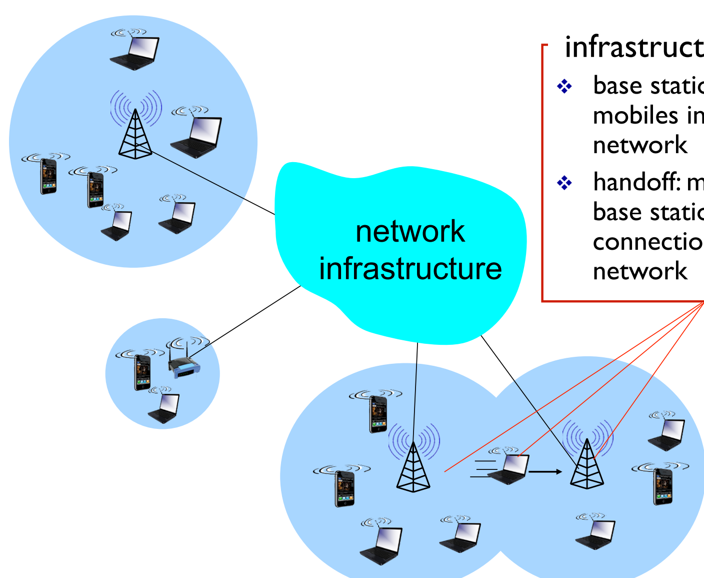
Elements of a wireless network



wireless link

- typically used to connect mobile(s) to base station
- also used as backbone link
- multiple access protocol coordinates link access
- various data rates, transmission distance

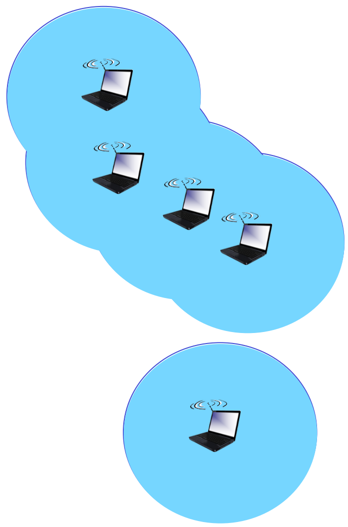
Elements of a wireless network



infrastructure mode

- base station connects mobiles into wired network
- handoff: mobile changes base station providing connection into wired network

Elements of a wireless network



ad hoc mode
- no base stations
- nodes can only transmit to other nodes within link coverage
- nodes organize themselves into a network: route among themselves

Wireless network taxonomy

	single hop	multiple hops
infrastructure (e.g., APs)	host connects to base station (WiFi, WiMAX, cellular) which connects to larger Internet	host may have to relay through several wireless nodes to connect to larger Internet: *mesh net*
no infrastructure	no base station, no connection to larger Internet (Bluetooth, ad hoc nets)	no base station, no connection to larger Internet. May have to relay to reach other a given wireless node MANET, VANET

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Wireless Link Characteristics (1)

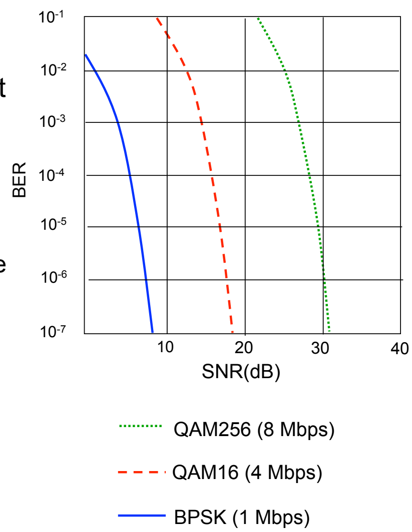
important differences from wired link ….

- *decreased signal strength:* radio signal attenuates as it propagates through matter (path loss)
- *interference from other sources:* standardized wireless network frequencies (e.g., 2.4 GHz) shared by other devices (e.g., phone); devices (motors) interfere as well
- *multipath propagation:* radio signal reflects off objects ground, arriving ad destination at slightly different times

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

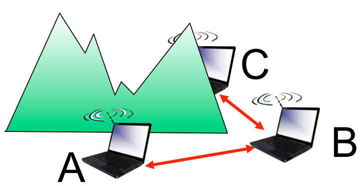
Wireless Link Characteristics (2)

- SNR: signal-to-noise ratio
  - larger SNR – easier to extract signal from noise
- *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: dynamically adapt physical layer (modulation technique, rate)

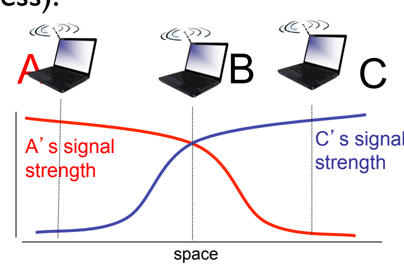


Wireless network characteristics

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



Hidden terminal problem
- B, A hear each other
- B, C hear each other
- A, C can not hear each other means A, C unaware of their interference at B

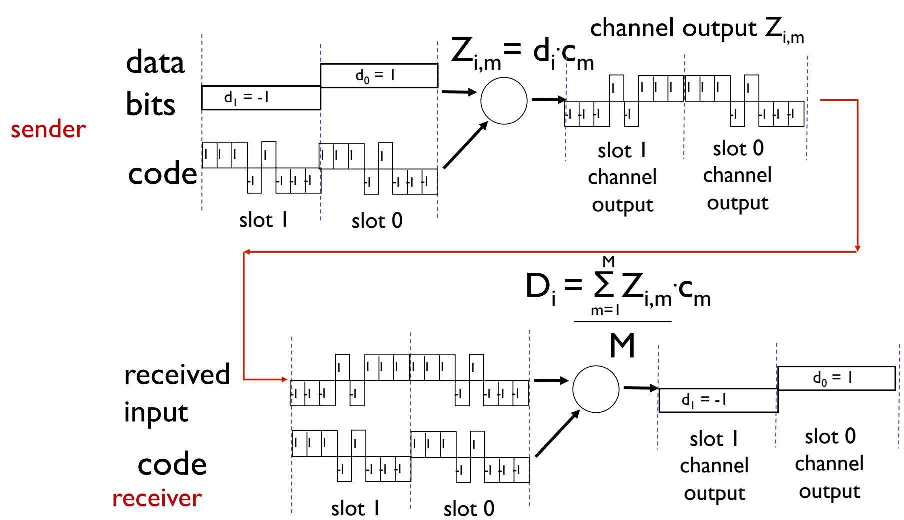


Signal attenuation:
- B, A hear each other
- B, C hear each other
- A, C can not hear each other interfering at B

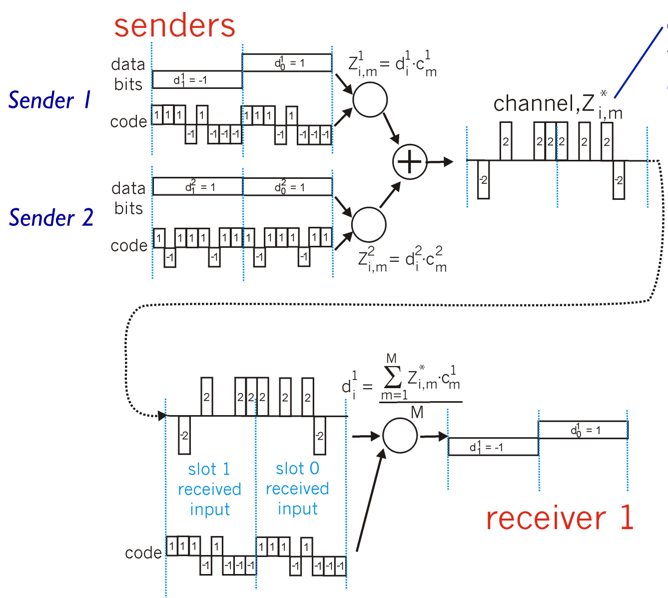
Code Division Multiple Access (CDMA)

- unique "code" assigned to each user; i.e., code set partitioning
  - all users share same frequency, but each user has own "chipping" sequence (i.e., code) to encode data
  - allows multiple users to "coexist" and transmit simultaneously with minimal interference (if codes are "orthogonal")
- *encoded signal* = (original data) X (chipping sequence)
- *decoding:* inner-product of encoded signal and chipping sequence

CDMA encode/decode



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!

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IEEE 802.11 Wireless LAN

802.11b

- 2.4-5 GHz unlicensed spectrum
- up to 11 Mbps
- direct sequence spread spectrum (DSSS) in physical layer
- all hosts use same chipping code

802.11a

- 5-6 GHz range
- up to 54 Mbps

802.11g

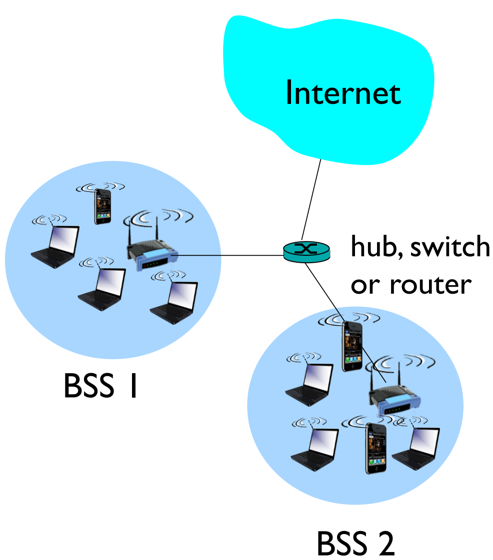
- 2.4-5 GHz range
- up to 54 Mbps

802.11n: multiple antennae

- 2.4-5 GHz range
- up to 200 Mbps

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

802.11 LAN architecture

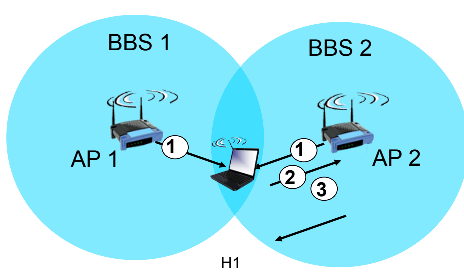


- wireless host communicates with base station
  - base station = access point (AP)
- Basic Service Set (BSS) (aka "cell") in infrastructure mode contains:
  - wireless hosts
  - access point (AP): base station
  - ad hoc mode: hosts only

802.11: Channels, association

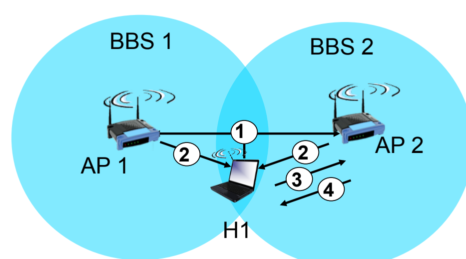
- 802.11b: 2.4GHz-2.485GHz spectrum divided into 11 channels at different frequencies
  - AP admin chooses frequency for AP
  - interference possible: channel can be same as that chosen by neighboring AP!
- host: must *associate* with an AP
  - scans channels, listening for *beacon frames* containing AP's name (SSID) and MAC address
  - selects AP to associate with
  - may perform authentication
  - will 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 from selected AP to H1

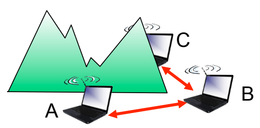


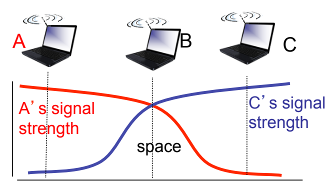
active scanning:

(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

- avoid collisions: 2^+ nodes transmitting at same time
- 802.11: CSMA - sense before transmitting
  - don't collide with ongoing transmission by other node
- 802.11: *no* collision detection!
  - difficult to receive (sense collisions) when transmitting due to weak received signals (fading)
  - can't sense all collisions in any case: hidden terminal, fading
  - goal: *avoid collisions:* CSMA/C(ollision)A(voidance)





IEEE 802.11 MAC Protocol: CSMA/CA

802.11 sender

1 if sense channel idle for **DIFS** then

transmit entire frame (no CD)

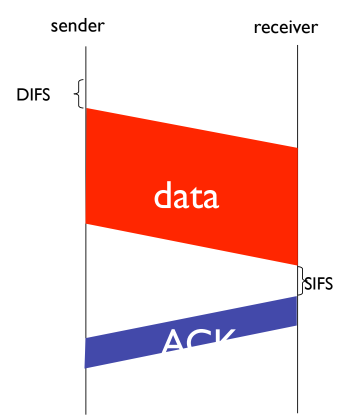
2 if sense channel busy then

start random backoff time

timer counts down while channel idle

transmit when timer expires

if no ACK, increase random backoff interval, repeat 2



802.11 receiver

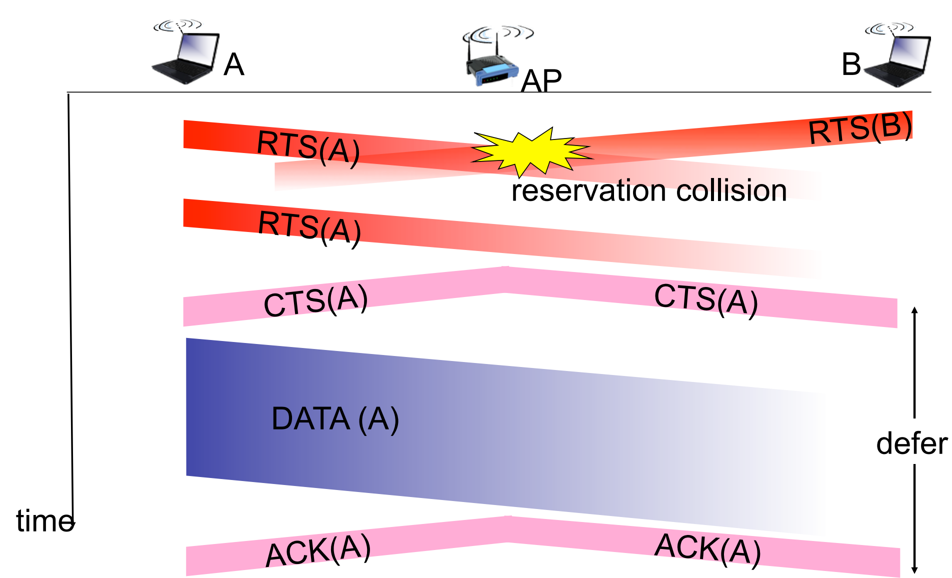
- if frame received OK

return ACK after **SIFS** (ACK needed due to hidden terminal problem) *idea:* allow sender to "reserve" channel rather than random access of data frames: avoid collisions of long data frames

- sender first transmits *small* request-to-send (RTS) packets 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

avoid data frame collisions completely using small reservation packets!

Collision Avoidance: RTS-CTS exchange



802.11 frame: addressing

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

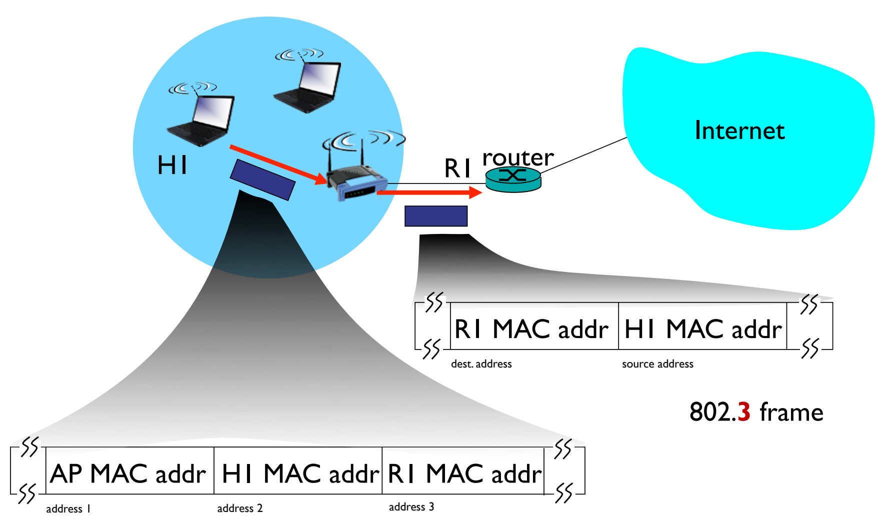
Address 1: MAC address of wireless host or AP to receive this frame

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

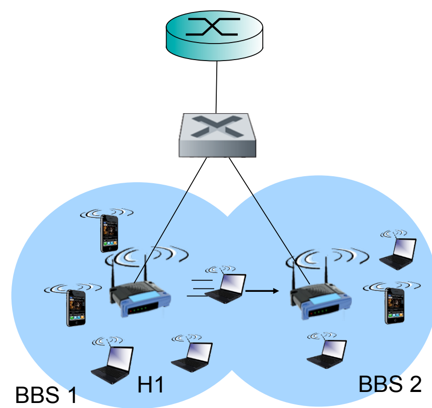
802.11 frame: addressing



802.11 frame

802.11: mobility within same subnet

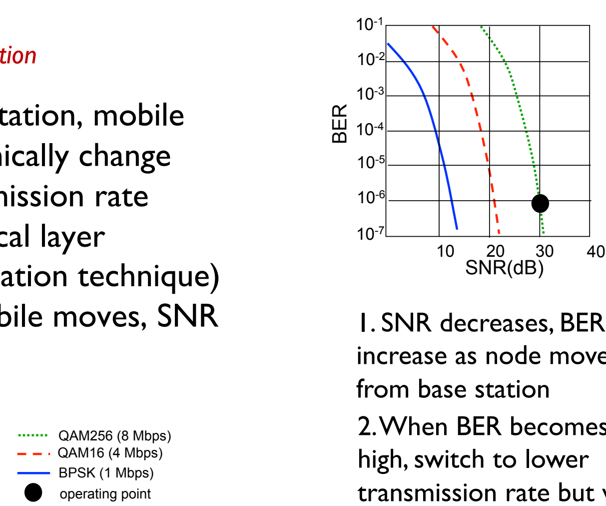
- H1 remains in same IP subnet: IP address can remain same
- switch: which AP is associated with H1?
  - self-learning: switch will see frame from H1 and "remember" which switch port can be used to reach H1



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

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- architecture
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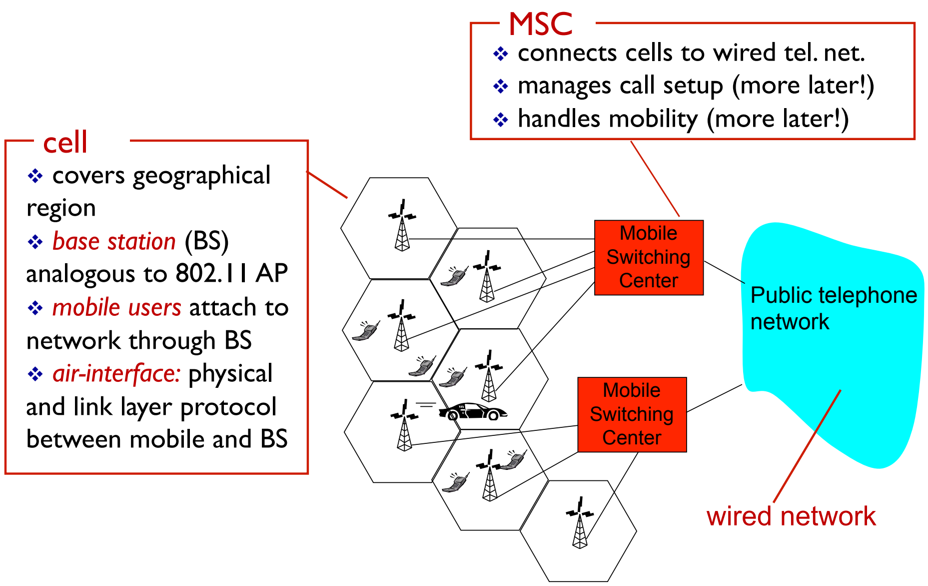
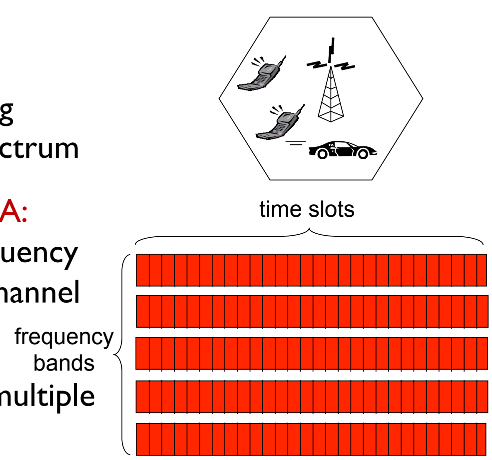
Components of cellular network architecture



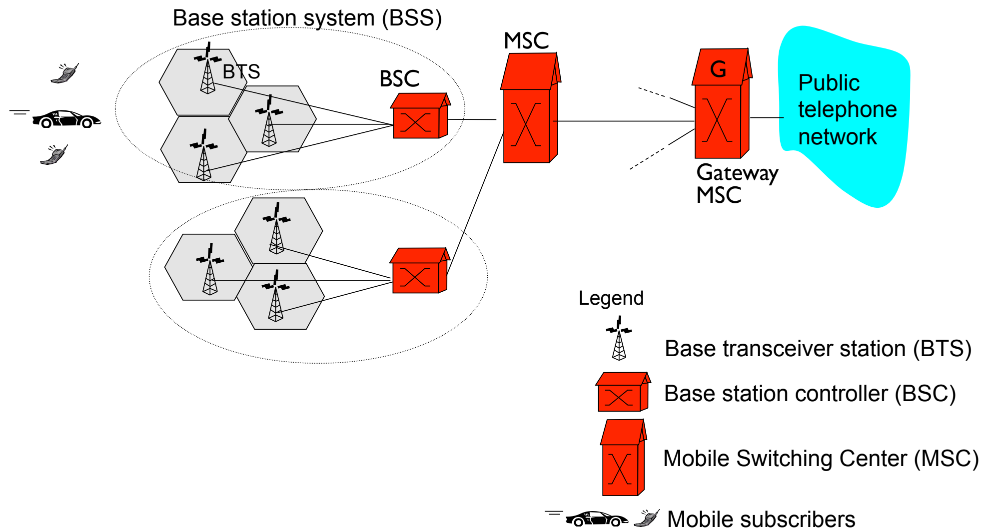
Cellular networks: the first hop

Two techniques for sharing mobile-to-BS radio spectrum

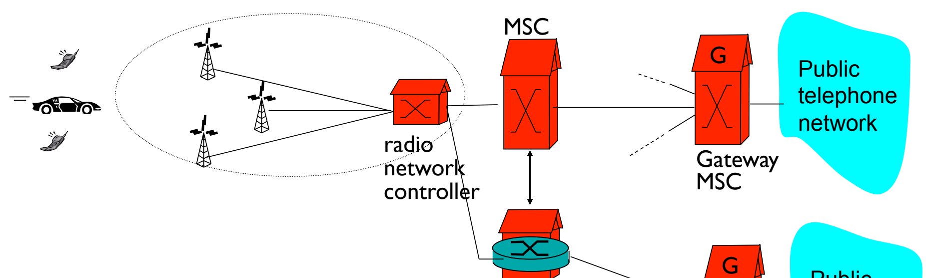
- combined FDMA/TDMA: divide spectrum in frequency channels, divide each channel into time slots
- CDMA: code division multiple access

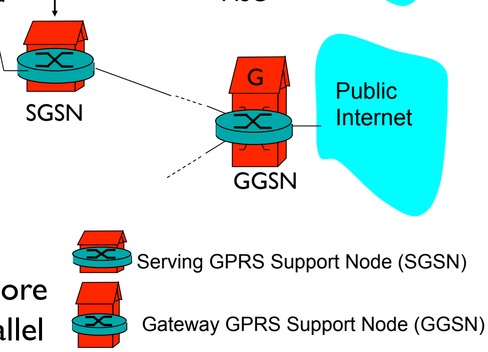


2G (voice) network architecture



3G (voice+data) network architecture

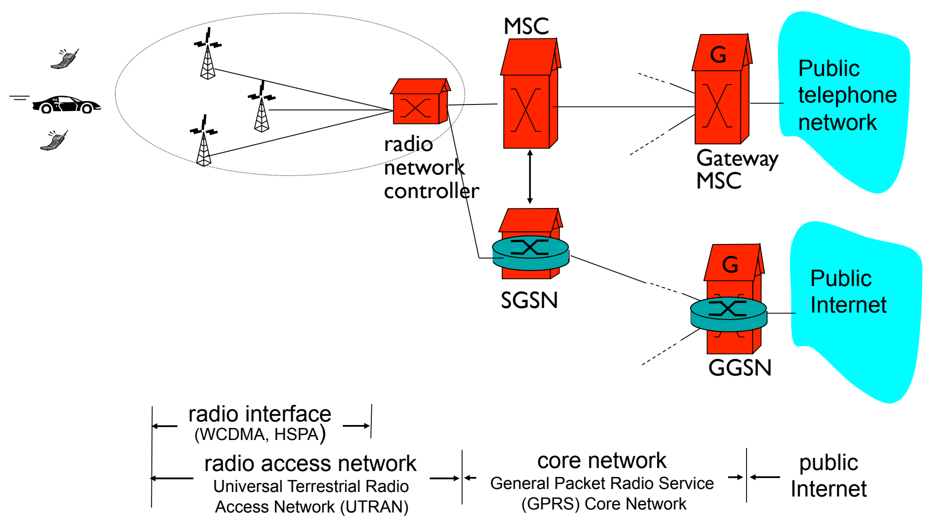




Key insight: new cellular data network operates *in parallel* (except at edge) with existing cellular voice network

- voice network unchanged in core
- data network operates in parallel

3G (voice+data) network architecture



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What is mobility?

- spectrum of mobility, from the *network* perspective:

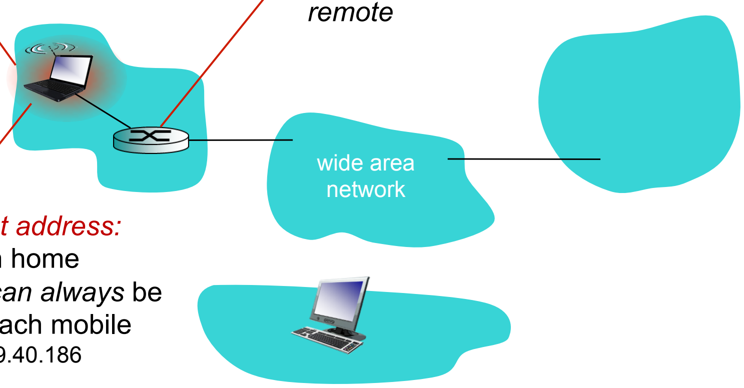
no mobility — high mobility

- mobile wireless user, using same access point
- mobile user, connecting/ disconnecting from network using DHCP
- mobile user, passing through multiple access point while maintaining ongoing connections (like cell phone)

Mobility: vocabulary

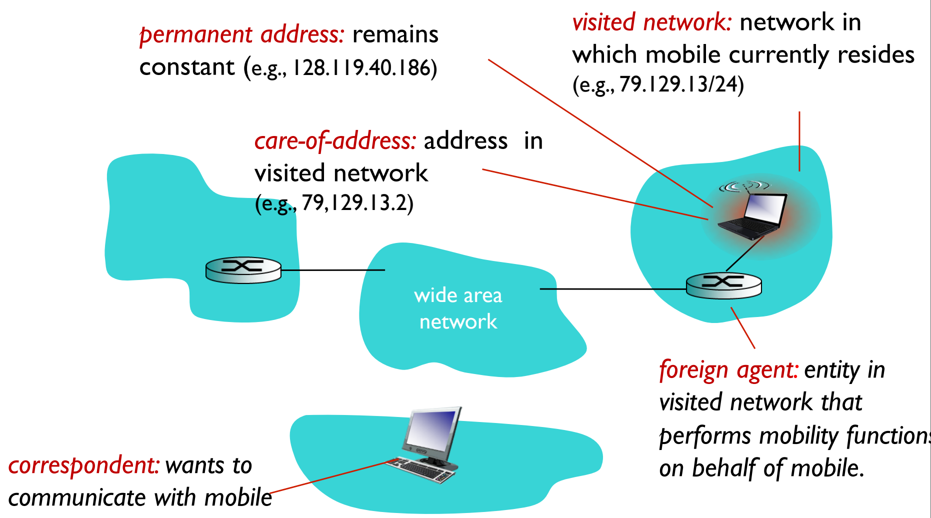
home network: permanent "home" of mobile (e.g., 128.119.40/24)

home agent: entity that will perform mobility functions on behalf of mobile, when mobile is remote



permanent address: address in home network, *can always* be used to reach mobile
e.g., 128.119.40.186

Mobility: more vocabulary



How do *you* contact a mobile friend:

Consider friend frequently changing addresses, how do you find her?

- search all phone books?
- call her parents?
- expect her to let you know where he/she is?

Mobility: approaches

- *let routing handle it:* routers advertise permanent address of mobile-nodes-in-residence via usual routing table exchange
  - routing tables indicate where each mobile located
  - no changes to end-systems
- *let end-systems handle it:*
  - *indirect routing:* communication from correspondent to mobile goes through home agent, then forwarded to remote
  - *direct routing:* correspondent gets foreign address of mobile, sends directly to mobile

Mobility: approaches

- *let routing handle it:* routers advertise permanent address of mobile-nodes-in-residence via usual routing table exchange.
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not scalable to millions of mobiles

- *let end-systems handle it:*
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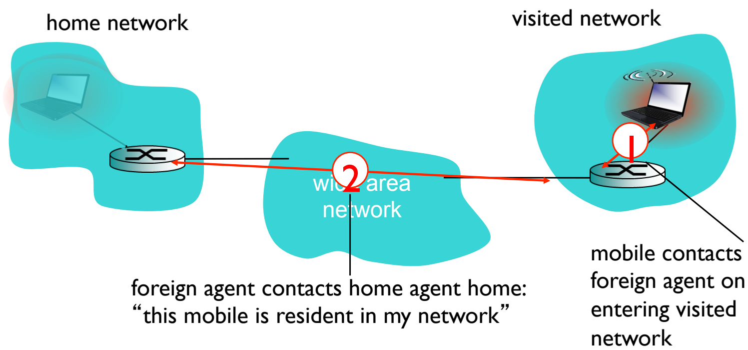
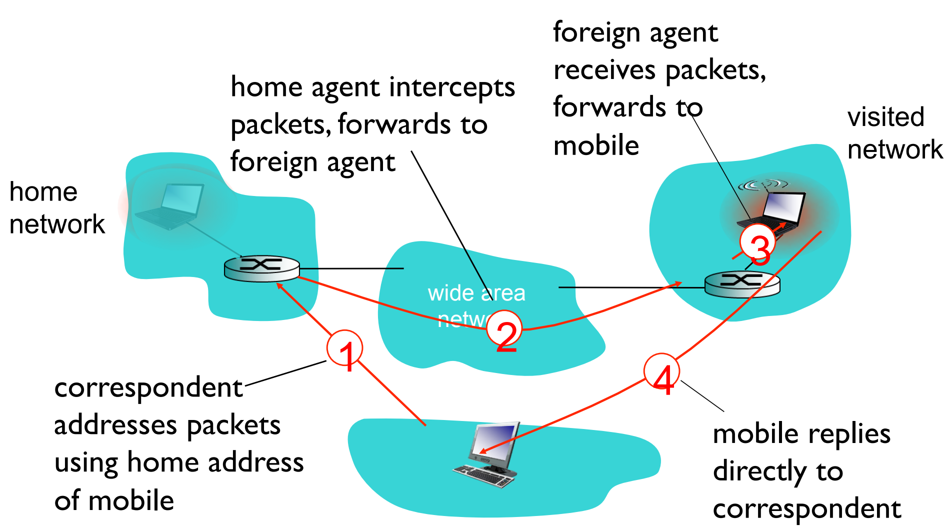
Mobility: registration



end result:

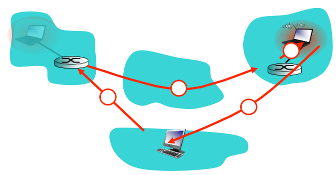
- foreign agent knows about mobile
- home agent knows location of mobile

Mobility via indirect routing



Indirect Routing: comments

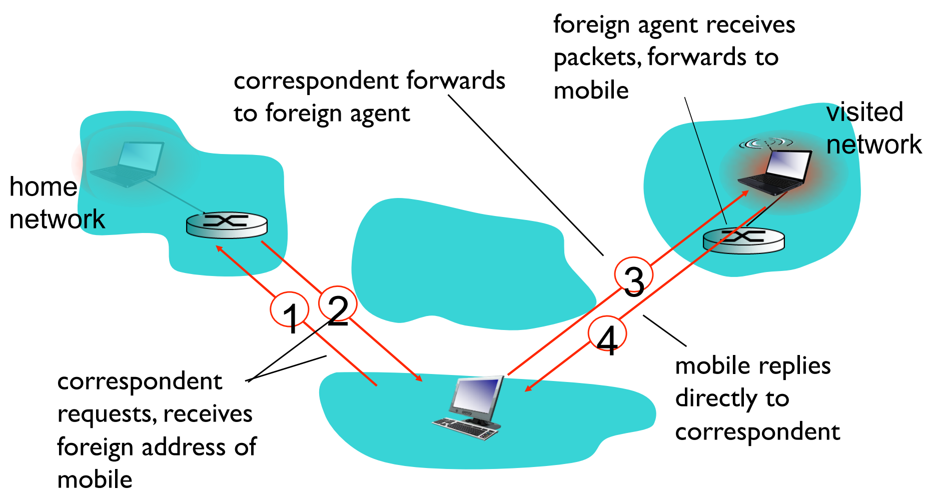
- mobile uses two addresses:
  - permanent address: used by correspondent (hence mobile location is *transparent* to correspondent)
  - care-of-address: used by home agent to forward datagrams to mobile
- foreign agent functions may be done by mobile itself
- triangle routing: correspondent-home-network-mobile
  - inefficient when correspondent, mobile are in same network



Indirect routing: moving between networks

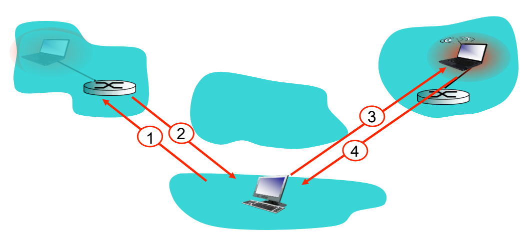
- suppose mobile user moves to another network
  - registers with new foreign agent
  - new foreign agent registers with home agent
  - home agent update care-of-address for mobile
  - packets continue to be forwarded to mobile (but with new care-of-address)
- mobility, changing foreign networks transparent: *on going connections can be maintained!*

Mobility via direct routing



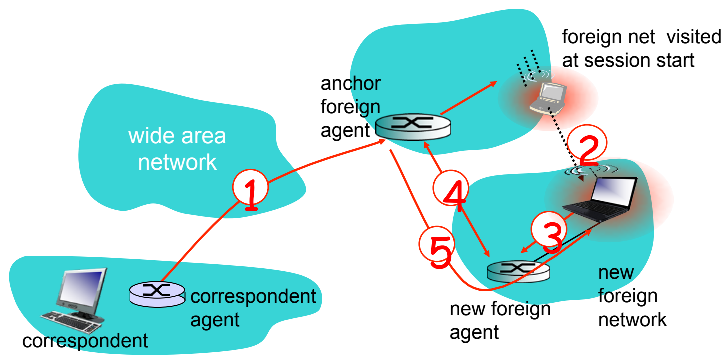
Mobility via direct routing: comments

- overcome triangle routing problem
- *non-transparent to correspondent:* correspondent must get care-of-address from home agent
  - what if mobile changes visited network?



Accommodating mobility with direct routing

- anchor foreign agent: FA in first visited network
- data always routed first to anchor FA
- when mobile moves: new FA arranges to have data forwarded from old FA (chaining)



Outline

Wireless

Wireless links, characteristics

- CDMA

IEEE 802.11 wireless LANs ("Wi-Fi")

Cellular Internet Access

- architecture
- standards (e.g., GSM)

Mobility

Principles: addressing and routing to mobile users

Mobile IP

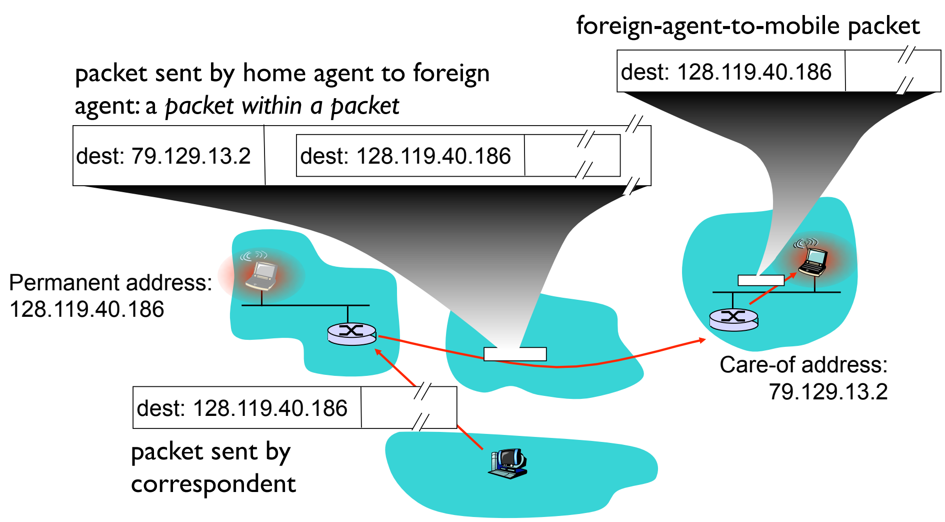
Handling mobility in cellular networks

Mobility and higher-layer protocols

Mobile IP

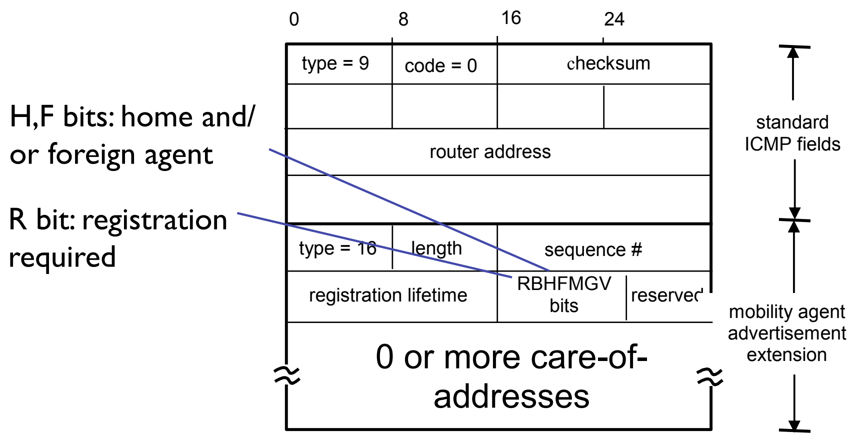
- RFC 3344
- has many features we've seen:
  - home agents, foreign agents, foreign-agent registration, care-of-addresses, encapsulation (packet-within-a-packet)
- three components to standard:
  - indirect routing of datagrams
  - agent discovery
  - registration with home agent

Mobile IP: indirect routing

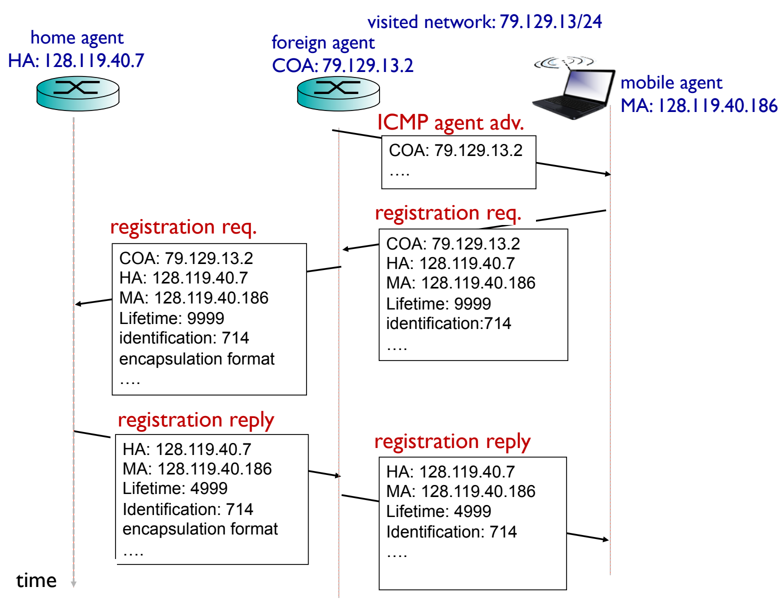


Mobile IP: agent discovery

- *agent advertisement:* foreign/home agents advertise service by broadcasting ICMP messages (typefield = 9)

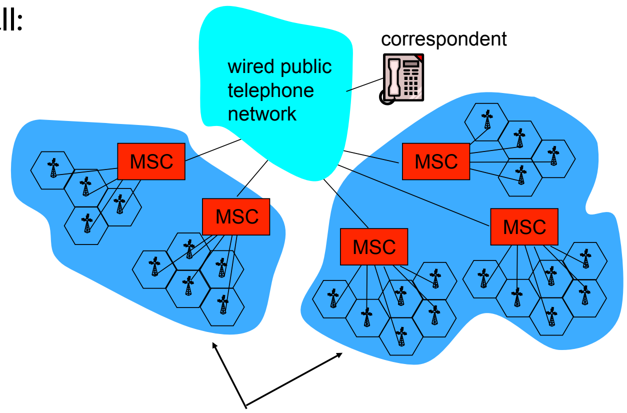


Mobile IP: registration example



Components of cellular network architecture

recall:

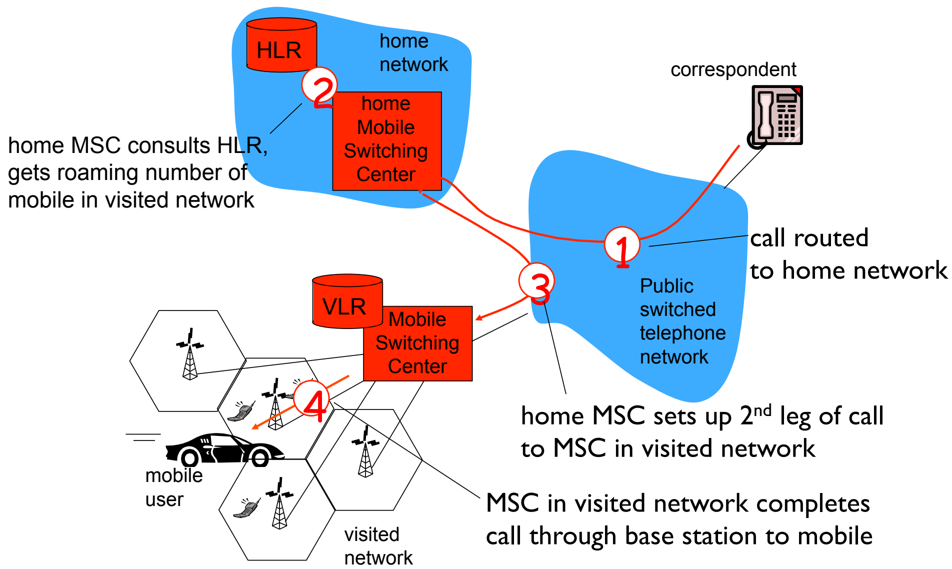


different cellular networks, operated by different providers

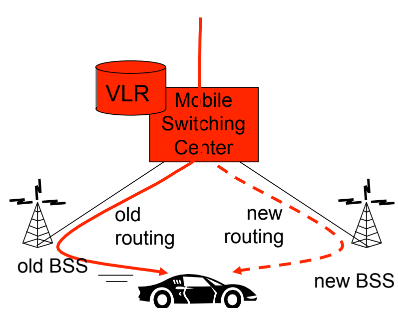
Handling mobility in cellular networks

- *home network:* network of cellular provider you subscribe to (e.g., Sprint PCS, Verizon)
  - *home location register (HLR):* database in home network containing permanent cell phone #, profile information (services, preferences, billing), information about current location (could be in another network)
- *visited network:* network in which mobile currently resides
  - *visitor location register (VLR):* database with entry for each user currently in network
  - could be home network

GSM: indirect routing to mobile

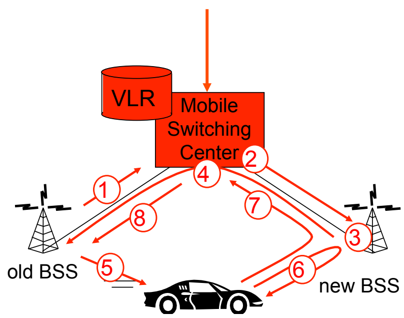


GSM: handoff with common MSC



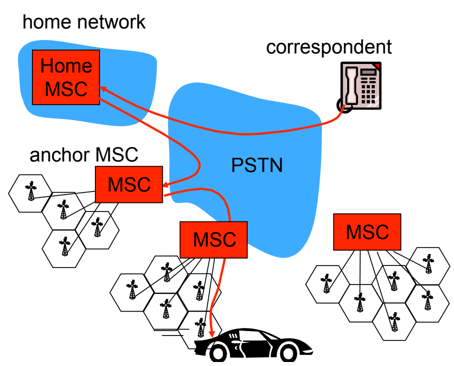
- *handoff goal:* route call via new base station (without interruption)
- reasons for handoff:
  - stronger signal to/from new BSS (continuing connectivity, less battery drain)
  - load balance: free up channel in current BSS
  - GSM doesn't mandate why to perform handoff (policy), only how (mechanism)
- handoff initiated by old BSS

GSM: handoff with common MSC



1. old BSS informs MSC of impending handoff, provides list of 1+ new BSSs
2. MSC sets up path (allocates resources) to new BSS
3. new BSS allocates radio channel for use by mobile
4. new BSS signals MSC, old BSS: ready
5. old BSS tells mobile: perform handoff to new BSS
6. mobile, new BSS signal to activate new channel
7. mobile signals via new BSS to MSC: handoff complete. MSC reroutes call
8 MSC-old-BSS resources released

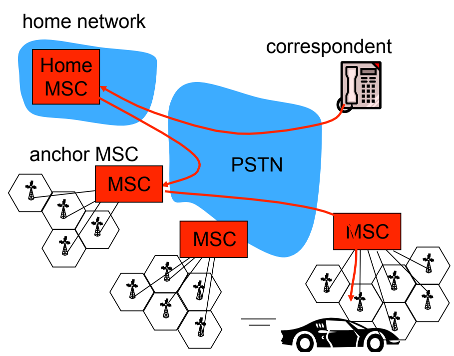
GSM: handoff between MSCs



(a) before handoff

- *anchor MSC:* first MSC visited during call
  - call remains routed through anchor MSC
- new MSCs add on to end of MSC chain as mobile moves to new MSC
- optional path minimization step to shorten multi-MSC chain

GSM: handoff between MSCs



(b) after handoff

- *anchor MSC:* first MSC visited during call
  - call remains routed through anchor MSC
- new MSCs add on to end of MSC chain as mobile moves to new MSC
- optional path minimization step to shorten multi-MSC chain

Mobility: GSM versus Mobile IP

GSM element	Comment on GSM element	Mobile IP element
Home system	Network to which mobile user's permanent phone number belongs	**Home network**
Gateway Mobile Switching Center, or "home MSC". Home Location Register (HLR)	Home MSC: point of contact to obtain routable address of mobile user. HLR: database in home system containing permanent phone number, profile information, current location of mobile user, subscription information	**Home agent**
Visited System	Network other than home system where mobile user is currently residing	**Visited network**
Visited Mobile services Switching Center. Visitor Location Record (VLR)	Visited MSC: responsible for setting up calls to/from mobile nodes in cells associated with MSC. VLR: temporary database entry in visited system, containing subscription information for each visiting mobile user	**Foreign agent**
Mobile Station Roaming Number (MSRN), or "roaming number"	Routable address for telephone call segment between home MSC and visited MSC, visible to neither the mobile nor the correspondent.	**Care-of-address**

Wireless, mobility: impact on higher layer protocols

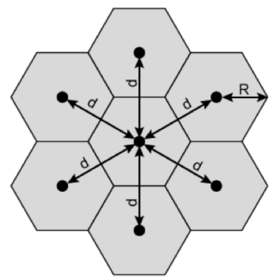
- logically, impact *should* be minimal …
  - best effort service model remains unchanged
  - TCP and UDP can (and do) run over wireless, mobile
- … but performance-wise:
  - packet loss/delay due to bit-errors (discarded packets, delays for link-layer retransmissions), and handoff
  - TCP interprets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

Cellular Network Organization

- Area divided into cells
  - Around 10 square miles
  - Each with own antenna
  - Each with own range of frequencies
  - Served by base station
    - Transmitter, receiver, control unit
  - Adjacent cells on different frequencies to avoid cochannel interference

Shape of Cells

- Ideally, a cell could be represented by a circular cell with a radius R from the center of a BS
- Hexagonal cells
  - Provides full coverage
  - Radius defined as radius of circum-circle
    - Distance from center to vertex equals length of side
  - Distance between centers of cells radius R is $\sqrt{3}\,R$
  - Not always precise hexagons
    - Topographical limitations
    - Local signal propagation conditions
    - Location of antennas

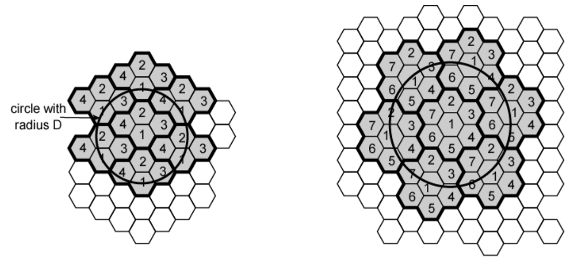


Frequency Reuse

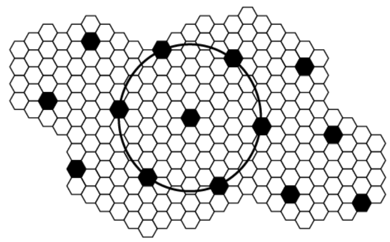
- By power control at the Base Station:
  - Allow communications within cell on given frequency
  - Limit interefering power to adjacent cells
  - Allow re-use of frequencies in nearby cells
  - Use same frequency for multiple transmissions

  e.g.
  - N cells sharing full set of frequencies
  - K total number of frequencies used in systems
  - Each cell has K/N frequencies

Frequency Reuse



(a) Frequency reuse pattern for N = 4 (b) Frequency reuse pattern for N = 7



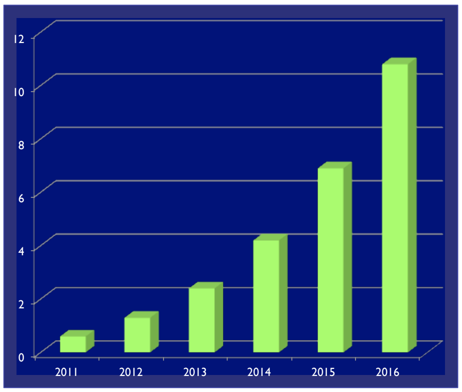
(c) Black cells indicate a frequency reuse for N = 19

Contents

- Part 2: LTE and LTE Advanced
  - Key Technologies in LTE
  - Key Technologies in LTEA

Prediction of Future Wireless Traffic

Exabytes per month



Source: Cisco VNI Mobile 2012

3GPP Subscriptions (millions)

Source: Informa Telecoms & Media Forecast

Requirements

Explosion of Users' Demand for Mobile Data

Many new Services and Applications

Ubiquitous Wireless Broadband Access to a Very Large Cloud Platform

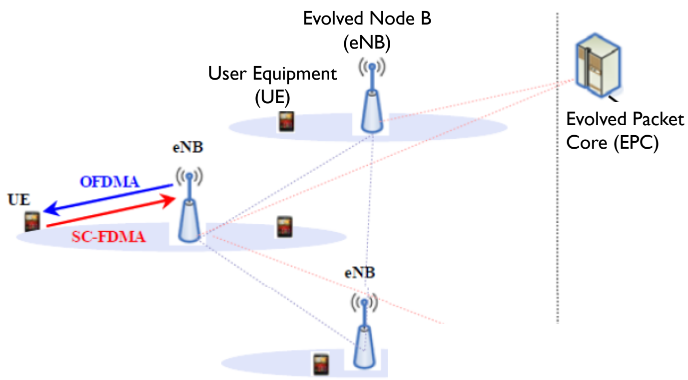
Why LTE?

- Further demand for higher data rates
- How to achieve these?
  - Using features like adaptive modulation and coding, HARQ (Hybrid ARQ), etc.
  - Using higher bandwidths, but flexible and scalable, only possible by using another transmission scheme
  - Using MIMO and smart antennas

LTE Key Parameters

Frequency Range	**UMTS FDD bands and UMTS TDD bands**						
Channel bandwidth 1 Resource Block (RB) =180 kHz	**1.4 MHz**	**3 MHz**	**5 MHz**	**10 MHz**	**15 MHz**	**20 MHz**	
	6 RB	15 RB	25 RB	50 RB	75 RB	100 RB	
Modulation Schemes	**Downlink**	QPSK, 16QAM, 64QAM					
	Uplink	QPSK, 16QAM, 64QAM (⇨ optional for handset)					
Multiple Access	**Downlink**	OFDMA (Orthogonal Frequency Division Multiple Access)					
	Uplink	SC-FDMA (Single Carrier Frequency Division Multiple Access)					
MIMO technology	**Downlink**	Wide choice of MIMO configuration options for transmit diversity, spatial multiplexing, and cyclic delay diversity (max. 4 antennas at base station and handset)					
	Uplink	Multi-user collaborative MIMO					
Peak Data Rate	**Downlink**	150 Mbps (UE category 4, 2x2 MIMO, 20 MHz) 300 Mbps (UE category 5, 4x4 MIMO, 20 MHz)					
	Uplink	75 Mbps (20 MHz)					

Basic Architecture of LTE

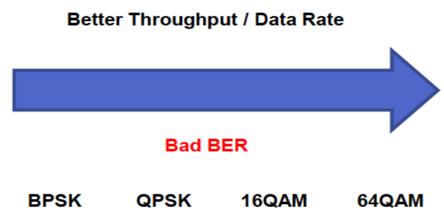


Contents

- Key Technologies in LTE
  - Adaptive Modulation and Coding (AMC)
  - Hybrid ARQ (HARQ)
  - Spectrum flexibility: OFDMA and SC-FDMA
  - MIMO Transmission
- Key Technologies in LTEA

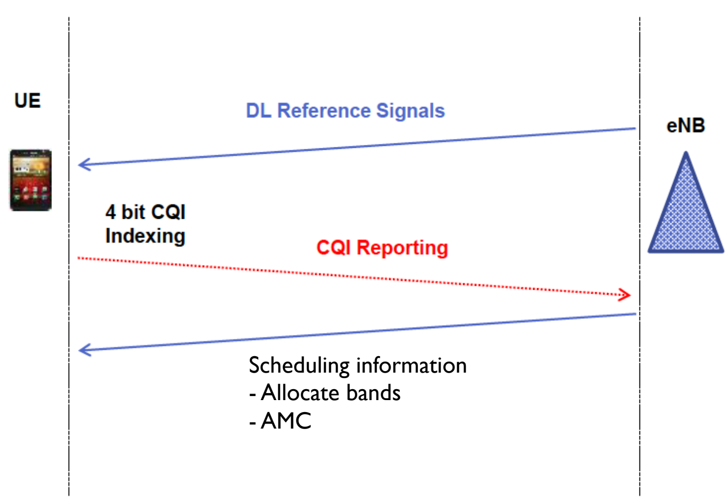
Adaptive Modulation & Coding (AMC)

- Modulation without coding:

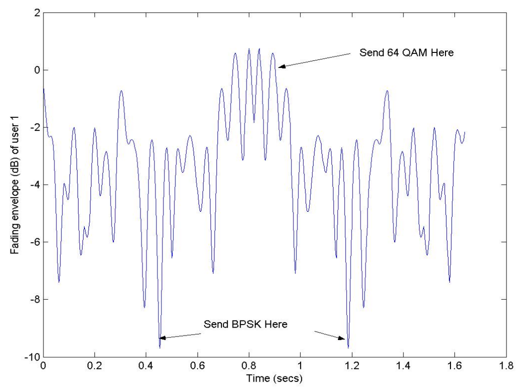


- Channel coding: better BER but lower data rate
- By using channel Channel Quality Indication (CQI), the transmitter can adaptively determine the modulation and coding schemes
  - Tradeoff between better BER and higher data rate

Channel Quality Indication (CQI)



Adaptive Modulation

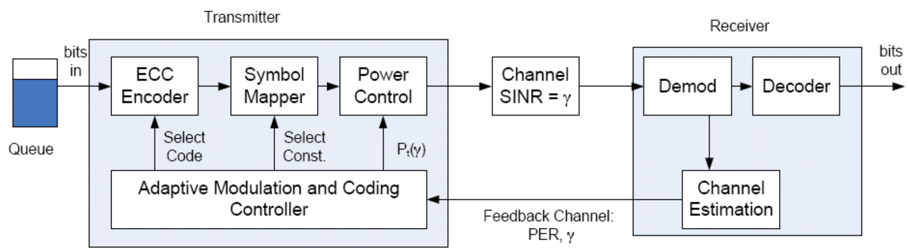


Vary the “M” in the MQAM constellation to the appropriate SNR.

Adaptive modulation & coding: Multi-User

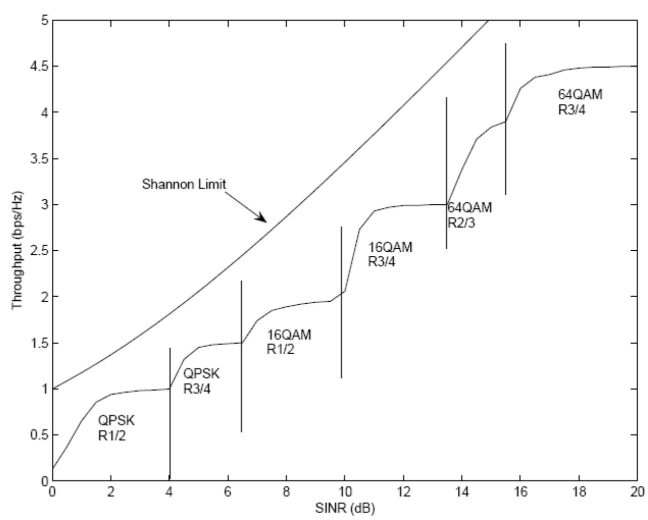
- Exploit *multi-user* diversity
  - Users with **high SNR**: use MQAM (large M) + high code rates
  - Users with **low SNR:** use BPSK + low code rates (i.e. heavy error protection)
- In LTE, different users (assigned to time-frequency slots within a frame) would be getting a different rate
  - i.e., be using different code/modulation combos..

Adaptive Modulation & Coding (AMC)



- Lower data rates are achieved by using a small constellation – such as QPSK – and low rate error correcting codes such as rate 1/2 convolutional or turbo codes.
- The higher data rates are achieved with large constellations – such as 64QAM – and less robust error correcting codes, for example rate 3/4 convolutional, turbo, or LDPC codes.

AMC vs Shannon Limit



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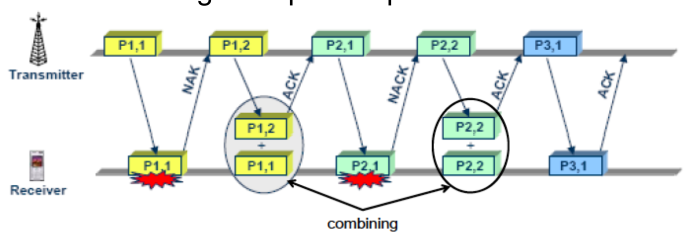
Hybrid Automatic Repeat Request (HARQ)

- What happens when there are error packets received on UE or eNB? – HARQ
- Combination of FEC and ARQ:
  - FEC: correct a subset of errors
  - ARQ: if still error detected
- Works at PHY layer but controlled by MAC layer
- If the received data has an error then the Receiver buffers the data and requests a re-transmission from the sender

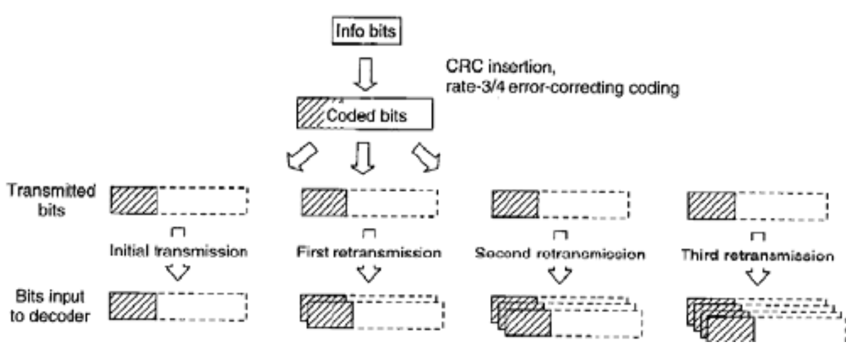
HARQ

- When the receiver receives the re-transmitted data, it then combines it with buffered data prior to channel decoding and error detection
- This helps the performance of the re-transmissions
- Hybrid ARQ with soft combining:
  - Erroneously received packet stored in a buffer memory
  - Later combined with the retransmission
  - Soft-combining -> improved performance



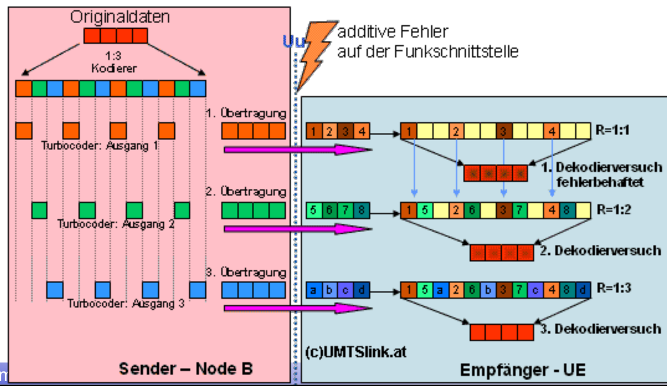
HARQ

- Chase Combining
  - Retransmission of the same set of data, i.e., additional repetition coding
  - Maximum-ratio combining: (re-transmission diversity)
  - Accumulated increasing SNR



HARQ

- Incremental Redundancy
  - Multiple sets of the information.
  - Retransmission of a different set.
  - Combine to recover the same information.



HARQ Process in LTE

- In LTE, there are 8 HARQ processes
- Once a process sends a packet, it waits for an ACK/ NACK
- Till it receives ACK/NACK, the process will be in-active state and will not process other packets
- This significantly increases the round trip time and does impact throughput
- Therefore, multiple HARQ processes are used

HARQ Process in LTE

- When the 1st process is waiting for an ACK, the 2nd process will send data and so on with the eight processes
- MAC layer manages these HARQ processes
- Data is removed when:
  - ACK is received
  - Max number of re-transmission has been reached

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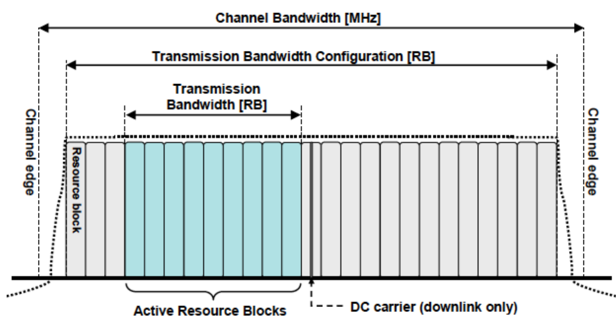
Spectrum flexibility: OFDMA and SC-FDMA

- LTE physical layer supports any bandwidth from 1.4 to 20 MHz.
- Current LTE specification supports a subset of 6 different system bandwidths

Channel bandwidth $BW_{Channel}$ [MHz]	1.4	3	5	10	15	20
Number of resource blocks	6	15	25	50	75	100

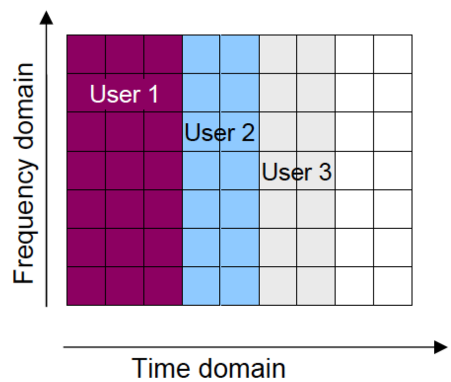


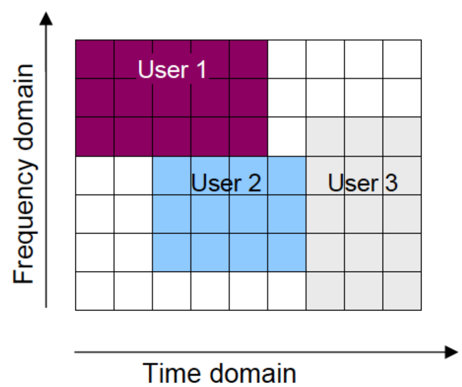
Spectrum flexibility: OFDMA and SC-FDMA

- In LTE, the uplink (from UE to eNB) uses SC-FDMA (Single Carrier Frequency Division Multiple Access)
- The downlink (from eNB to UE) uses OFDMA (Orthogonal Frequency Division Multiple Access)

OFDMA in Downlink

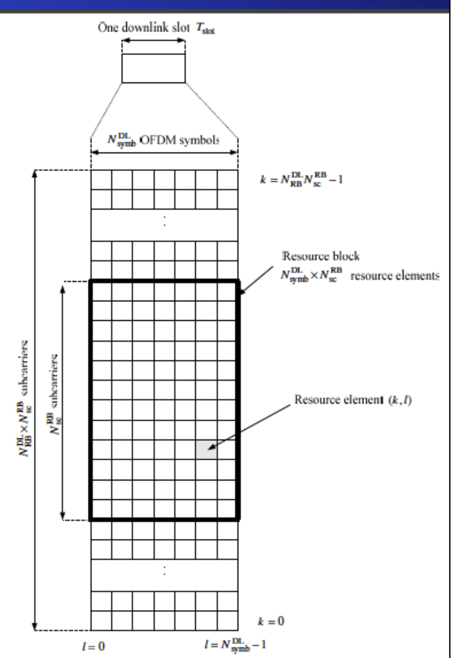
- Comparison between OFDMA and OFDM:
  - OFDM allocates user just in time domain
  - OFDMA allocates user in time and frequency domain





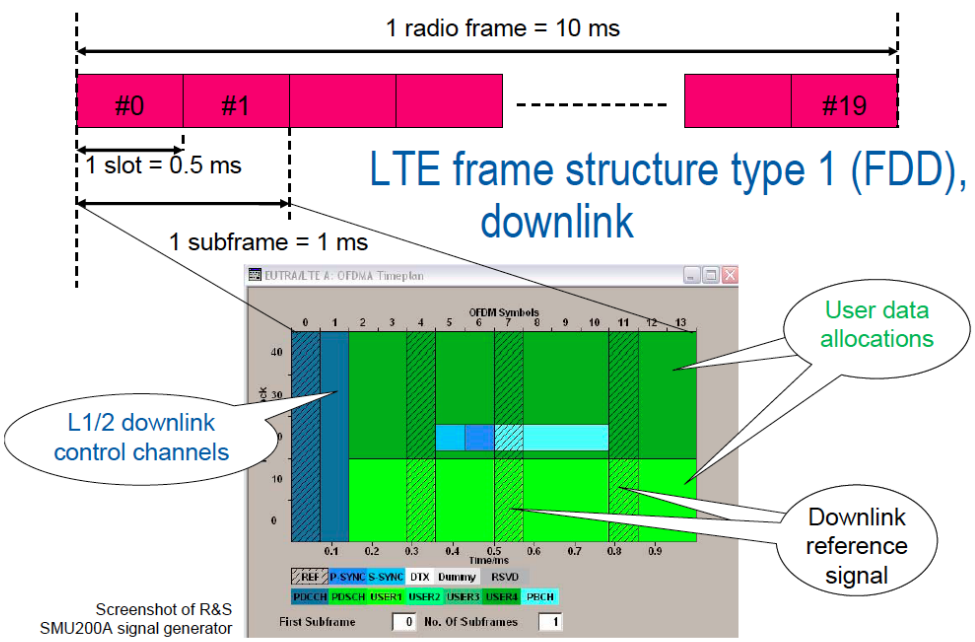
Resource Allocation

- Smallest resource unit is Resource Element: 1 symbol on 1 subcarrier
  - Uniquely identified by the index pair (k,l) in a slot
- But minimum allocation for transmission is a Resource Block (RB)
- 1 RB spans 12 sub-carriers (12*15 kHz =180 kHz) in the frequency domain and 1 Time Slot (= 0.5 ms) in the time domain

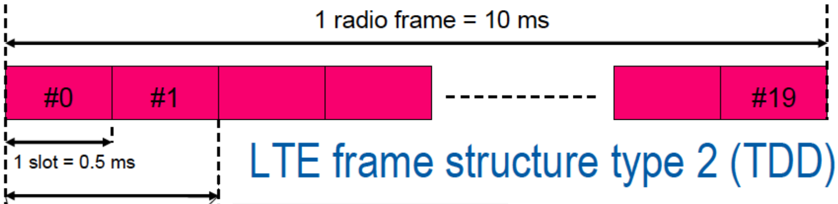


- 10 MHz = 50 RB ->
  50 RB*180 kHz = 9.0 MHz +1 unused DC subcarrier
  = 9.015 MHz
- 1 subframe has 2 time slots.
- With normal (extended) cyclic prefix (CP) we got 7 (6) OFDM symbols per time slot

LTE frame structure type 1 (FDD), downlink



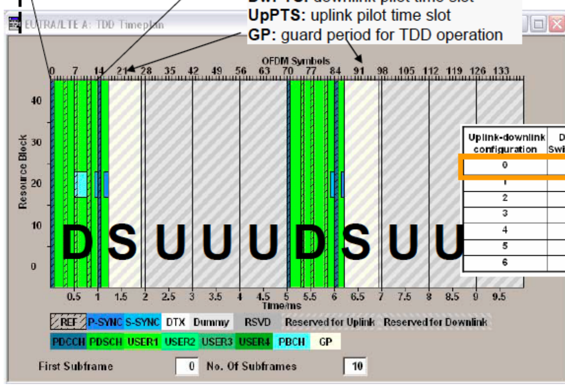
Screenshot of R&S SMU200A signal generator



LTE frame structure type 2 (TDD)

Special subframes containing:

DwPTS: downlink pilot time slot
UpPTS: uplink pilot time slot
GP: guard period for TDD operation

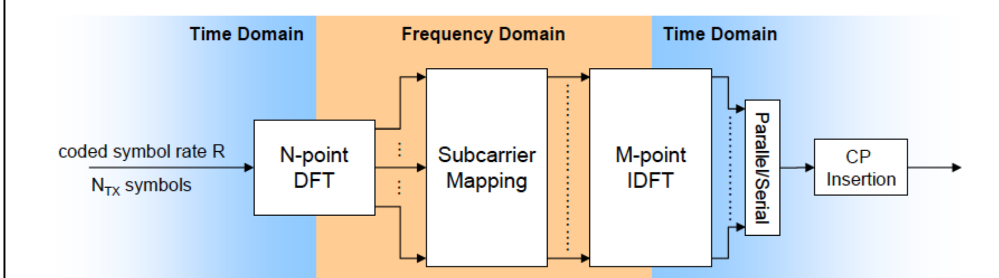


Possible uplink-downlink configurations (D=Downlink, U=Uplink, S=Special Subframe):

Uplink-downlink configuration	Downlink-to-Uplink Switch-point periodicity	Subframe number									
		0	1	2	3	4	5	6	7	8	9
0	5 ms	D	S	U	U	U	D	S	U	U	U
1	5 ms	D	S	U	U	D	D	S	U	U	D
2	5 ms	D	S	U	D	D	D	S	U	D	D
3	10 ms	D	S	U	U	U	D	D	D	D	D
4	10 ms	D	S	U	U	D	D	D	D	D	D
5	10ms	D	S	U	D	D	D	D	D	D	D
6	5 ms	D	S	U	U	U	D	S	U	U	D

Screenshot of R&S SMU200A signal generator

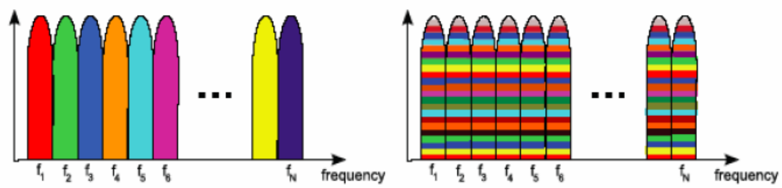
SC-FDMA in Uplink



- DFT “pre-coding” is performed on modulated data symbols to transform them into frequency domain
- Sub-carrier mapping allows flexible allocation of signal to available subcarriers
- Each subcarrier carries a portion of superposed DFT spread data symbols, therefore SC-FDMA is also referred to as DFT-spread-OFDM (DFT-s-OFDM)

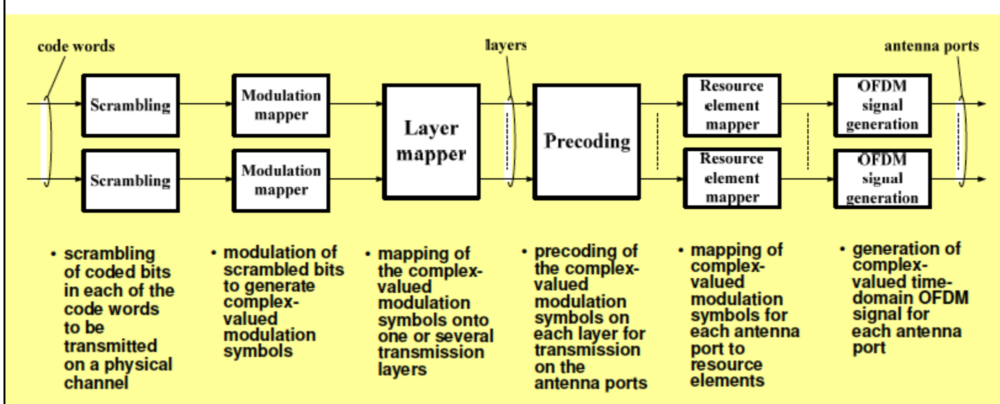
OFDMA vs SC-FDMA

- In OFDMA, each sub-carrier only carries information related to one specific symbol
- In SC-FDMA, each sub-carrier contains information of ALL transmitted symbols

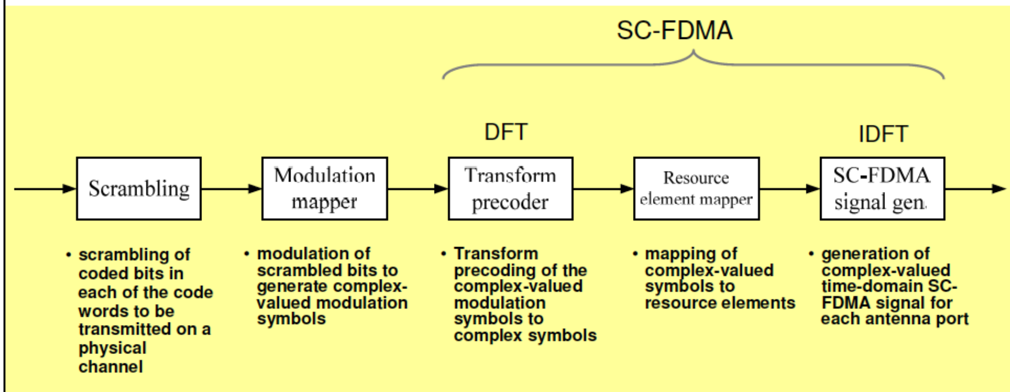


(a) OFDM subcarriers (b) DFT-s-OFDM subcarriers

Downlink Physical Channel Processing



Uplink Physical Channel Processing



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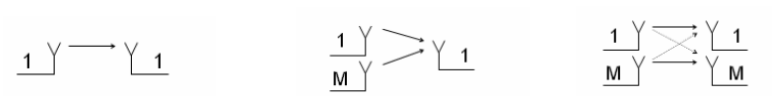
MIMO Transmission

- MIMO = Multiple Input Multiple Output
- Refers to the use of multiple antennas at transmitter and/or receiver side
- LTE requires 100 Mbps peak downlink data rate

  => MIMO needed in LTE



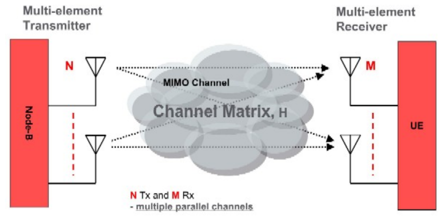
SISO	MISO	MIMO
Single Input Single Output	Multiple Input Single Output	Multiple Input Multiple Output

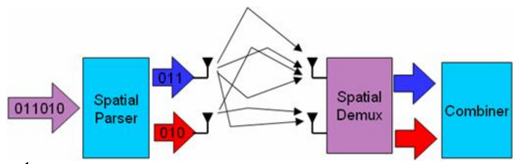
MIMO in LTE

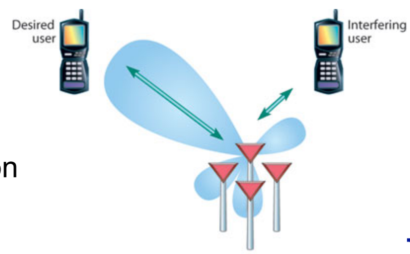
- Classical configuration with 2 Tx and 2Rx antennas.
  - 4 Tx antennas are also supported
- Modes of operation of multiple transmit antennas:
  - Spatial multiplexing
  - Beamforming
  - Single stream transmit diversity
- Single User (SU)-MIMO and Multiple User (MU)-MIMO systems are supported.

MIMO Modes

- Transmit diversity (TxD)
  - Combat fading
  - Replicas of the same signal sent on several Tx antennas
  - Get a higher SNR at the Rx
- Spatial multiplexing (SM)
  - Different data streams sent simultaneously on different antennas
  - Higher data rate
  - No diversity gain
  - Limitation due to path correlation
- Beamforming





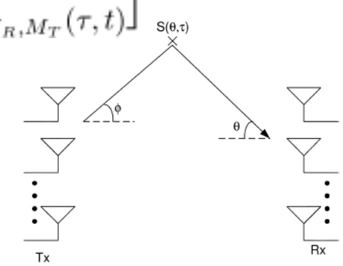


Transmit Diversity

- Under *slow fading*, the MIMO channel matrix H is
- $$\mathbf{H}(\tau, t) = \begin{bmatrix} h_{1,1}(\tau,t) & h_{1,2}(\tau,t) & \cdots & h_{1,M_T}(\tau,t) \\ h_{2,1}(\tau,t) & h_{2,2}(\tau,t) & \cdots & h_{2,M_T}(\tau,t) \\ \vdots & \vdots & \ddots & \vdots \\ h_{M_R,1}(\tau,t) & h_{M_R,2}(\tau,t) & \cdots & h_{M_R,M_T}(\tau,t) \end{bmatrix}.$$

Channel Time-variance

Time-spread



- With suitable choices of array geometry and antenna element patterns,
  H( ) = H which is an MR x MT matrix with complex Gaussian i. i. d random variables
  τ
- Accurate for NLOS rich-scattering environments, with sufficient antenna spacing at transmitter and receiver with all elements identically polarized

Capacity of MIMO Channels

$$y = Hs + n$$

- s is the transmitted vector; n is normalized noise. If the total transmitted power available per symbol period be P. Then,

$$C = \log_2 (I_M + HQH^H) \text{ b/s/Hz}$$

where $Q = E\{ss^H\}$ and trace(Q) < P according to the power constraint

- Consider specific case when we have users transmitting at equal power over the channel, then,

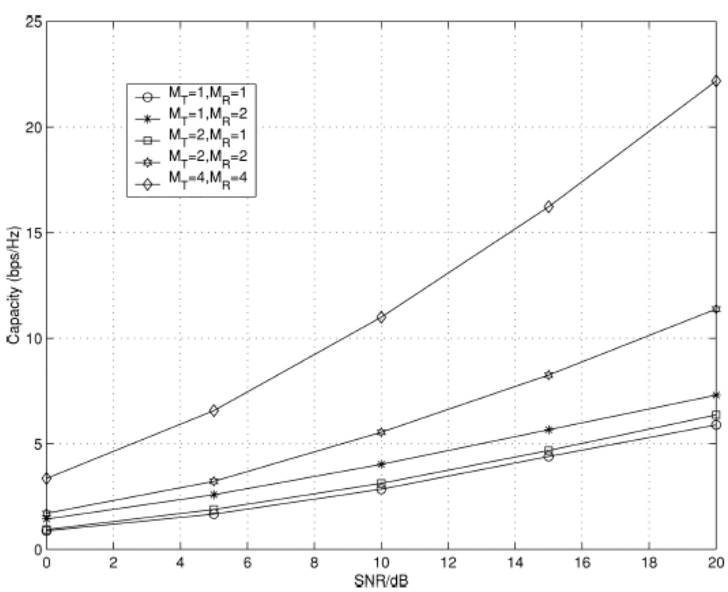
$$C_{EP} = \log_2 [I_M + (P/M_T)HH^H] \text{ b/s/Hz}$$

The optimal choice for *blind* transmission

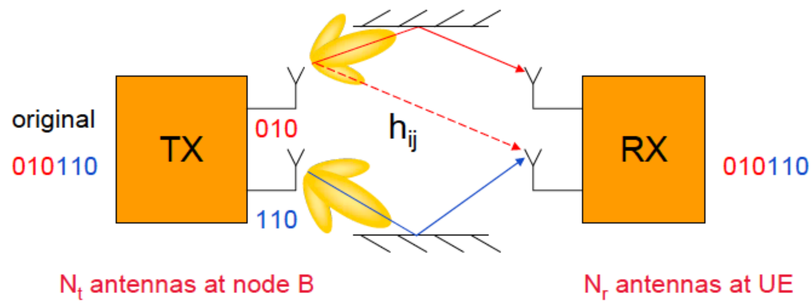
- As M_T and M_R grow, and if SNR is large enough,

$$C_{EP} = \min (M_T, M_R) \log_2 (P/M_T) + \text{constant b/s/Hz}$$

Capacity of MIMO Channels

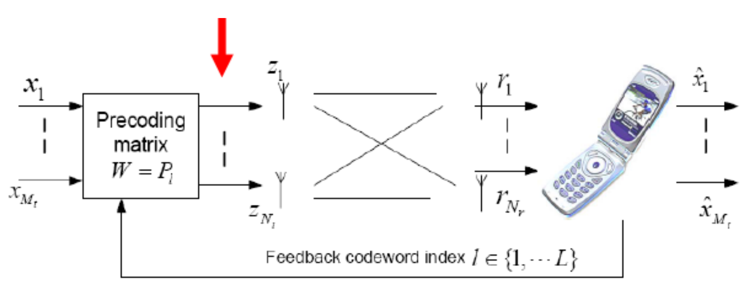


Increasing Data Rate with Spatial Multiplexing



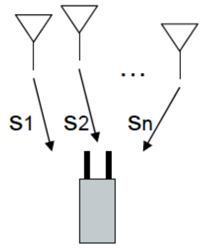
LTE Downlink Spatial Multiplexing

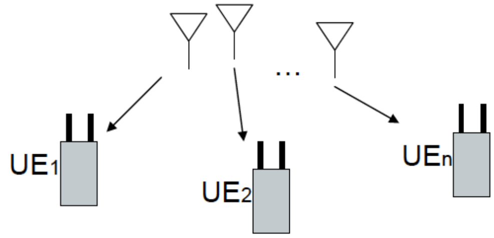
- The signal is "pre-coded" at eNB side before transmission.



- Optimum precoding matrix is selected from predefined "codebook" known at both eNB and UE
- UE estimates the channel, selects the best precoding matrix at the moment and sends back its index

SU-MIMO versus MU-MIMO

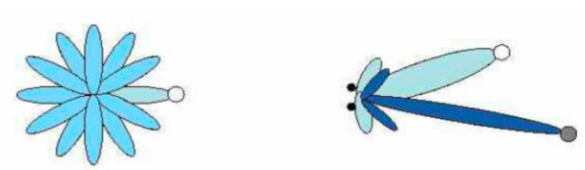


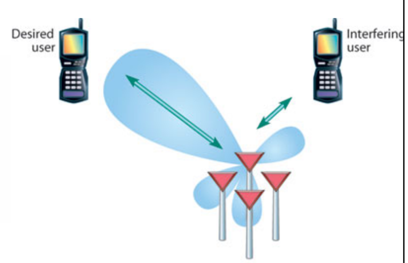


- **SU (Single User)-MIMO**
  - Goal: to increase user data rate
  - Simultaneous transmission of different data streams to 1 user
  - Efficient when the user experiences good channel conditions
- **MU (Multiple User)-MIMO**
  - Goal: to increase sector capacity
  - Selection of the users experiencing good channel conditions
  - Efficient when a large number of users have an active data transmission simultaneously

Beamforming

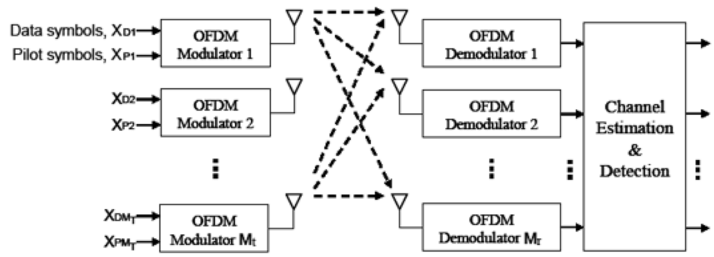
- Smart antennas are divided into two groups:
  - Phased array systems (switched beamforming) with a finite number of fixed predefined patterns
  - Adaptive array systems (AAS) (adaptive beamforming) with an infinite number of patterns adjusted to the scenario in realtime





MIMO-OFDM

- OFDM extends directly to MIMO channels at each of the transmit and receive antennas
- MIMO-OFDM decouples the frequency-selective MIMO channel into a set of parallel MIMO channels



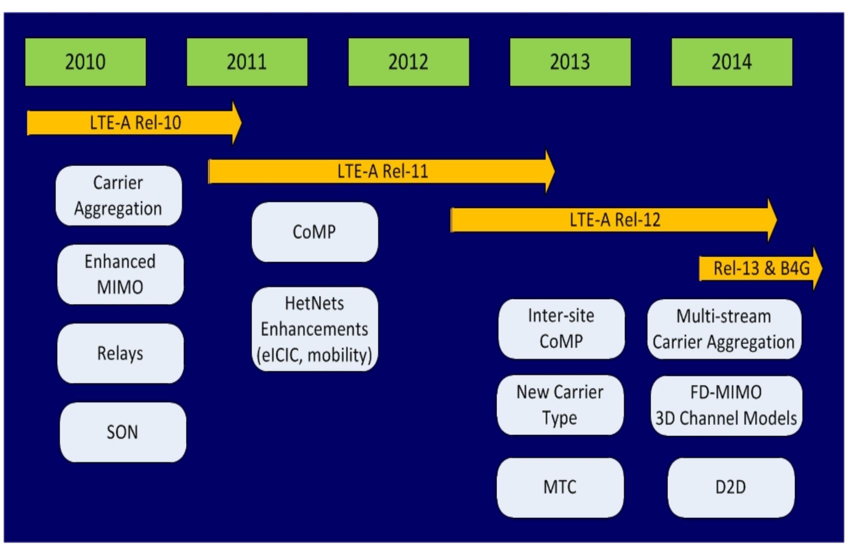
Contents

- Fundamentals of Cellular System
- Key Technologies in LTE
- Key Technologies in LTEA

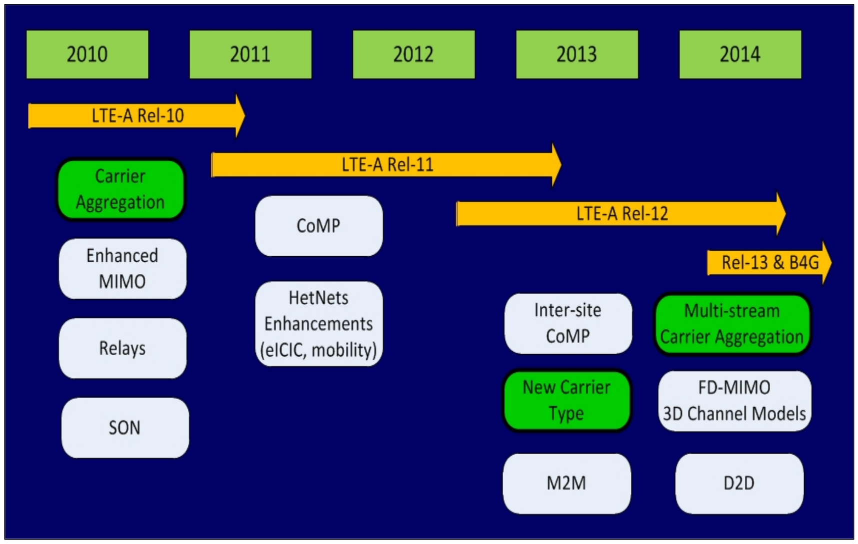
LTE vs LTEA

		LTE	LTE-Advanced
Data Rate	DL	300 Mbps	1 Gbps
	UL	75 Mbps	500 Mbps
Spectrum Efficiency (bps/Hz)	DL	15	30
	UL	3.75	15
Bandwidth (MHz)		1.4 to 20	1.4 to 100
Antenna Configuration		Up to 4x4	Up to 8x8
Coverage		Full performance up to 5 km	Same as LTE. Optimized for local area environments
Mobility		High performance up to 120 km/hr	Same as LTE

Key Technologies in LTEA



Key Technologies in LTEA



Carrier aggregation

- Purpose: increase the amount of utilized bandwidth?
- LTE-A uses BWs of up to 100 MHz in several freq. bands:
  - 450-470 MHz; 698-960 MHz, 1710-2025 MHz, 2110-2200 MHz;
  - 2300-2400 MHz; 2500-2690 MHz and 3400-3600 MHz
- Problem: UE that works in one country or region may not in another.
- One solution: design devices which can work on multiple freq. bands → costly

Carrier aggregation

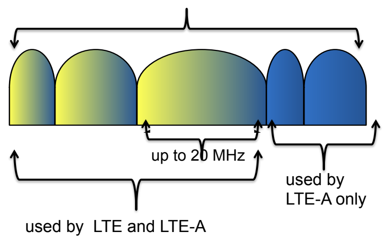
CA consists of grouping several COMPONENT CARRIERS (CC) to achieve wider BWs.

LTE-A device can aggregate up to 5 CCs, each up to 20 MHz.

LTE-A supports 3 CA schemes:

BASIC ONE: Single Spectrum Band

Easy to implement but not practical as operators do not have contigious spectrums.

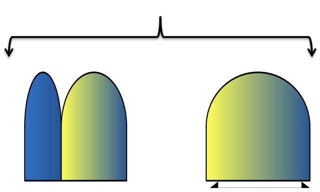


Aggregation of 5 CCs of diff. BWs

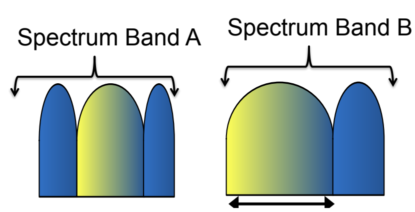
Carrier aggregation

Intraband Non-Contiguous Carrier Aggregation

Single Spectrum Band



Interband Non-Contiguous Carrier Aggregation



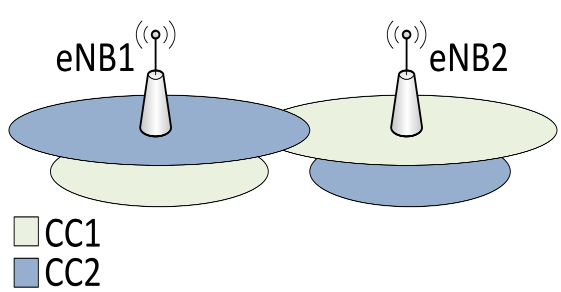
Useful for operators since they can effectively reuse their spectrum fragments and obtain more capacity.

Carrier aggregation: current status

- Around 40 operating bands for LTE and LTE-A
  - Supporting CA across all bands is complex & costly.
- Possible Combinations:
  - For Contiguous CA → 5 bands studied in Rel-11; 3 bands under study.
  - For Non-contiguous CA (INTRABAND) → 4 bands under study (Rel-12).
  - For Non-contiguous CA (INTERBAND) → 20 bands studied in Rel-11; 11 bands under study in Rel-12.

Carrier aggregation: Benefits

- Higher Throughput
  - Wider BWs lead to very high bit rates (up to 1Gbps)
- Inter-Cell Interference and Mobility Improvements:
  - Continuous and non-interfering coverage is provided by power adjustments for each carrier

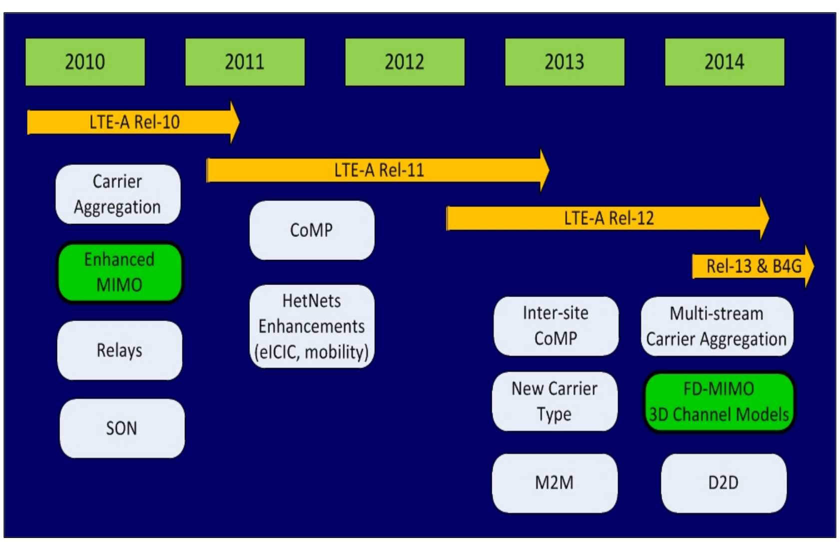


Carrier aggregation: Benefits

- Load Balancing
  - Load is distributed across multiple carriers to reduce NW congestion
- Energy Savings
  - Current specification allows dynamically turning on and off the carriers

    → Energy consumption can be adjusted according to NW load

Key Technologies in LTEA



Enhanced MIMO for LTEA

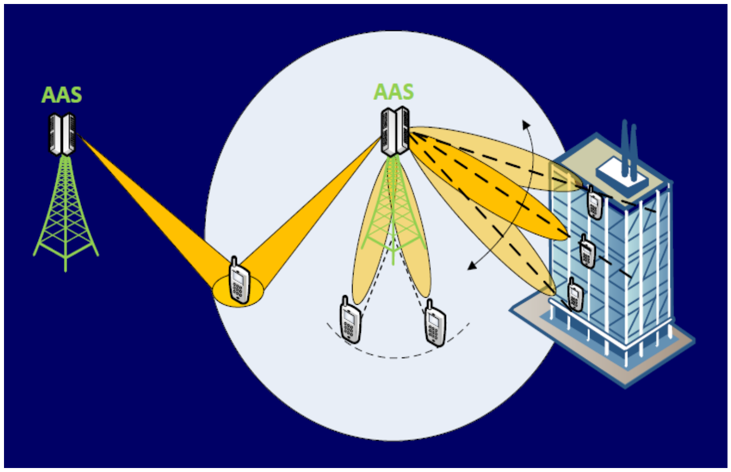
- Novel Features:
  - Antenna Configuration
    - 8x8 in DL; 4x4 in UL
  - Dynamic SU/MU-MIMO Switching
    - Fast timescale adaptation transparent to higher layers
  - Advanced beamforming and scheduling techniques
    - Proprietary and implementation-specific
  - Implications on reference signals, feedback design, precoding codebooks, MIMO detector, etc.
    - Very active research is being carried out

Full Dimension (FD) MIMO

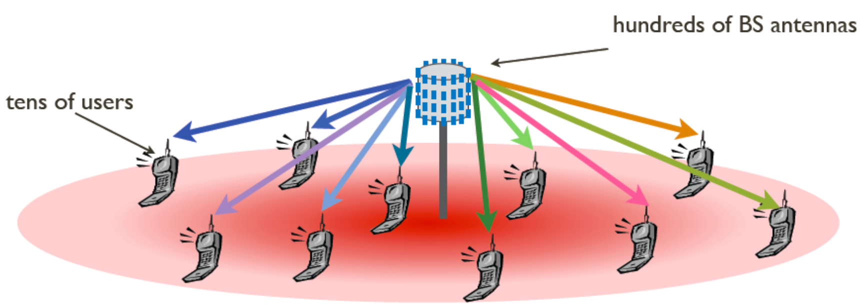
- A large two-dimensional array of transmit antenna ports (16, 32, or 64) at the eNB makes use of the so-called
  Active Antenna System (AAS)
  to provide accurate 3D beamforming to targeted users.

- FD MIMO allows tx beams to be steered by the eNBs in both the azimuth and elevation dimensions,
  - -> a higher degree of flexibility than traditional beamforming.

Full Dimension (FD) MIMO

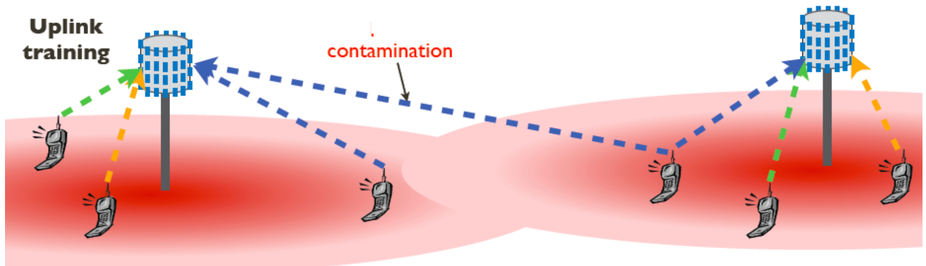


Massive MIMO



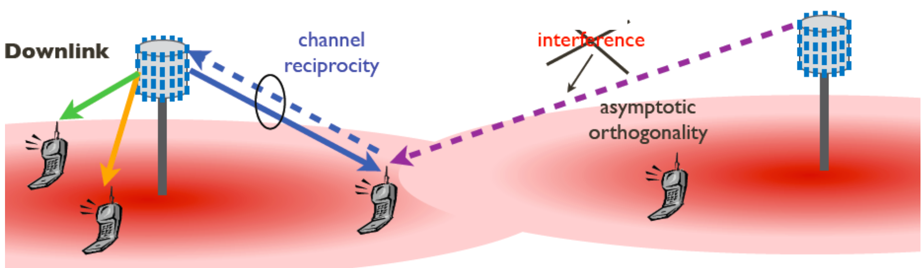
- A very large antenna array at each base station
  - An order of magnitude more antenna elements in conventional systems
- A large number of users are served simultaneously
- An excess of base station (BS) antennas

Massive MIMO



- Benefits from the (many) excess antennas
  - Simplified multiuser processing
  - Reduced transmit power
  - Thermal noise and fast fading vanish
- Differences with MU MIMO in conventional cellular systems
  - Time division duplexing used to enable channel estimation
  - Pilot contamination limits performance

Massive MIMO



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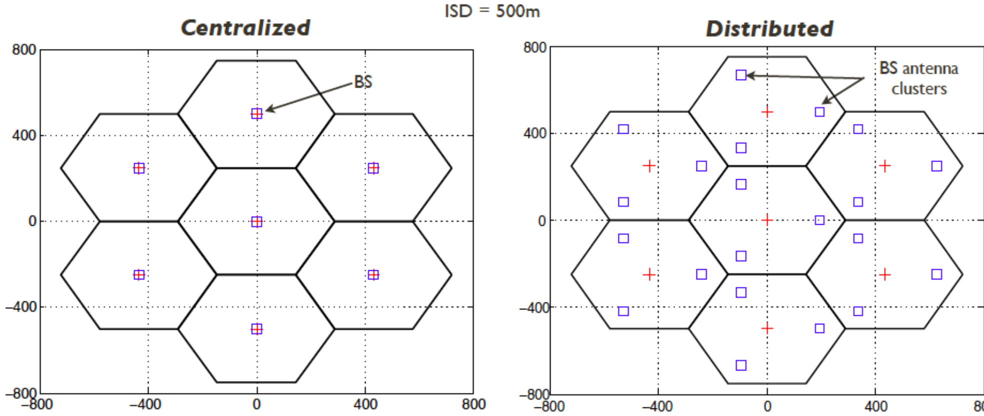
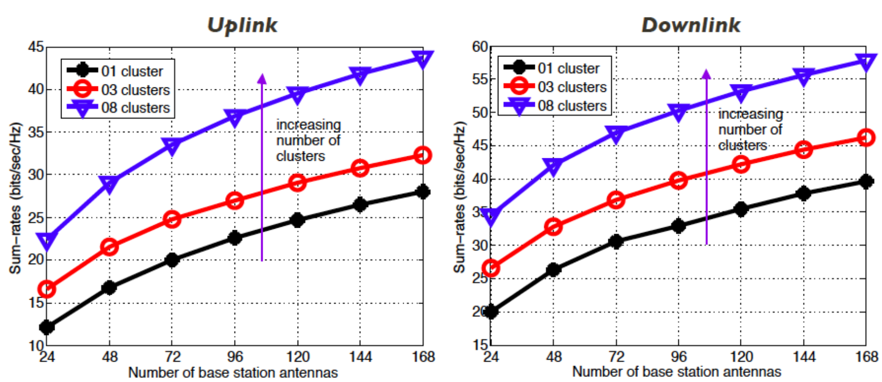
Centralized vs. Distributed

7 cells without sectorization
12 users uniformly distributed in each cell
ISD = 500m



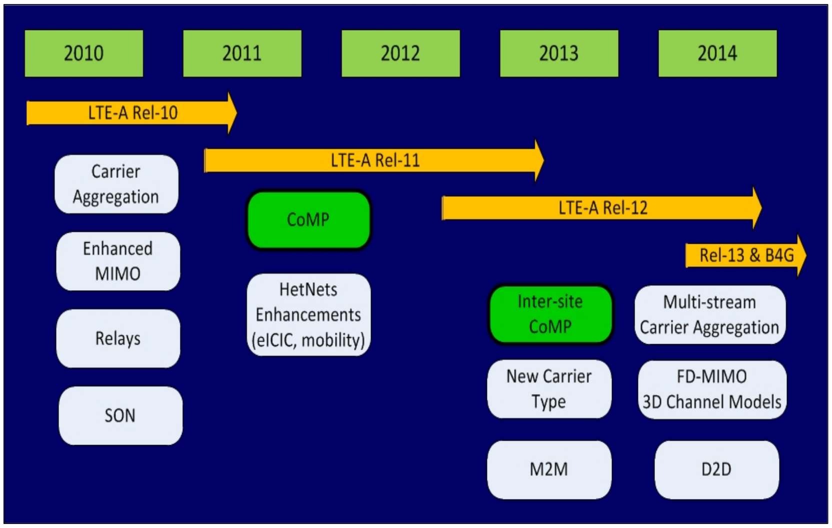
Potential Gains from Massive MIMO



7 cells without sectorization, 12 users uniformly distributed in each cell, ISD = 500m

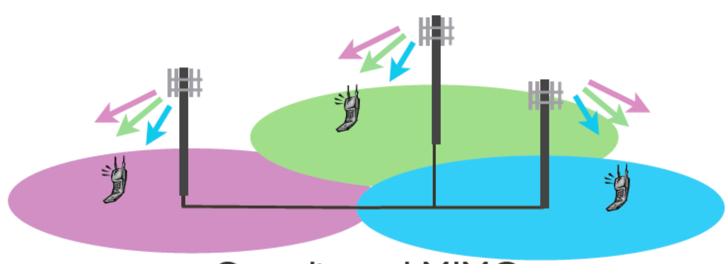
- Distributing antennas achieves higher gains
- Saturation is not observed without huge # of antennas

Key Technologies in LTEA



Network Infrastructures – Tommaso Melodia

Coordinated MIMO & CoMP



Coordinated MIMO

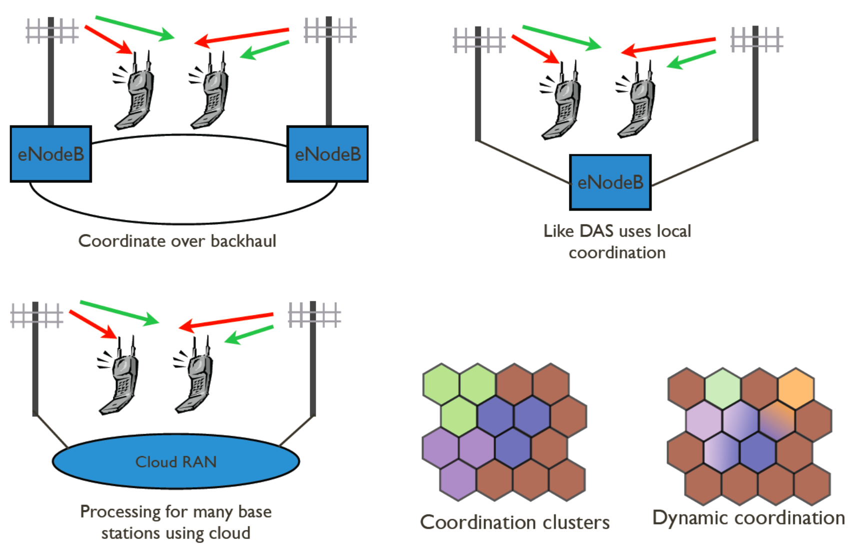
- Coordinated transmission from multiple base stations
- Known as
  - CoMP (Cooperative Multipoint Transmission & Reception)
  - or Cooperative MIMO
  - or Base station coordination

Network Infrastructures – Tommaso Melodia

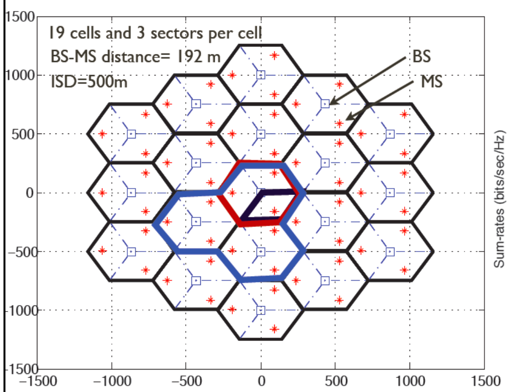
Coordinated MIMO & CoMP

- Set of techniques to improve coverage, cell-edge throughput and system efficiency.
- Principle: UEs at the cell-edge can communicate with several cell sites, both for the DL and UL.
  - Also viewed as Distributed MIMO
  - Coordination can be simple (e.g. signaling to avoid interference) or complex.
    (e.g., data is transmitted from multiple cell sites)
- Moved to Rel-11 due to challenges in practical implementation

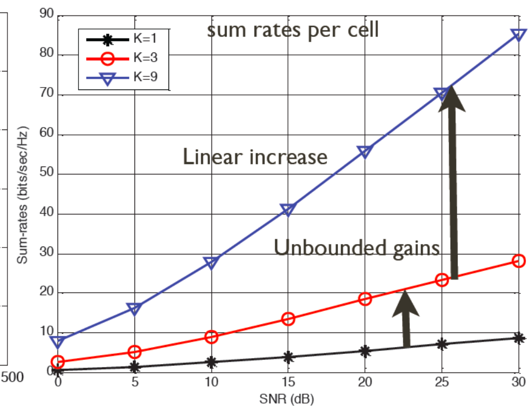
CoMP Architecture



Potential Gains from Coordination

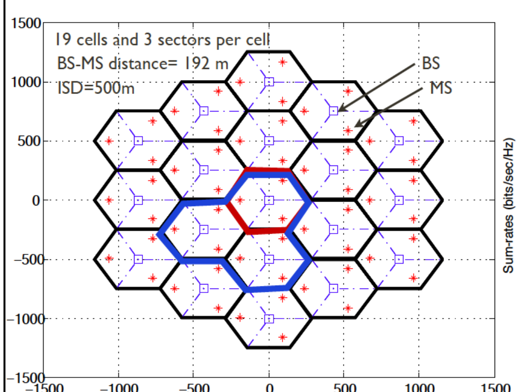


Grid model for a cellular network

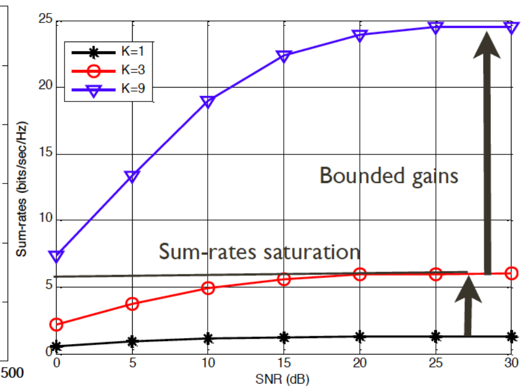


- Throughput gains when out-of-cluster interference is ignored
- More cooperation leads to higher gains
- Cell edge pushed further out, no uncoordinated interference in the cell

Addressing Out-of-Cell Interference

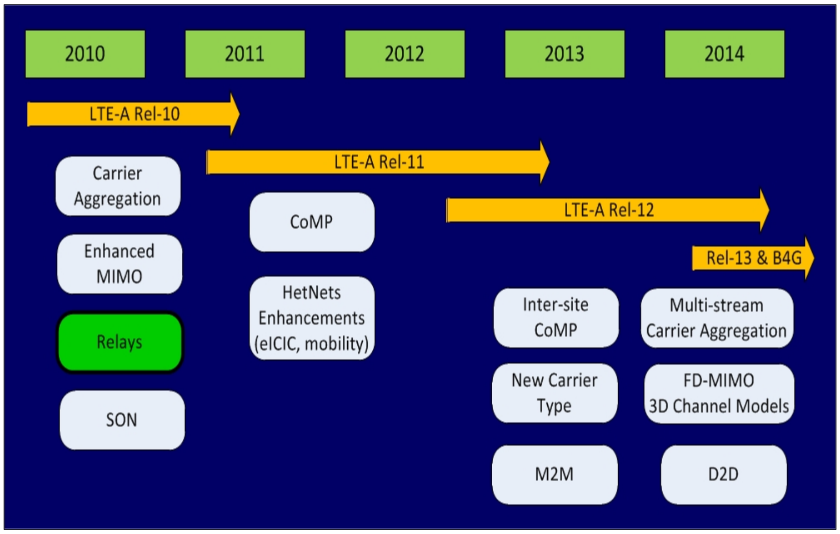


Grid model for a cellular network



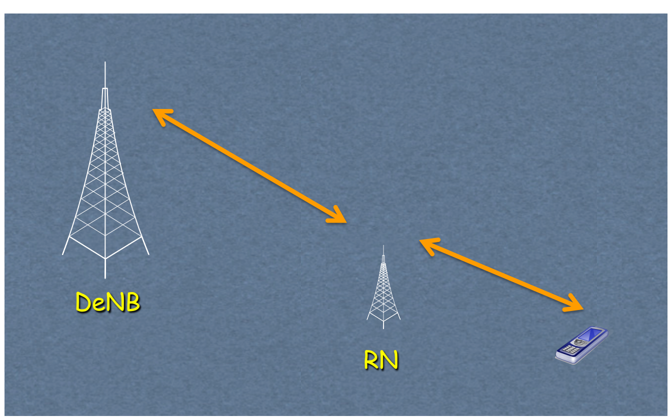
- Performance saturates with out-of-cluster interference
- 30% performance gains observed in industrial settings

Key Technologies in LTEA



Relays

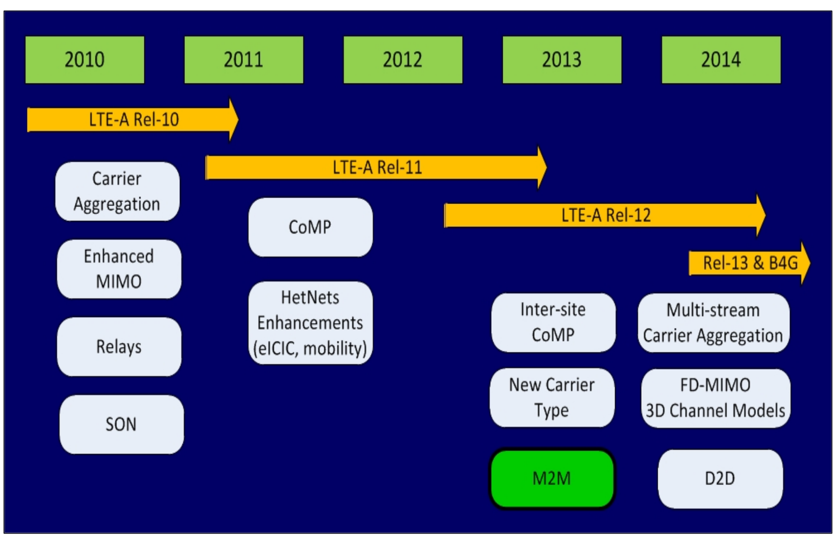
Introduce intermediate relay node (RN) to forward traffic from a Donor eNB (DeNB) to areas of no coverage (notspots) or high traffic demand (hotspots)



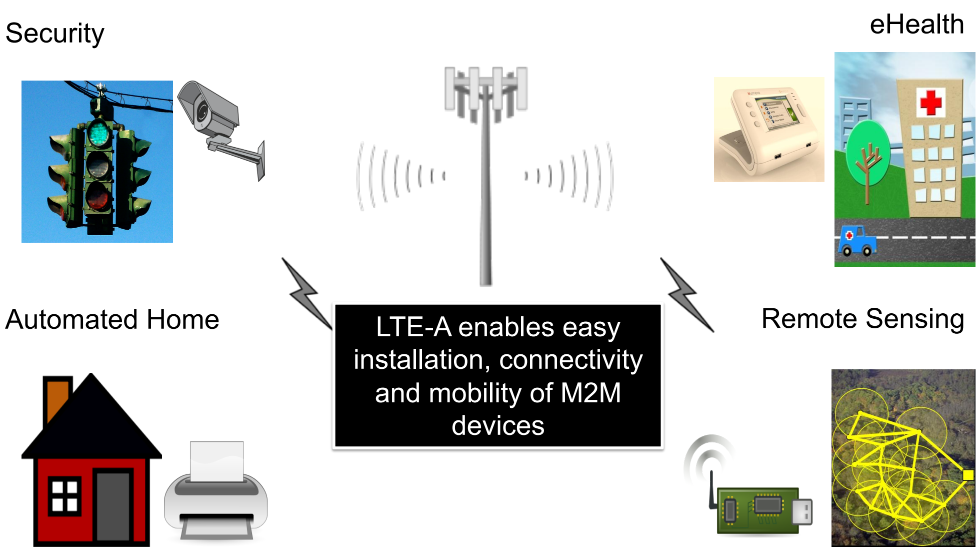
Benefits of Relays

- Improved performance
  - Coverage and data rate
- Lower OPEX and CAPEX
  - Lower H/W requirements than eNB's
  - Easier to install
  - Do not require dedicated locations
- Reach new areas
  - Can be deployed in locations where eNBs cannot
- Temporary network deployment
  - Their ease of installation allows faster deployment and removal

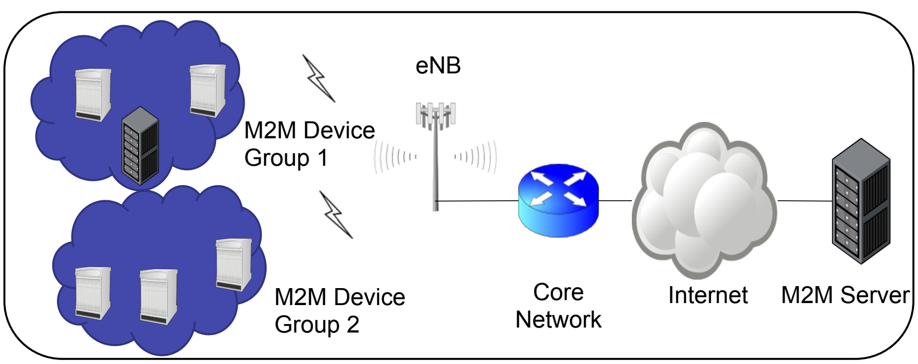
Key Technologies in LTEA



Machine to machine communication (M2M)



Machine to machine communication (M2M)

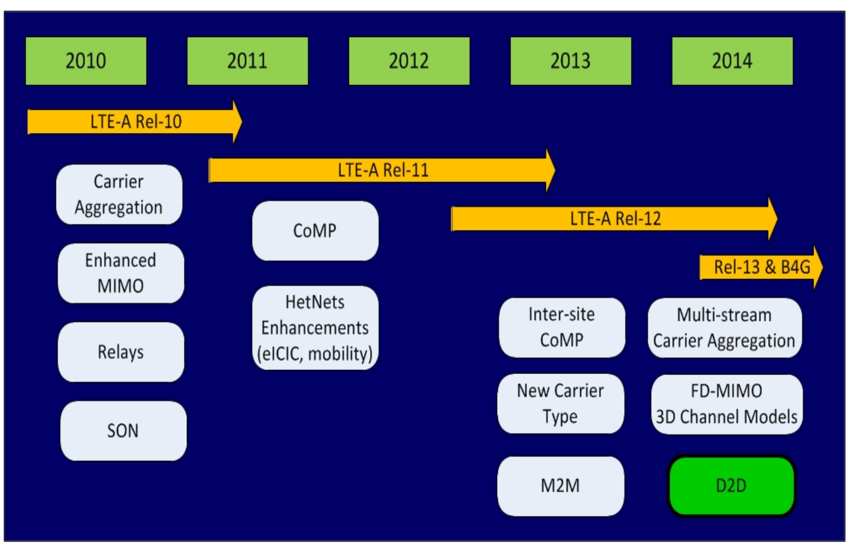


M2M Key Issues

- Massive Deployment of M2M Devices
  - Huge amount of signaling/data overload of the access and core NW
  - High Collision Probability during Channel Access
  - Insufficient control resources to respond to resource request

Need: Efficient congestion handling, mainly, in the control plane.

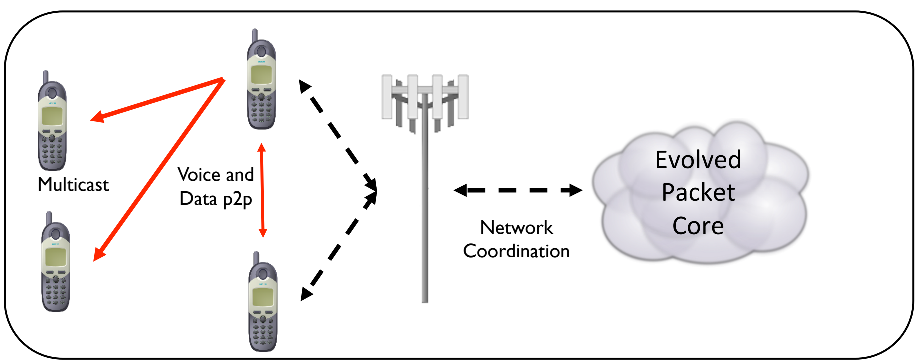
Key Technologies in LTEA



D2D vs M2M

- M2M:
  - Communications between non-human devices
  - Requires a cellular infrastructure, i.e., a core NW & a BS
- D2D (Device-to-Device Communications):
  - Ad-hoc peer-to-peer communication between devices
  - Does not require communication through the core NW

D2D

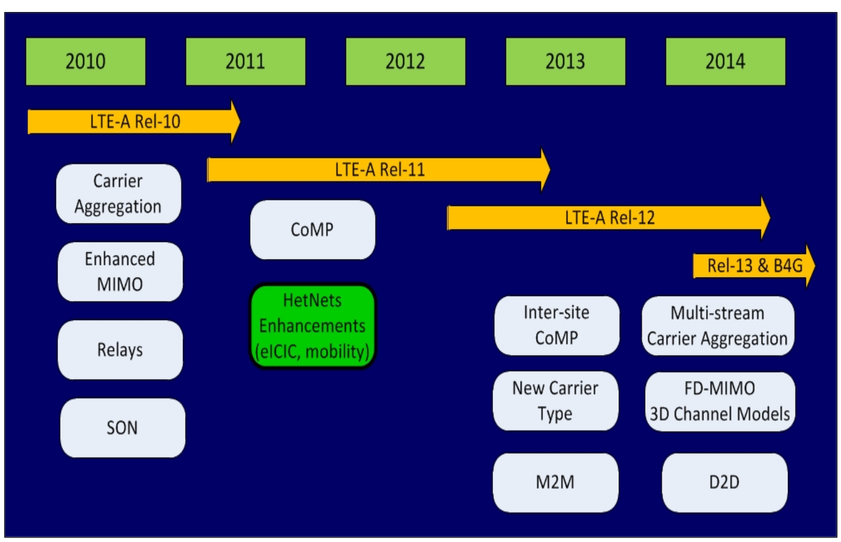


- NW coordinated communication between local devices bypassing core NW for data traffic
- Reduce NW capacity demand, provide higher QoS and increased security over unlicensed D2D like Bluetooth
- FCC will start using LTE for Public Safety NWs (natural disasters)

D2D

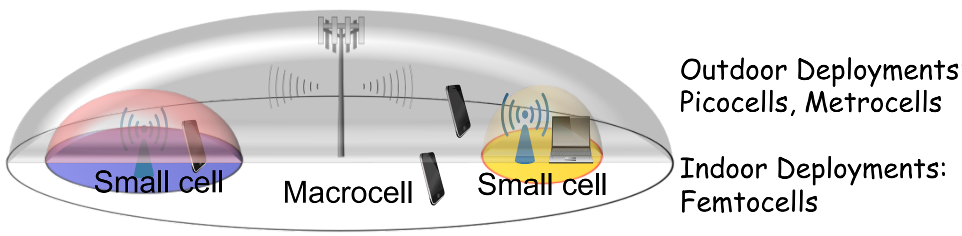
- Unlicensed Operation
  - Operators can add automated device pairing, authentication, and global identity
- Licensed Operation
  - Same benefits as unlicensed, plus:
  - Can better guarantee availability
  - Requires expensive spectrum and interference coordination
  - Public Safety devices can operate with zero core NW interaction

Key Technologies in LTEA



Heterogeneous Networks (HetNets)

- Macrocell area underlaid with number of small cells



- Over 2000x increase in network capacity
- Cost-effective coverage extension and green radio solution

Heterogeneous Networks (HetNets)

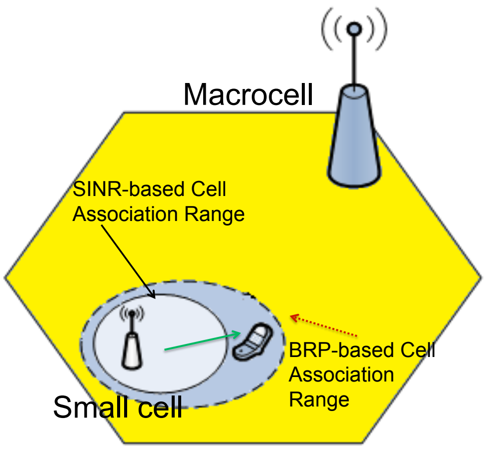
Conditions:		Association Policy:
High UL data rate	→	BS with minimum pathloss
High load	→	Offload to small cells
Low Load	→	BS with best DL SINR

Largest Downlink (DL) SINR based Cell Association

- Does not apply anymore to HetNets!

HetNets: Cell Association

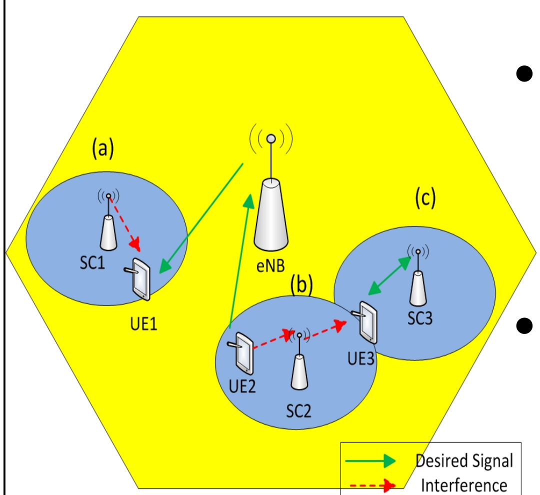
Maximum Biased Received Power (BRP) Based Cell Association



Advantage:
* Increased network capacity

Disadvantage:
* Low per-user throughput (due to interference)

HetNets: Inter Cell Interference



- Scenarios (a) and (c):
  - DL interference to a user coming from the small cell and macrocell.
- Scenario (b):
  - Interference in the UL caused by a macrocell user to a small cell BS

HetNets: Inter Cell Interference Cancellation (ICIC)

- Rel-8 and Rel-9: ICIC
  - Use different carrier freqs. for diff. cell layers
  - Power control schemes
  - Adaptive fractional frequency reuse
  - Spatial antenna techniques includ. MIMO &SDMA
  - Adaptive Beamforming
- Rel-11: Enhanced ICIC (eICIC) (due to Carrier Aggeregation)
  - Time-domain based schemes
  - Frequency domain based schemes