

# 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

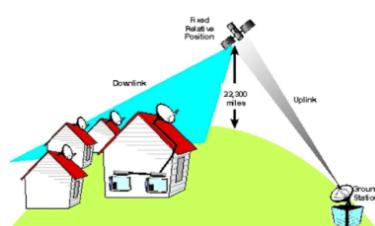
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## TV System vs Cellular System

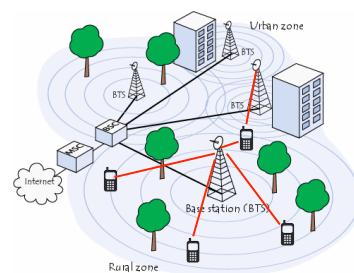
### • TV System:

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



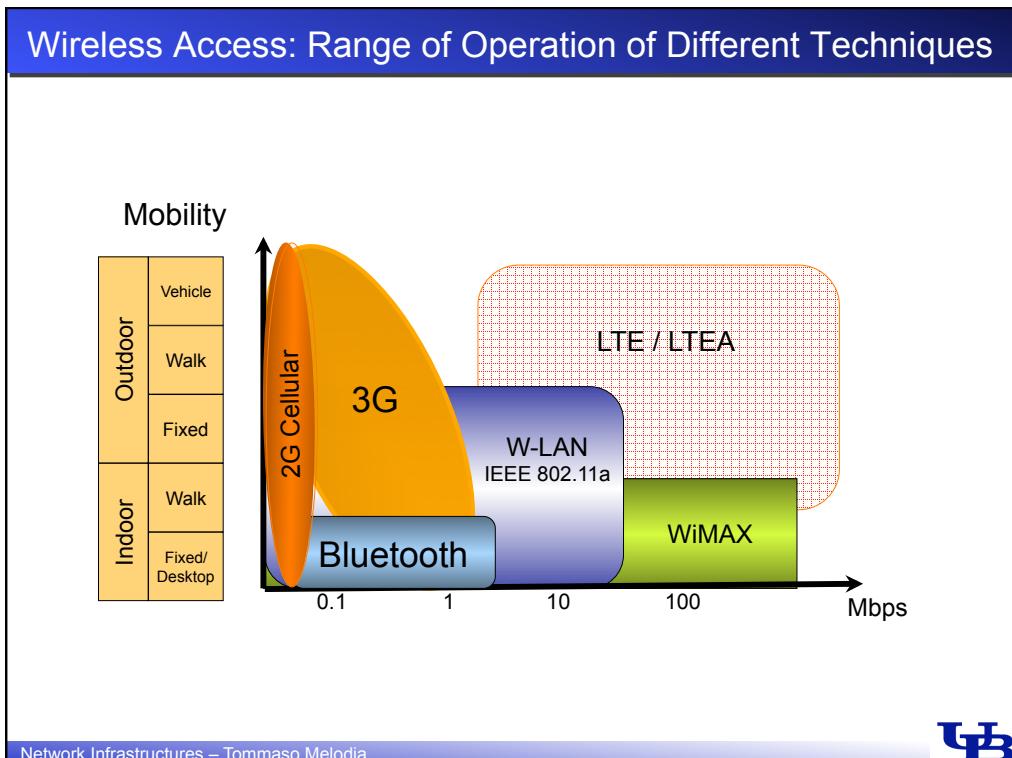
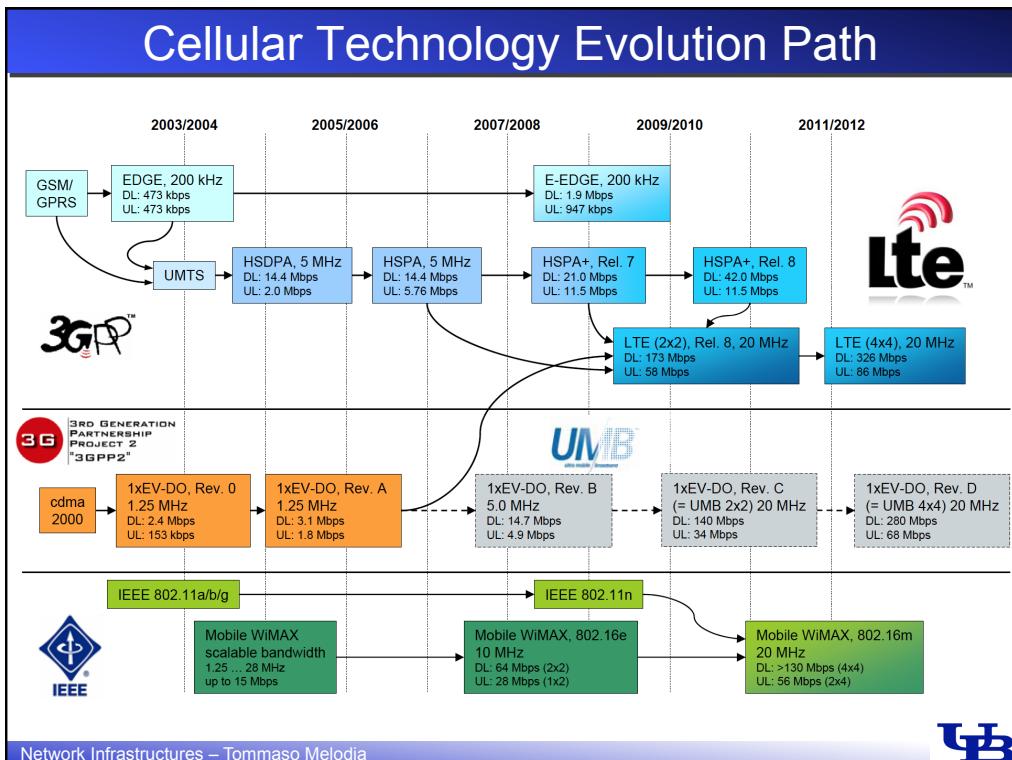
### • Cellular System:

- 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



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## 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

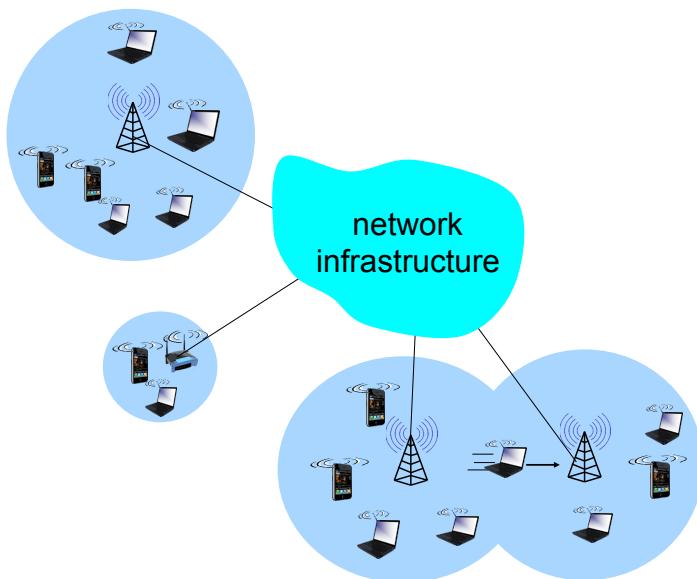
### Mobile IP

### 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**

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**UB**

## 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

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**UB**

## Elements of a wireless network

The diagram illustrates the elements of a wireless network. At the center is a cyan wavy shape labeled "network infrastructure". Four blue circles, each containing various mobile devices (laptops, smartphones, tablets) and base stations, are connected to this central infrastructure. A red box highlights a "wireless link" between one of the mobile devices and its corresponding base station. To the right of this link is a small icon of two curved arrows.

**wireless link** — (曲線)

- ❖ 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

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**UB**

## Elements of a wireless network

The diagram is similar to the first one, showing the same components: a central "network infrastructure" and four peripheral clusters of mobile devices and base stations. A red box highlights the "infrastructure mode" of operation. It includes a definition and a specific term: "handoff: mobile changes base station providing connection into wired network". To the right of this text is a red arrow pointing towards the diagram.

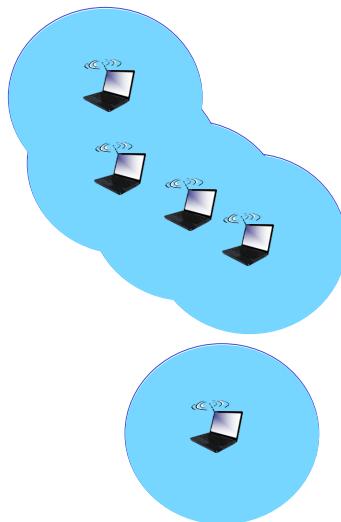
**infrastructure mode**

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

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**UB**

## 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

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## Wireless network taxonomy

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

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# Wireless Link Characteristics (I)

*important* differences from wired link ....

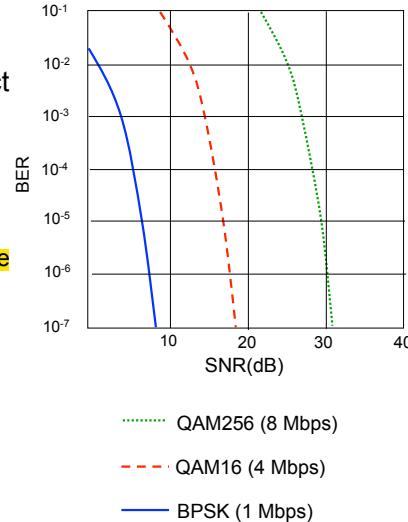
- **decreased signal strength:** radio signal attenuates as it propagates through matter (path loss)
- **interference from other sources:** standardized wireless network frequencies (e.g., 2.4 GHz) shared by other devices (e.g., phone); devices (motors) interfere as well
- **multipath propagation:**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



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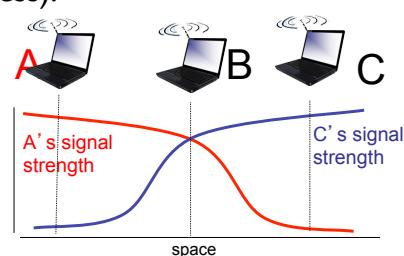
## Wireless network characteristics

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

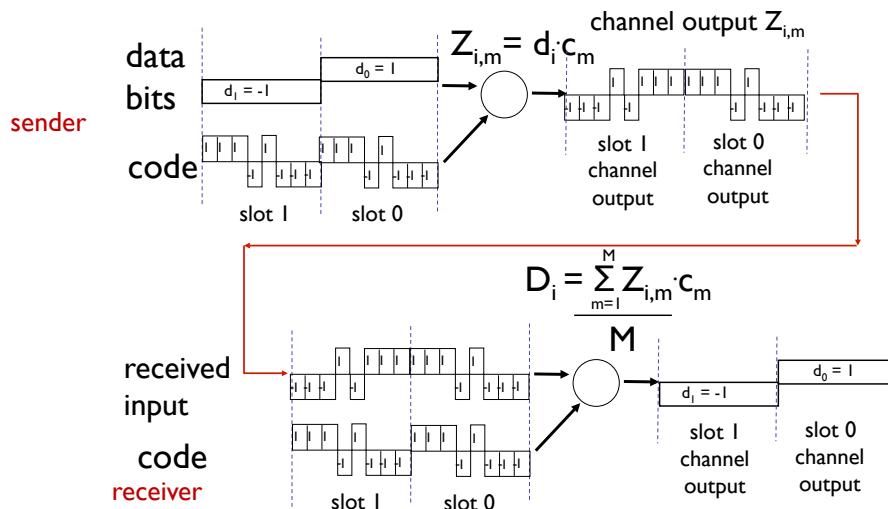
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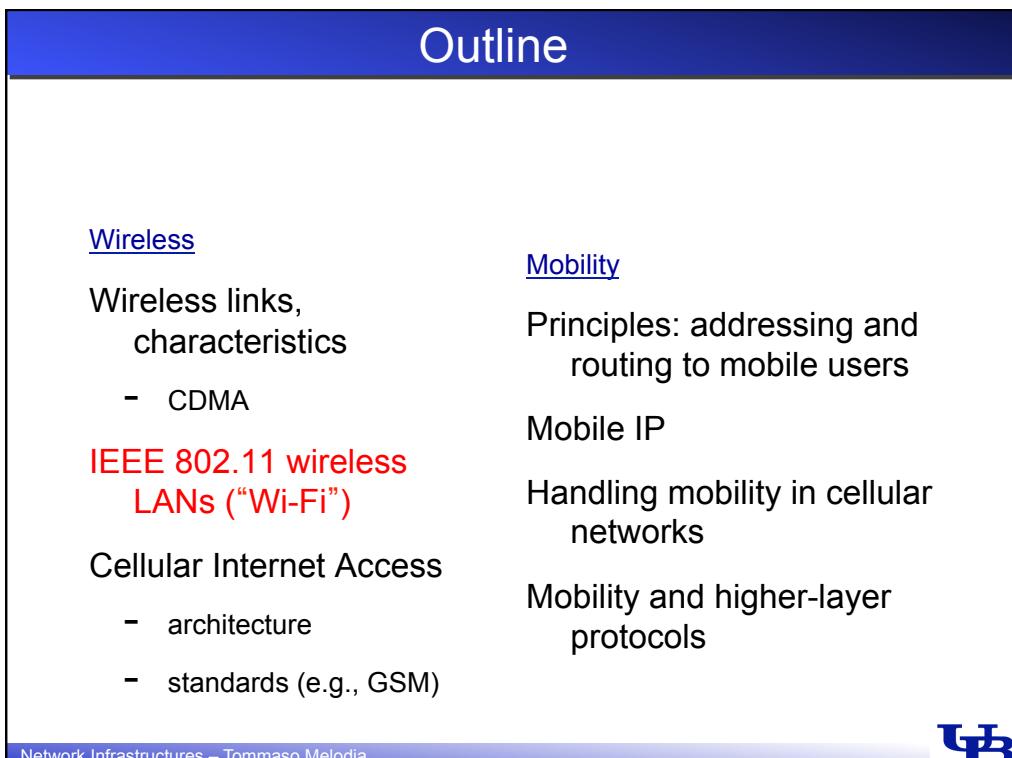
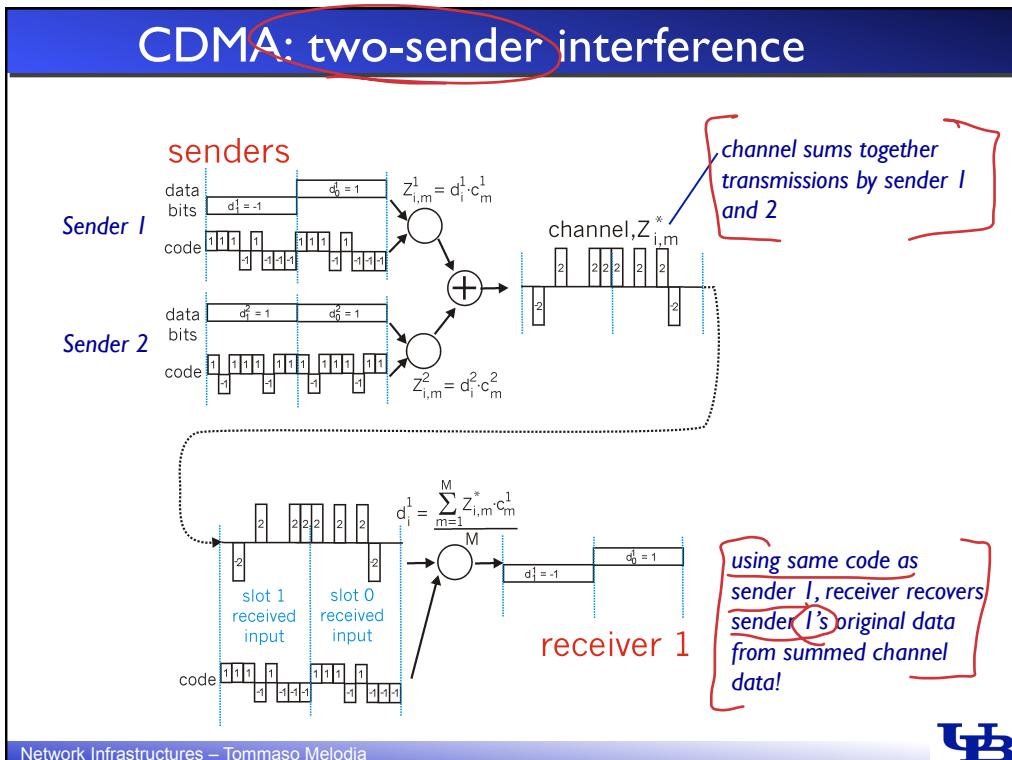


## Code Division Multiple Access (CDMA)

- **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





## IEEE 802.11 Wireless LAN

### 802.11a

- 5-6 GHz range
- up to 54 Mbps

### 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

### 802.11g

- 2.4-5 GHz range
- up to 54 Mbps

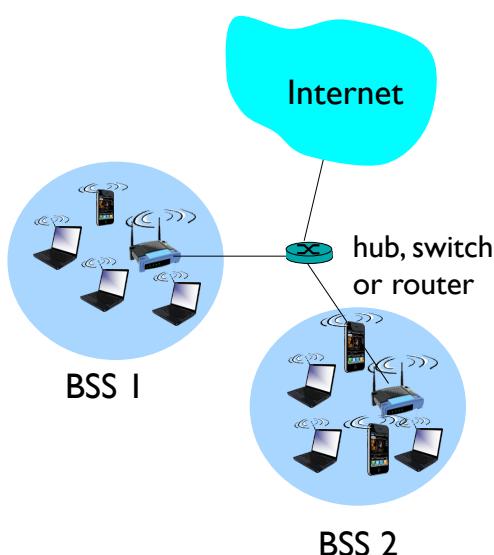
### 802.11n: multiple antennae

- 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



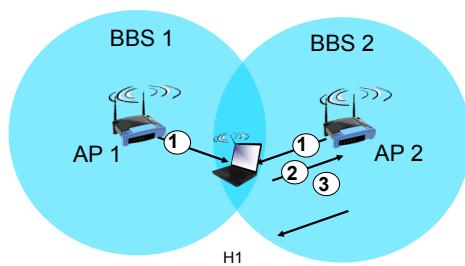
- ❖ wireless host communicates with base station
  - **base station = access point (AP)**
- ❖ **Basic Service Set (BSS) (aka “cell”)** in infrastructure mode contains:
  - **wireless hosts**
  - **access point (AP): base station**
  - **ad hoc mode: hosts only**



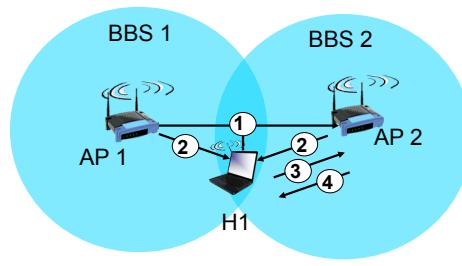
## 802.11: Channels, association

- 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:

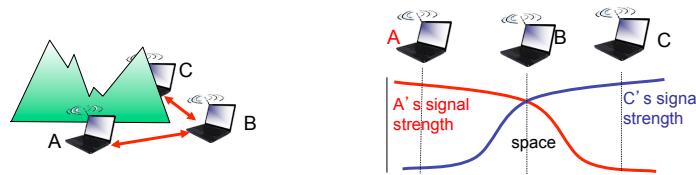
- (1) beacon frames sent from APs
- (2) association Request frame sent: H1 to selected AP
- (3) association Response frame sent from selected AP to H1

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<sup>+</sup> 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)**



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## IEEE 802.11 MAC Protocol: CSMA/CA

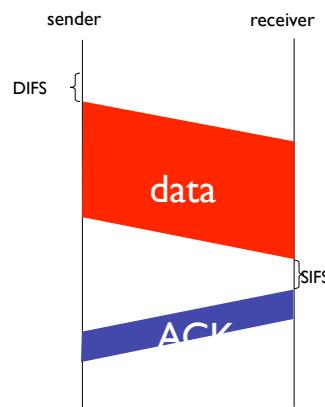
### 802.11 sender

?

- 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)



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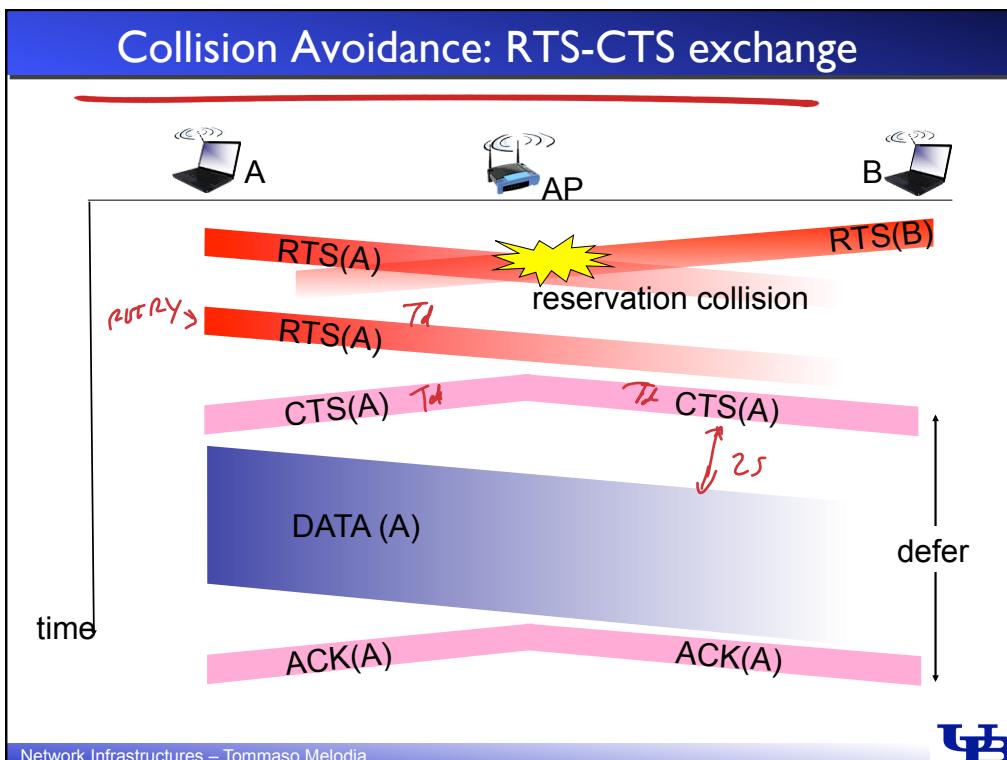


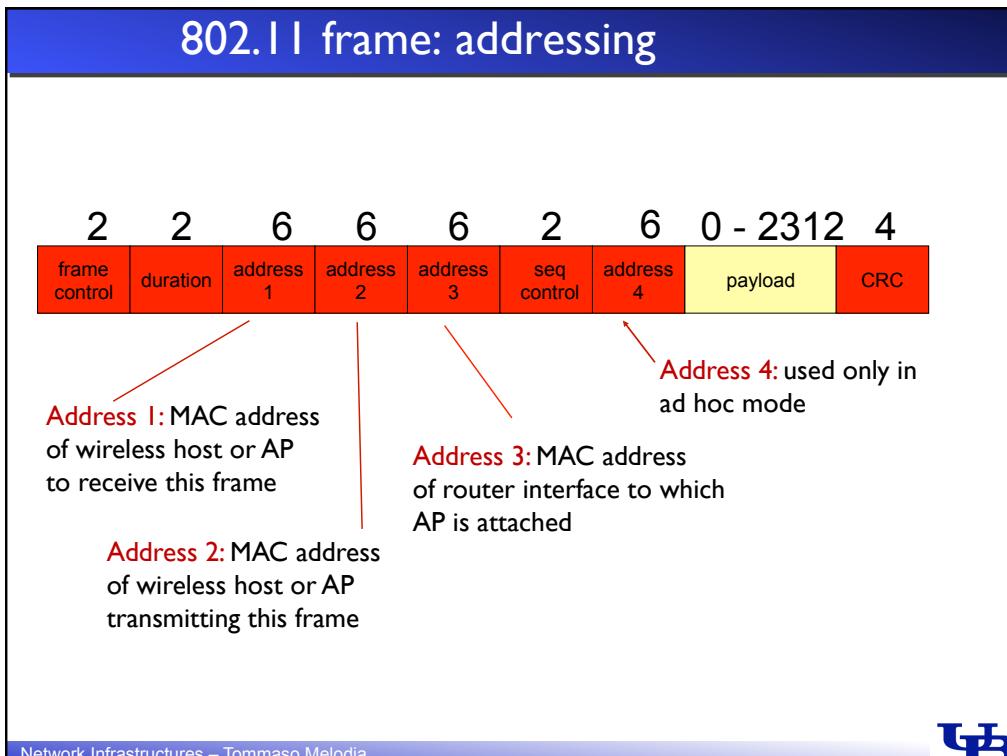
*idea:* allow sender to “reserve” channel rather than random access of data frames: avoid collisions of long data frames

- 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

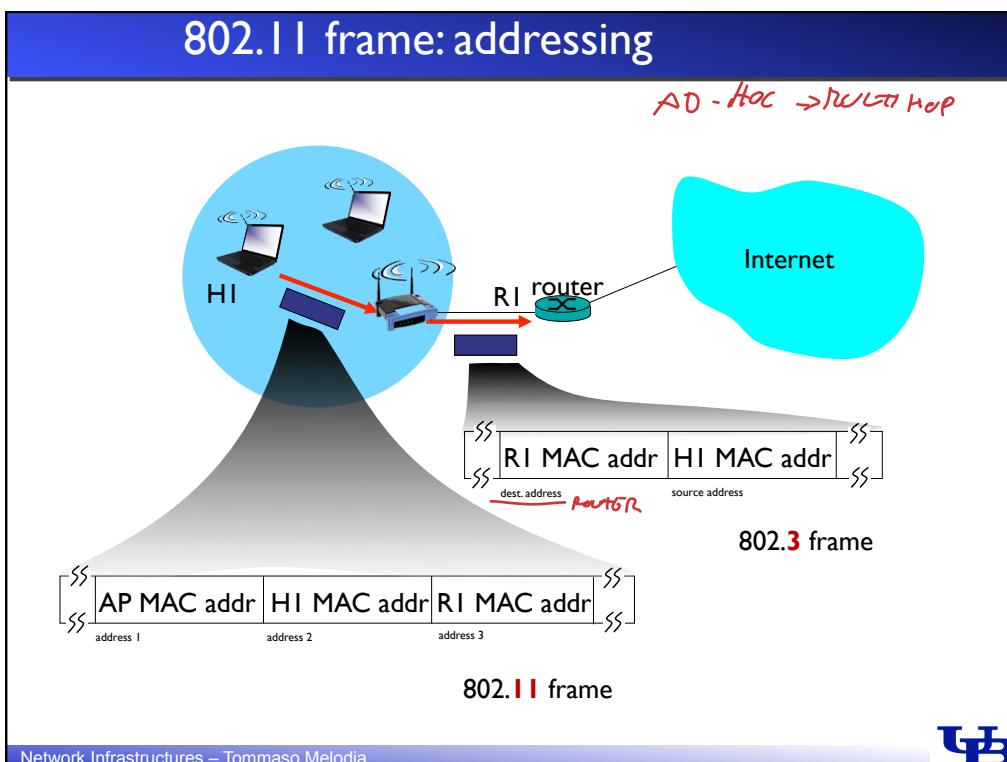
*avoid data frame collisions completely  
using small reservation packets!*

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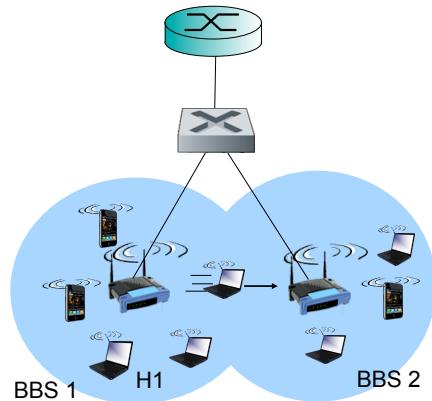


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## 802.11: mobility within same subnet

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



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## 802.11: advanced capabilities

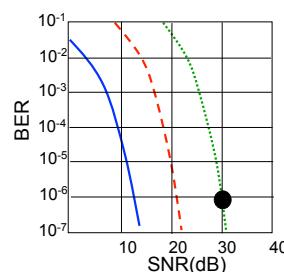
### Rate adaptation

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

*As increases  $\Rightarrow$*  {

- QAM256 (8 Mbps)
- QAM16 (4 Mbps)
- BPSK (1 Mbps)

operating point



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

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# 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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## Cellular Internet Access

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

## Mobility

Principles: addressing and routing to mobile users

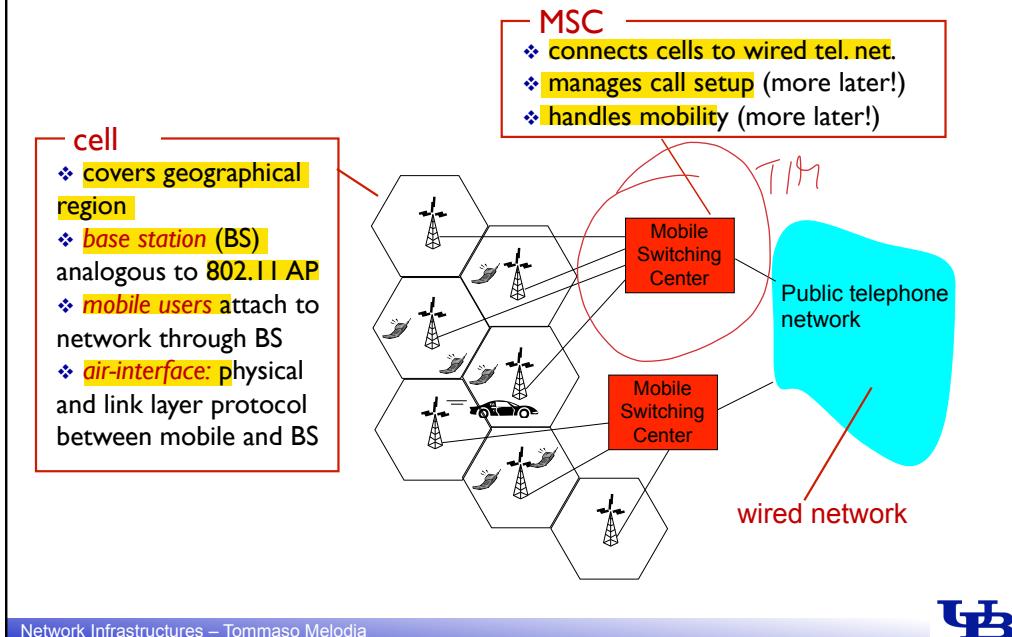
Mobile IP

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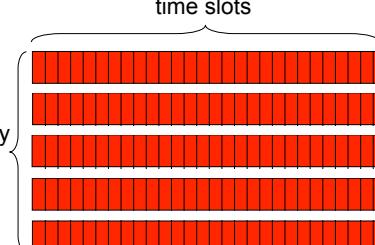
## Components of cellular network architecture



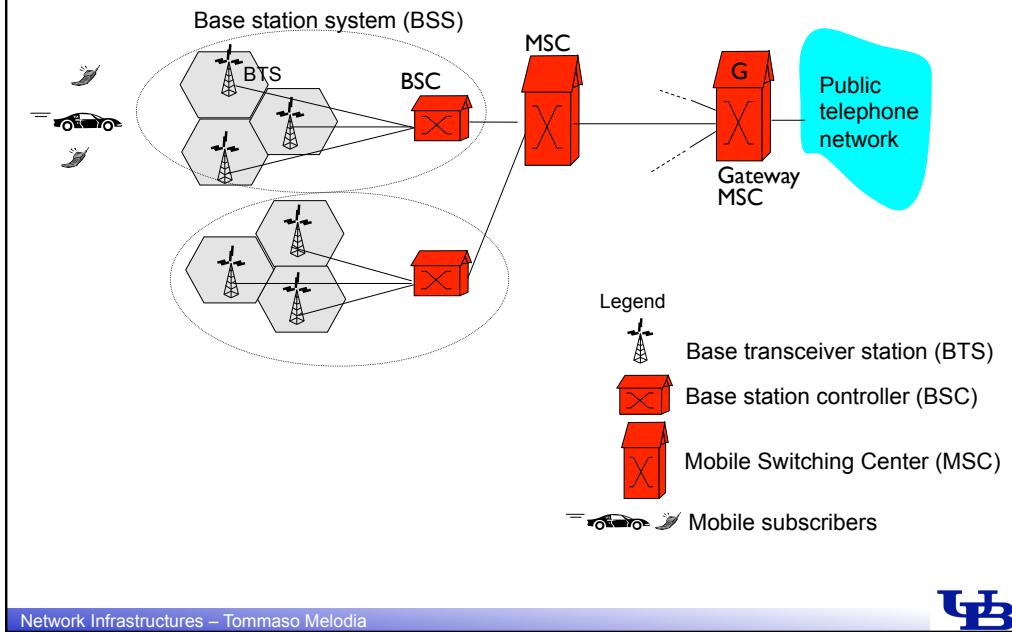
## Cellular networks: the first hop

Two techniques for sharing mobile-to-BS radio spectrum

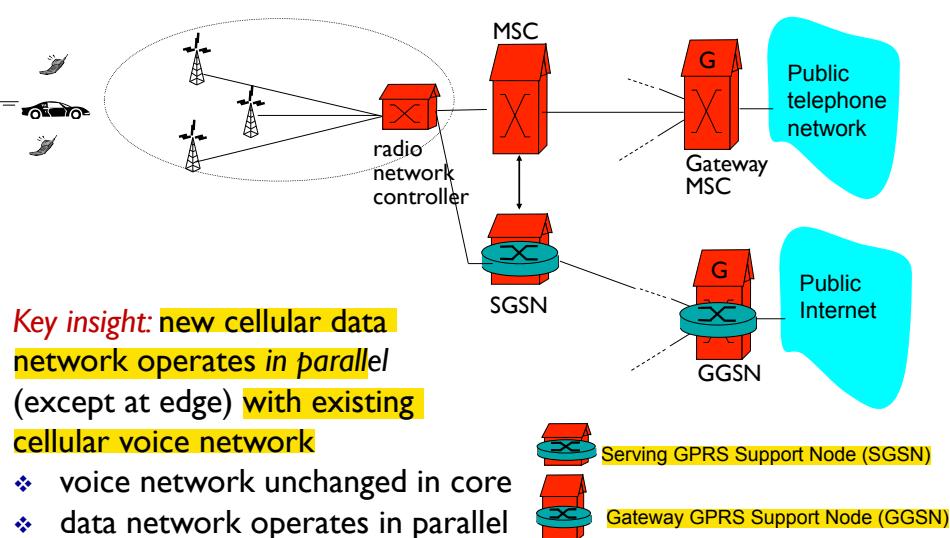
- combined FDMA/TDMA:  
divide spectrum in frequency channels, divide each channel into time slots
- CDMA: code division multiple access

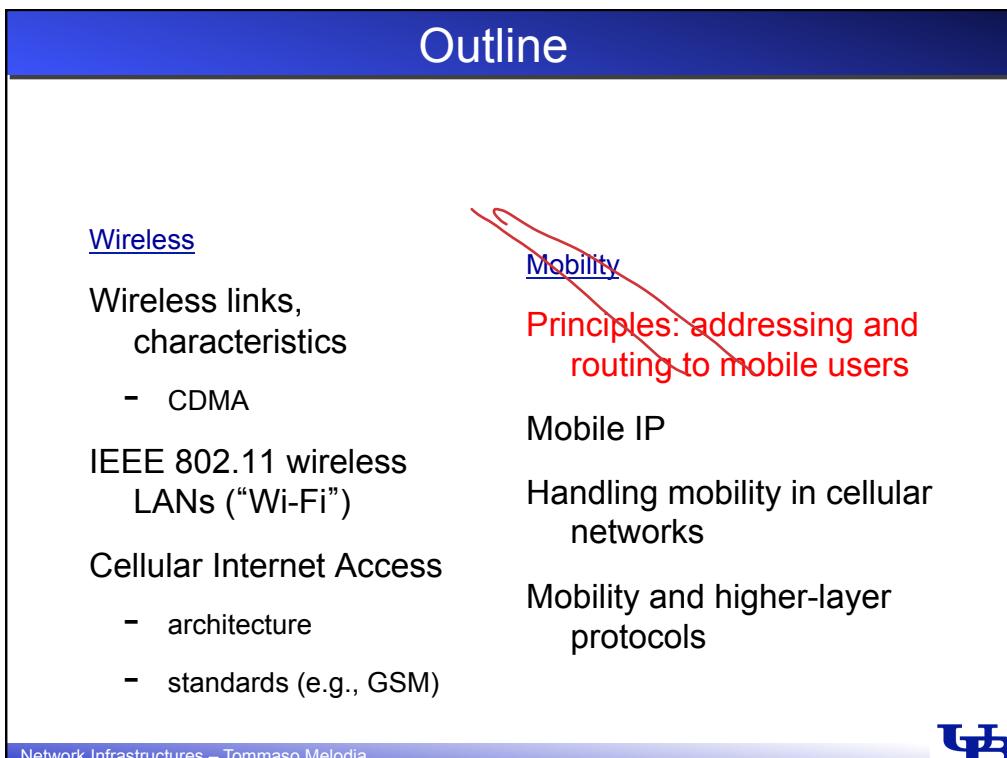
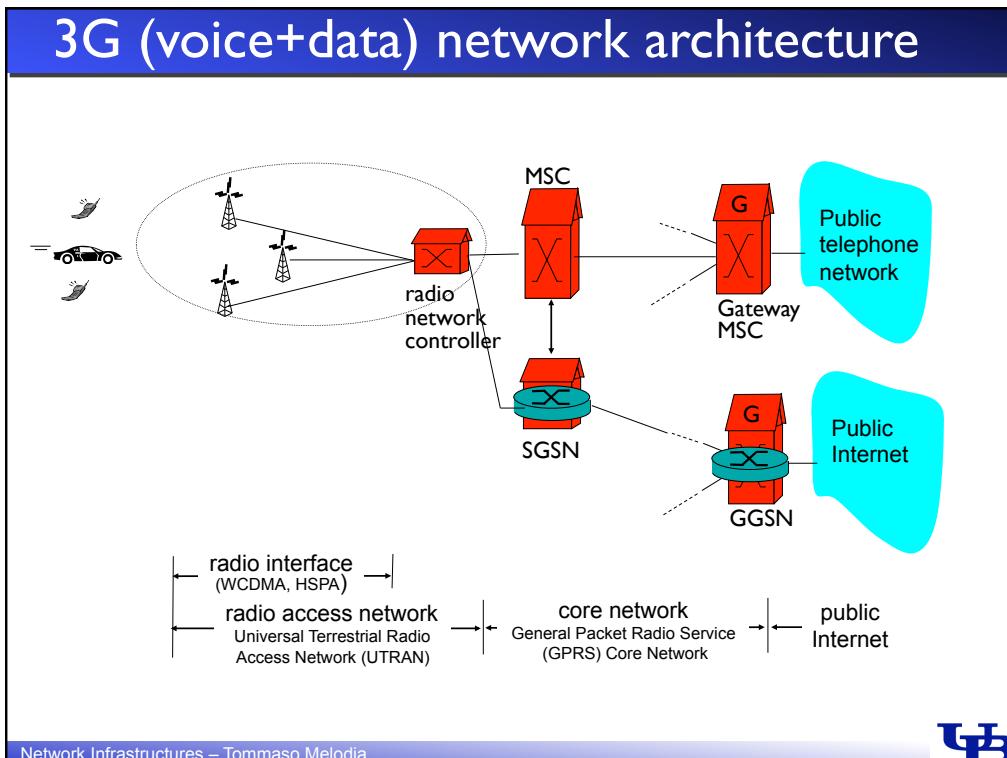


## 2G (voice) network architecture



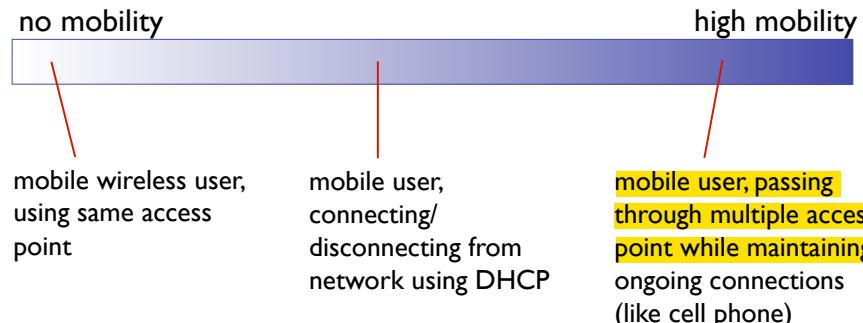
## 3G (voice+data) network architecture



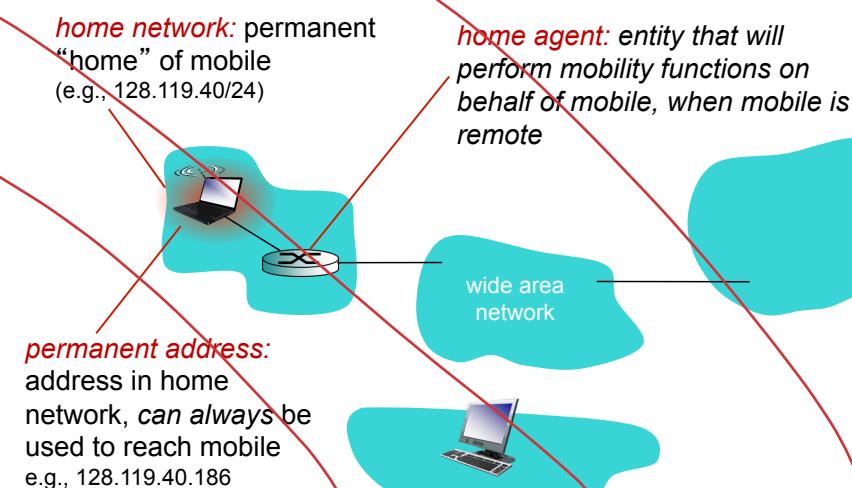


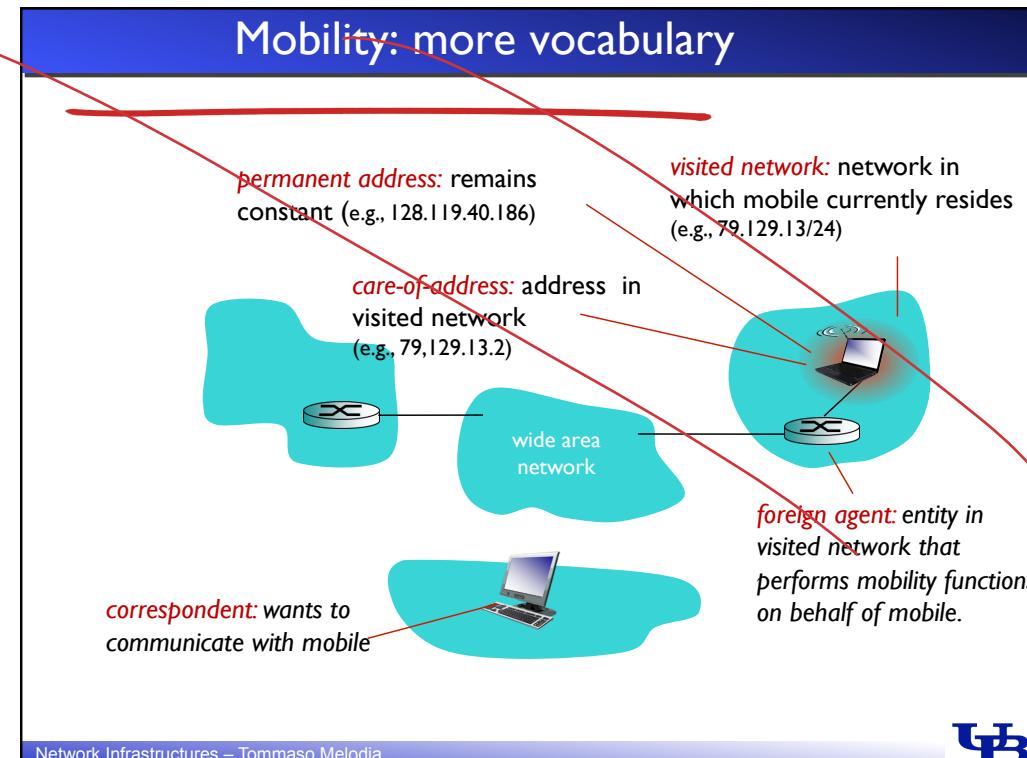
## What is mobility?

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



## Mobility: vocabulary



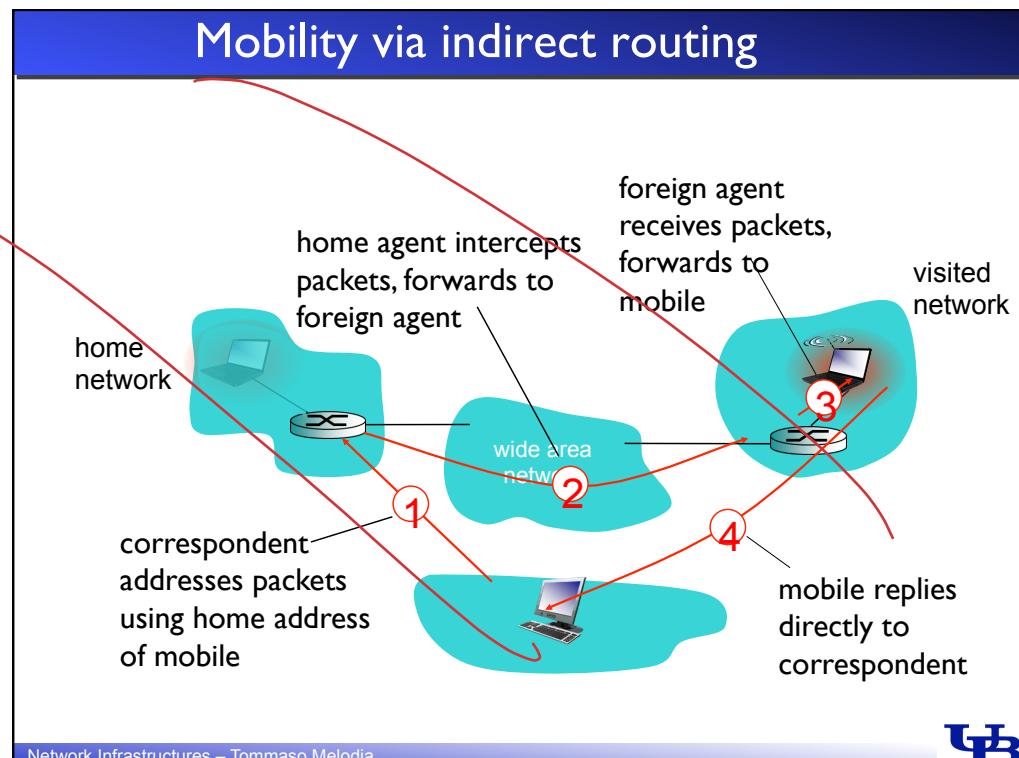
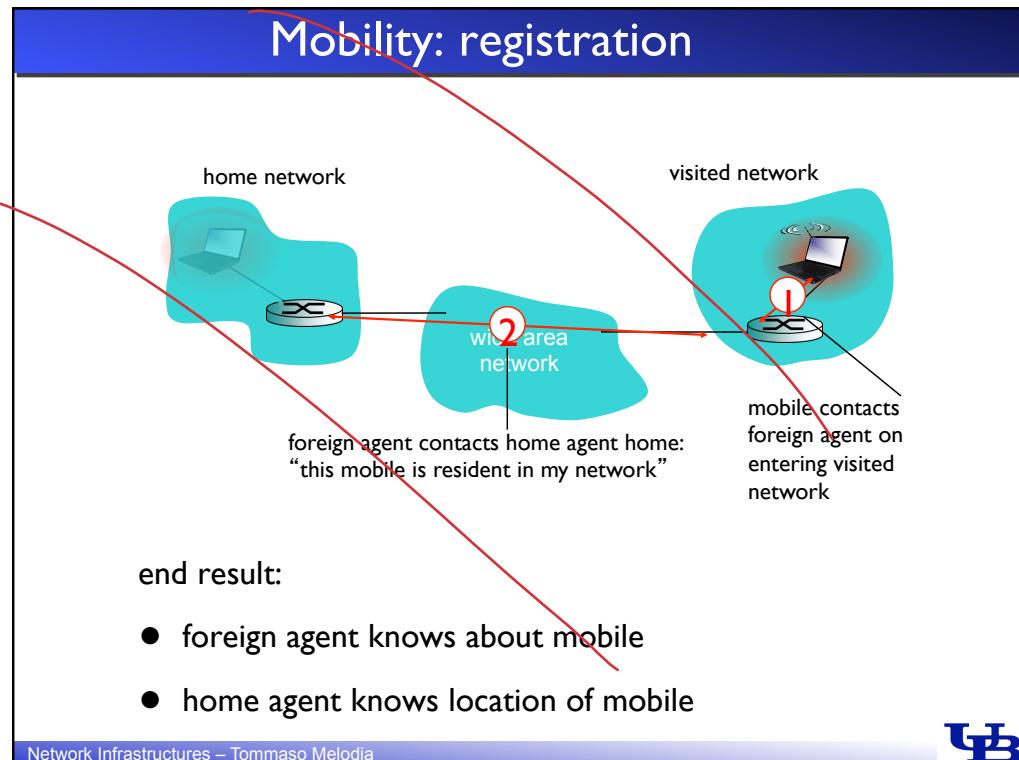


## Mobility: approaches

- *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

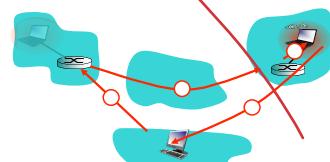
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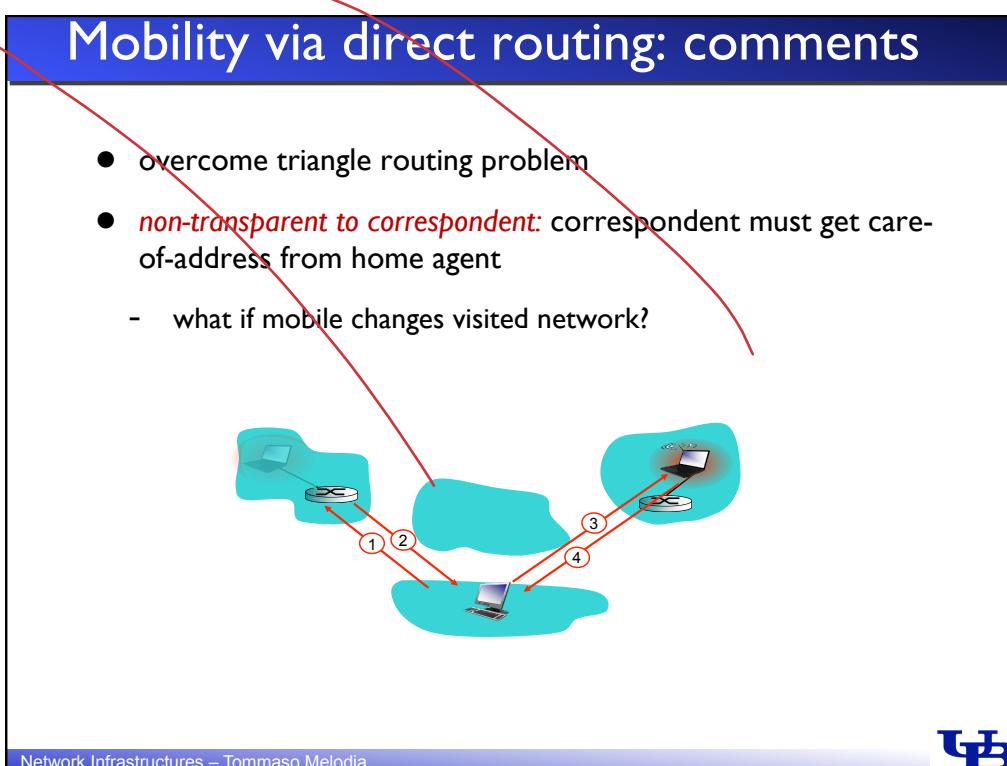
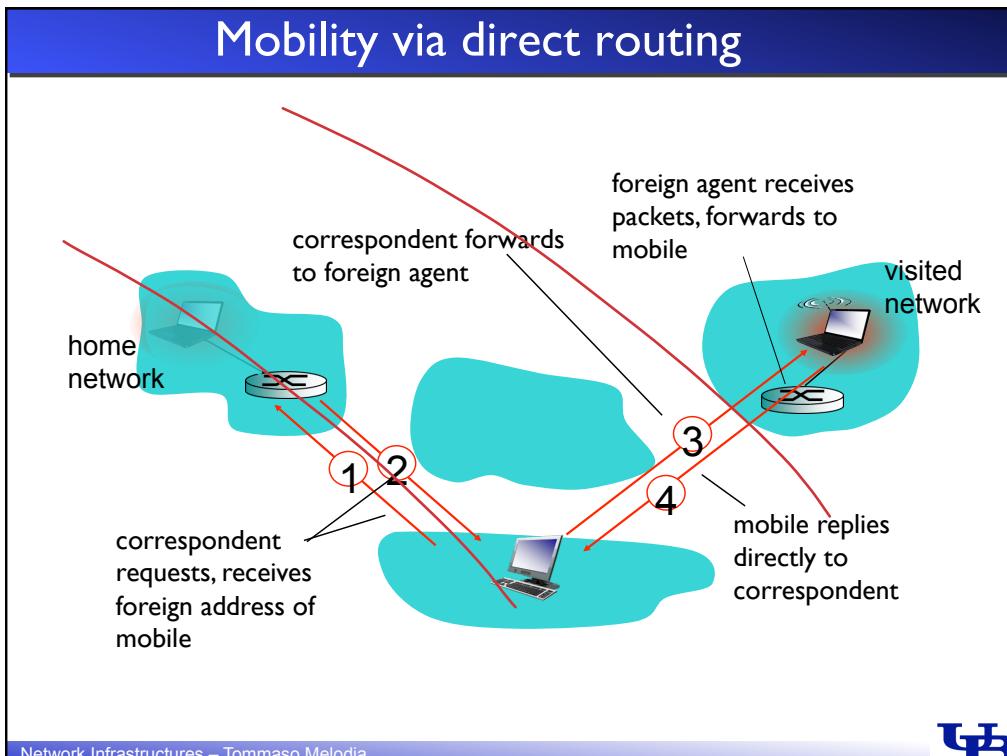
## Indirect Routing: comments

- 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



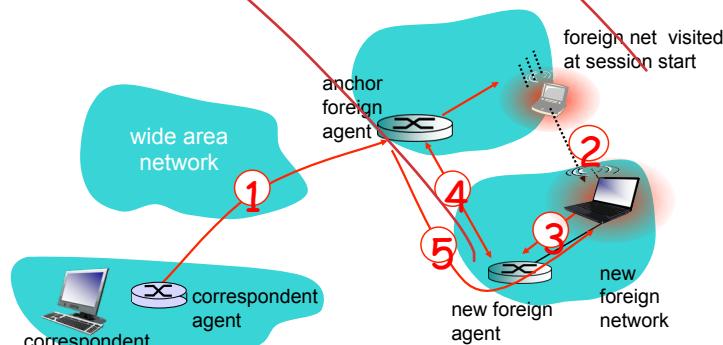
## Indirect routing: moving between networks

- 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!*



## 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)



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#### Handling mobility in cellular networks

#### Mobility and higher-layer protocols

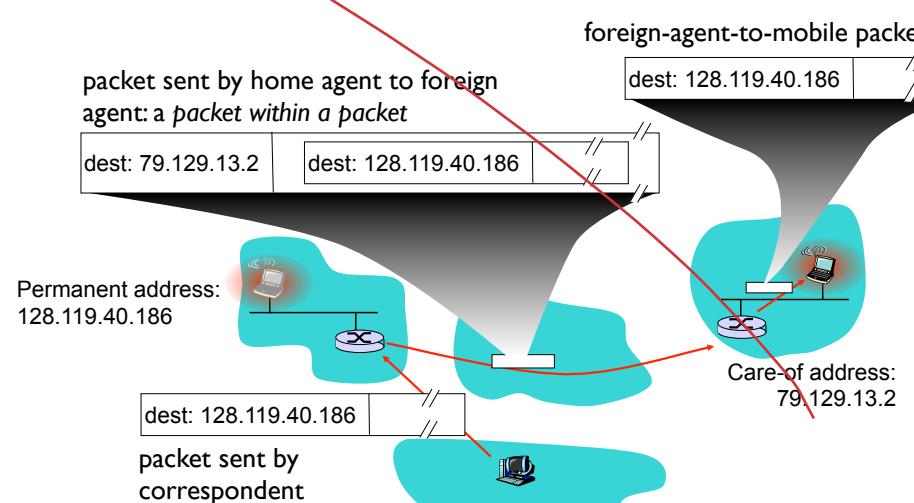
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## Mobile IP

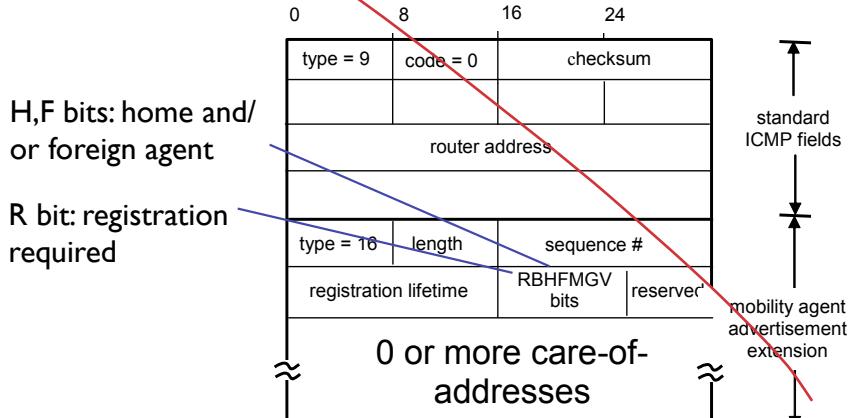
- RFC 3344
- has many features we've seen:
  - home agents, foreign agents, foreign-agent registration, care-of-addresses, encapsulation (packet-within-a-packet)
- three components to standard:
  - indirect routing of datagrams
  - agent discovery
  - registration with home agent

## Mobile IP: indirect routing



## Mobile IP: agent discovery

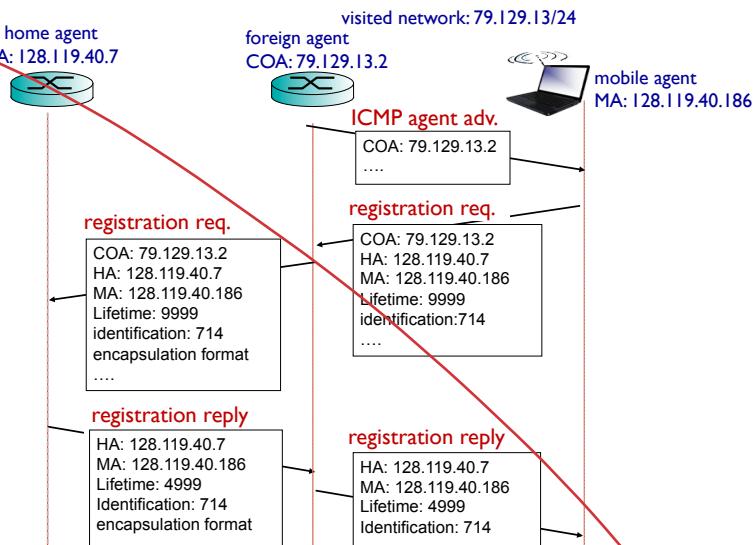
- **agent advertisement:** foreign/home agents advertise service by broadcasting ICMP messages (typefield = 9)



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## Mobile IP: registration example

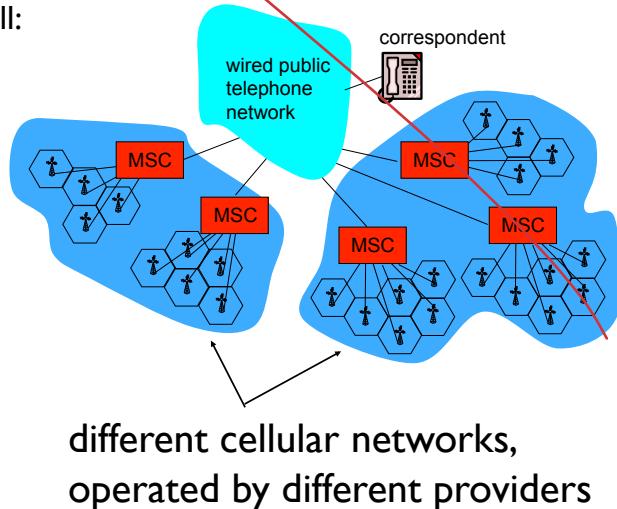


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## Components of cellular network architecture

recall:



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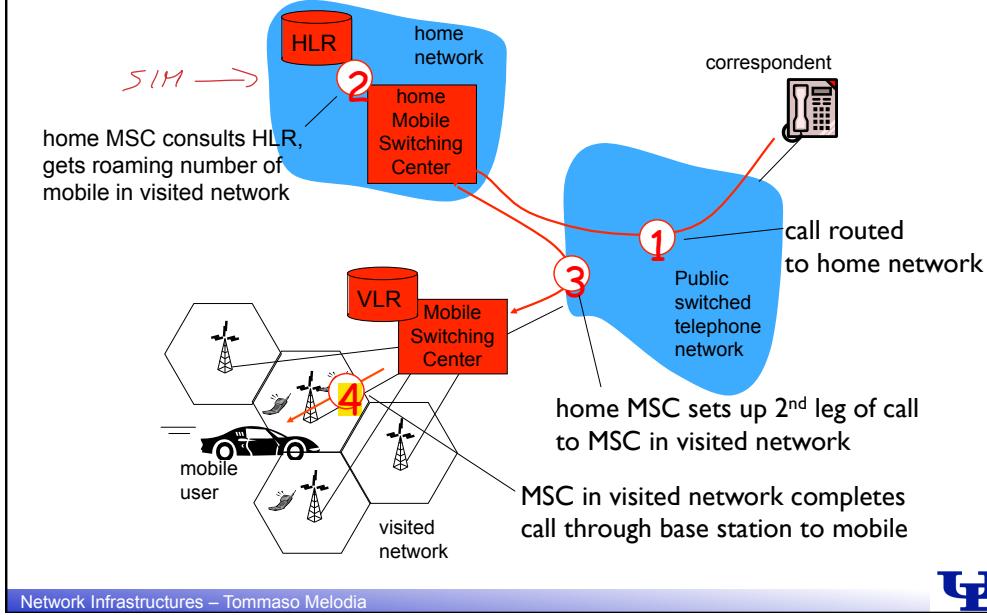
## Handling mobility in cellular networks

- ***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

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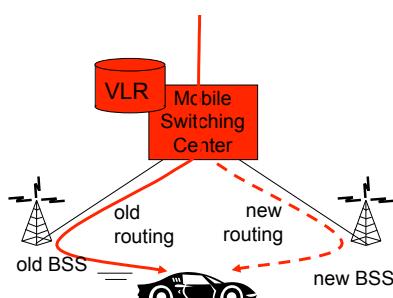


## GSM: indirect routing to mobile

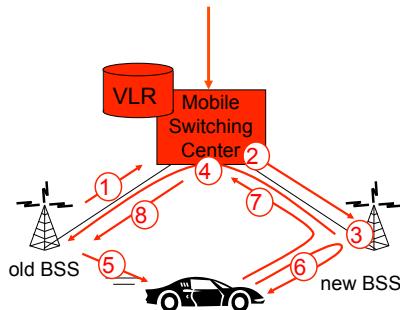


## GSM: handoff with common MSC

- **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

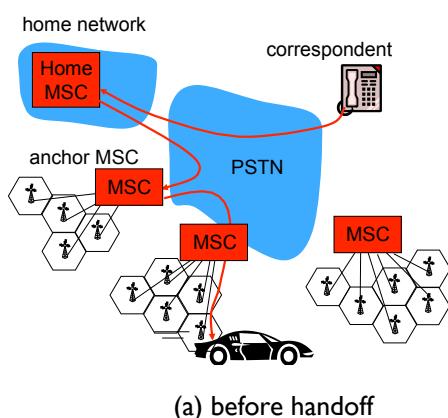


1. old BSS informs MSC of impending handoff, provides list of 1+ new BSSs
2. MSC sets up path (allocates resources) to new BSS
3. new BSS allocates radio channel for use by mobile
4. new BSS signals MSC, old BSS: ready
5. old BSS tells mobile: perform handoff to new BSS
6. mobile, new BSS signal to activate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

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## GSM: handoff between MSCs

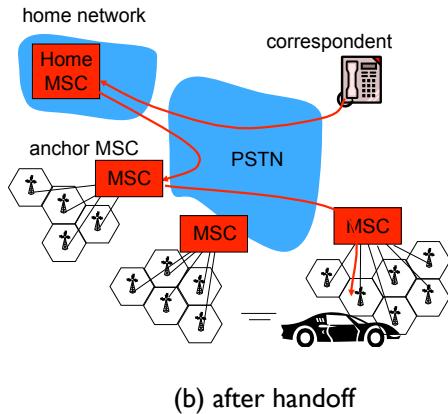


- **anchor MSC:** first MSC visited during call
  - call remains routed through anchor MSC
- **new MSCs add on to end of MSC chain** as mobile moves to **new MSC**
- optional path minimization step to shorten multi-MSC chain

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## GSM: handoff between MSCs



- ❖ **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

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## Mobility: GSM versus Mobile IP

| GSM element   | Comment on GSM element   | Mobile IP element      |
|---|--|------------------------|
| <b>Home system</b>  | Network to which mobile user's permanent phone number belongs  | <b>Home network</b>    |
| <b>Gateway Mobile Switching Center, or "home MSC". Home Location Register (HLR)</b> | 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 | <b>Home agent</b>      |
| <b>Visited System</b>   | Network other than home system where mobile user is currently residing   | <b>Visited network</b> |
| <b>Visited Mobile services Switching Center. Visitor Location Record (VLR)</b>      | 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  | <b>Foreign agent</b>   |
| <b>Mobile Station Roaming Number (MSRN), or "roaming number"</b>                    | Routable address for telephone call segment between home MSC and visited MSC, visible to neither the mobile nor the correspondent.   | <b>Care-of-address</b> |

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## Wireless, mobility: impact on higher layer protocols

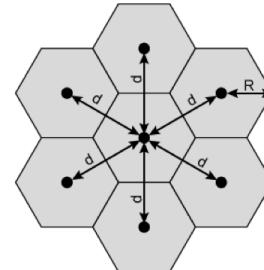
- logically, impact *should* be minimal ...
  - best effort service model remains unchanged
  - TCP and UDP can (and do) run over wireless, mobile
- ... but performance-wise:
  - packet loss/delay due to bit-errors (discarded packets, delays for link-layer retransmissions), and handoff
  - TCP interprets 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

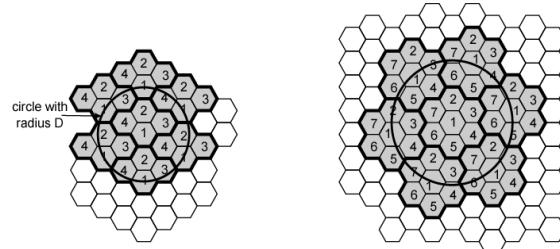
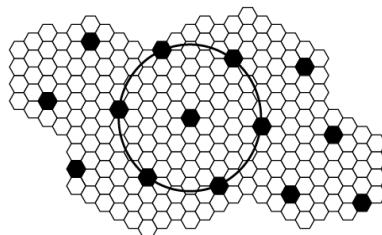
- By power control at the Base Station:
  - Allow communications within cell on given frequency
  - Limit interfering power to adjacent cells
  - Allow re-use of frequencies in nearby cells
  - Use same frequency for multiple transmissions

*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  $N = 19$ 

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## Contents

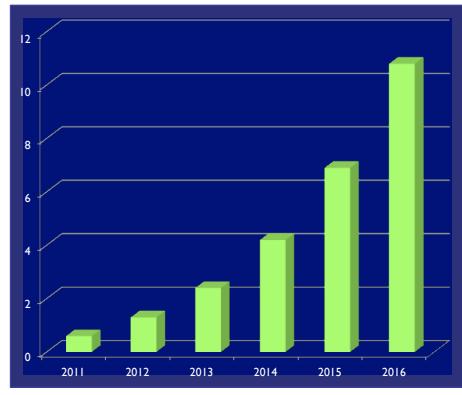
- Part 2: LTE and LTE Advanced
  - Key Technologies in LTE
  - Key Technologies in LTEA

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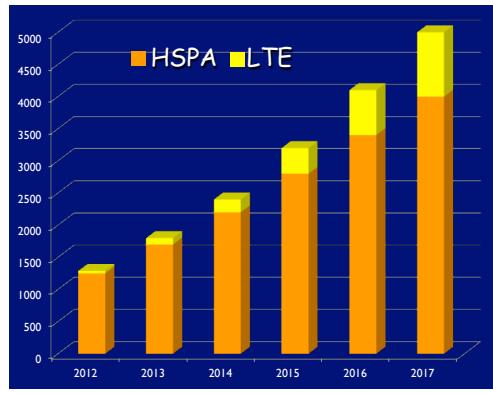
## Prediction of Future Wireless Traffic

Exabytes per month



Source: Cisco VNI Mobile 2012

3GPP Subscriptions (millions)



Source: Informa Telecoms &amp; Media Forecast

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## Requirements



Explosion of  
Users' Demand  
for Mobile Data

Many new  
Services and  
Applications



Ubiquitous Wireless  
Broadband Access to a Very  
Large Cloud Platform

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## 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

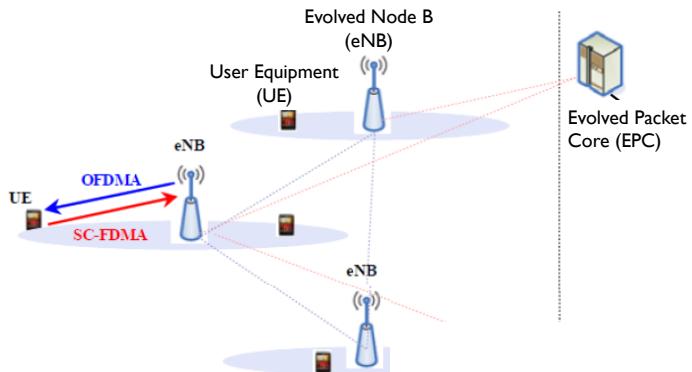


## LTE Key Parameters

| Frequency Range  | UMTS FDD bands and UMTS TDD bands |  |       |        |        |        |
|--|-----------------------------------|--|-------|--------|--------|--------|
| Channel bandwidth<br>1 Resource Block (RB)<br>=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)<br>300 Mbps (UE category 5, 4x4 MIMO, 20 MHz)   |       |        |        |        |
|  | Uplink                            | 75 Mbps (20 MHz)   |       |        |        |        |



## Basic Architecture of LTE



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## Contents

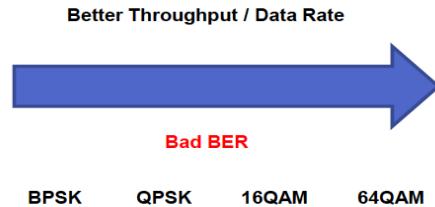
- Key Technologies in LTE
  - Adaptive Modulation and Coding (AMC)
  - Hybrid ARQ (HARQ)
  - Spectrum flexibility: OFDMA and SC-FDMA
  - MIMO Transmission
- Key Technologies in LTEA

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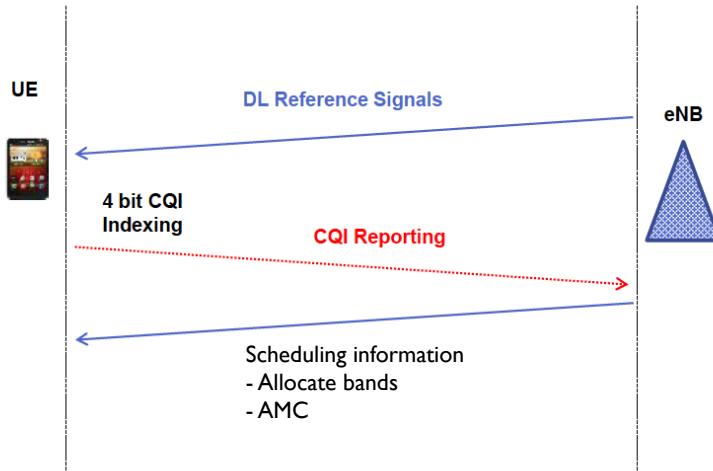
## Adaptive Modulation & Coding (AMC)

- Modulation without coding:

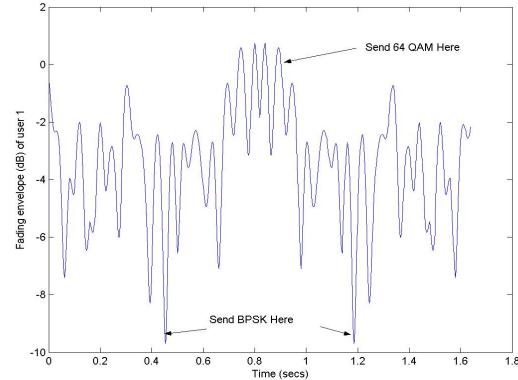


- Channel coding: better BER but lower data rate
- By using channel Quality Indication (CQI), the transmitter can adaptively determine the modulation and coding schemes
  - Tradeoff between better BER and higher data rate

## Channel Quality Indication (CQI)



## Adaptive Modulation

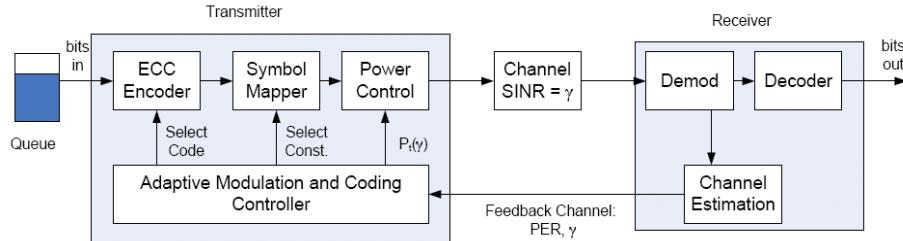


Vary the “M” in the MQAM constellation to the appropriate SNR.

## Adaptive modulation & coding: Multi-User

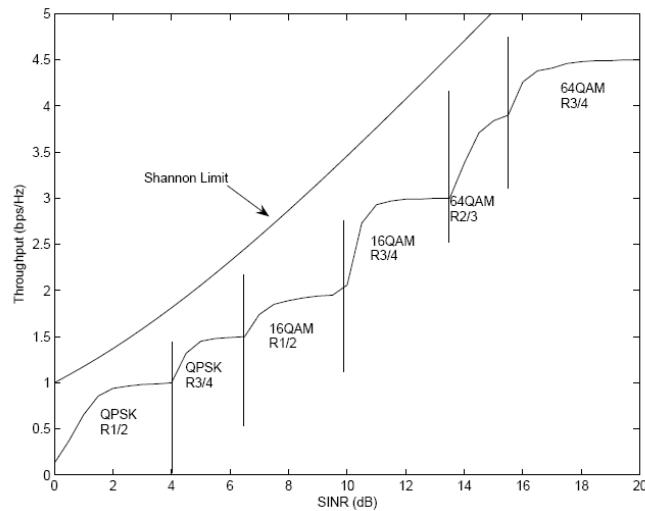
- Exploit multi-user diversity
  - Users with **high SNR**: use MQAM (large M) + high code rates
  - Users with **low SNR**: use BPSK + low code rates (i.e. heavy error protection)
  
- In LTE, different users (assigned to time-frequency slots within a frame) would be getting a different rate
  - i.e.,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



## Contents

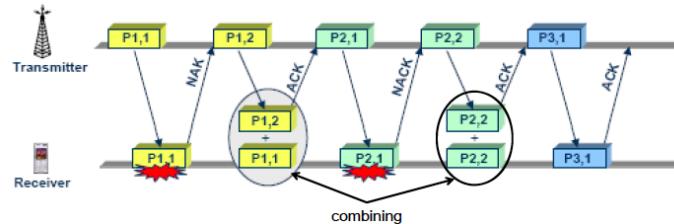
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## Hybrid Automatic Repeat Request (HARQ)

- 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

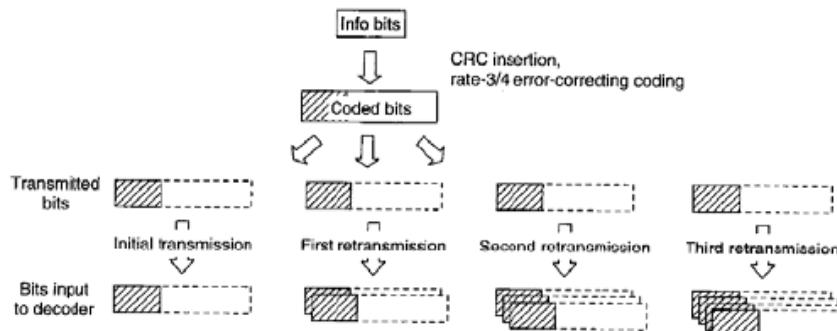


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## HARQ

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

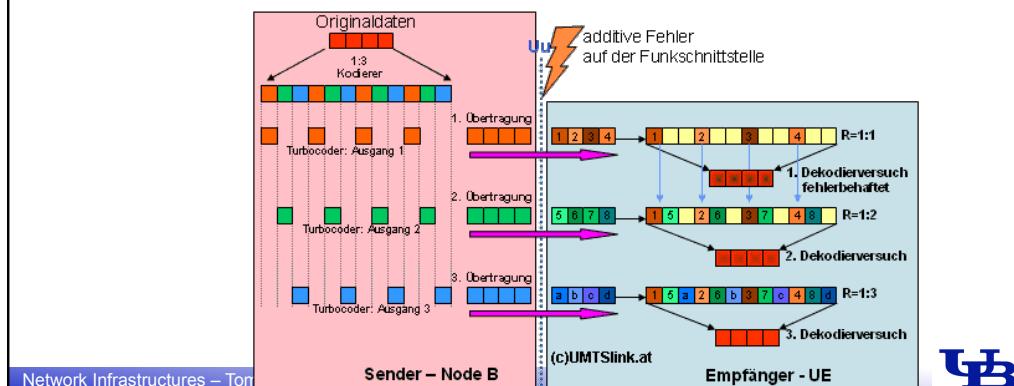


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## HARQ

- 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 inactive 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 2<sup>nd</sup> 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



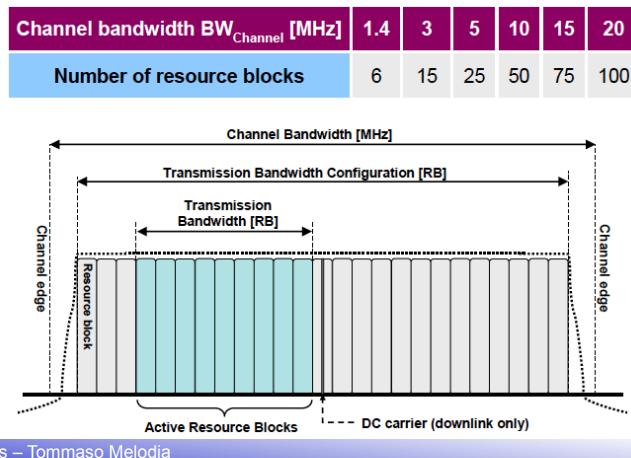
## Contents

- Key Technologies in LTE
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  - Spectrum flexibility: OFDMA and SC-FDMA
  - MIMO Transmission
- Key Technologies in LTEA



## 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



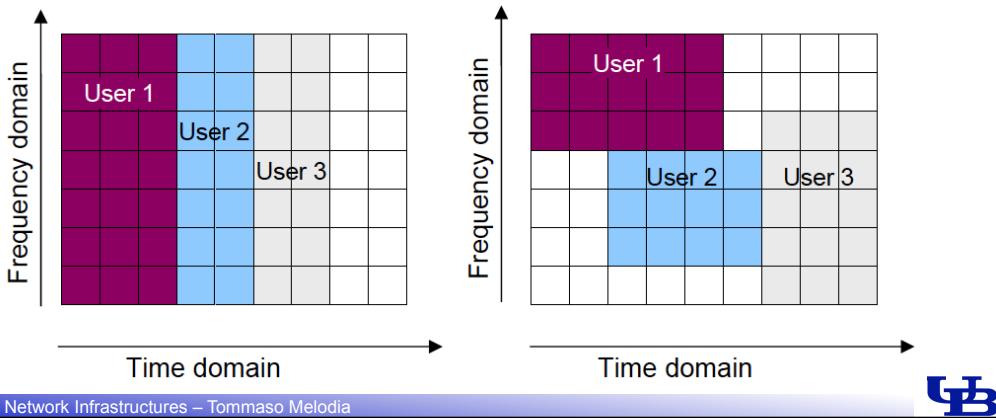
## Spectrum flexibility: OFDMA and SC-FDMA

- 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

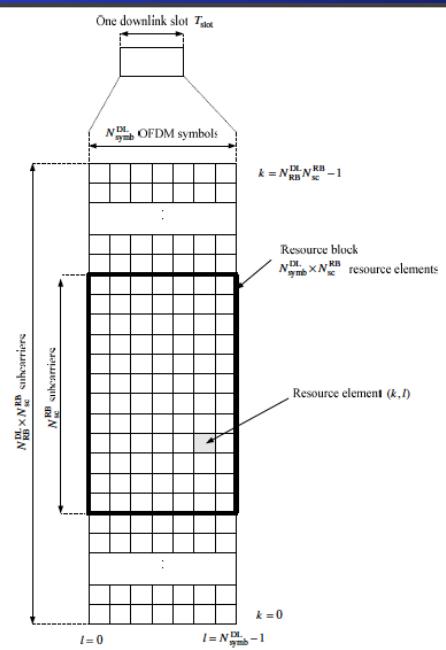


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## Resource Allocation

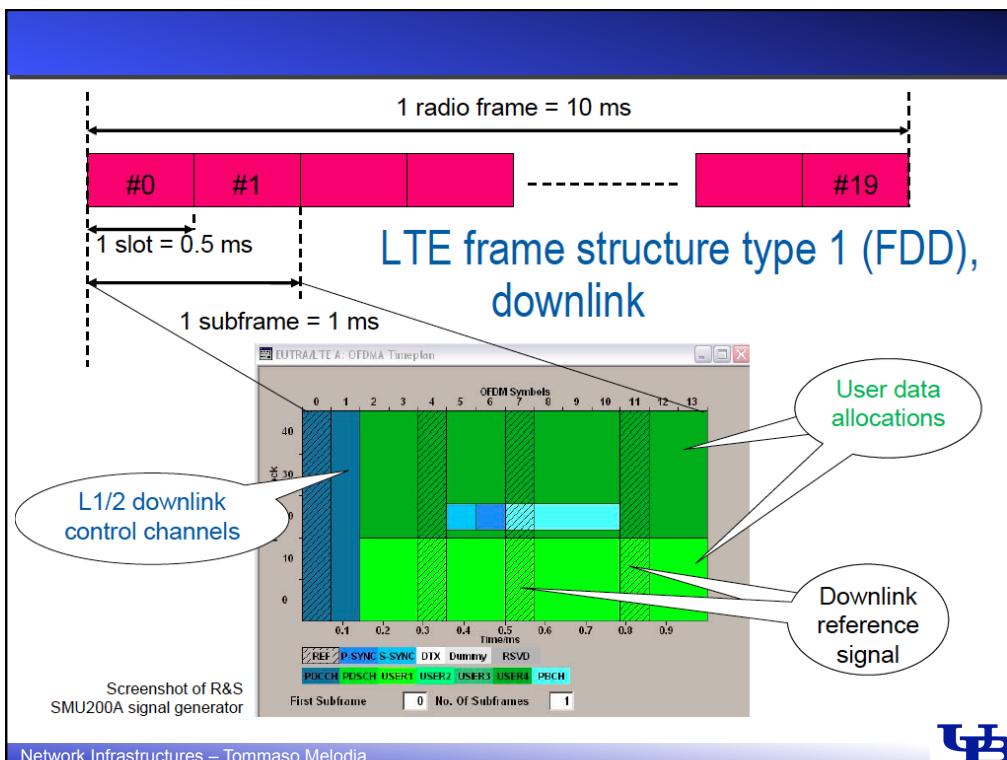
- Smallest resource unit is Resource Element: 1 symbol on 1 subcarrier
  - Uniquely identified by the index pair  $(k,l)$  in a slot
- But minimum allocation for transmission is a Resource Block (RB)
- 1 RB spans 12 sub-carriers ( $12 \times 15$  kHz = 180 kHz) in the frequency domain and 1 Time Slot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

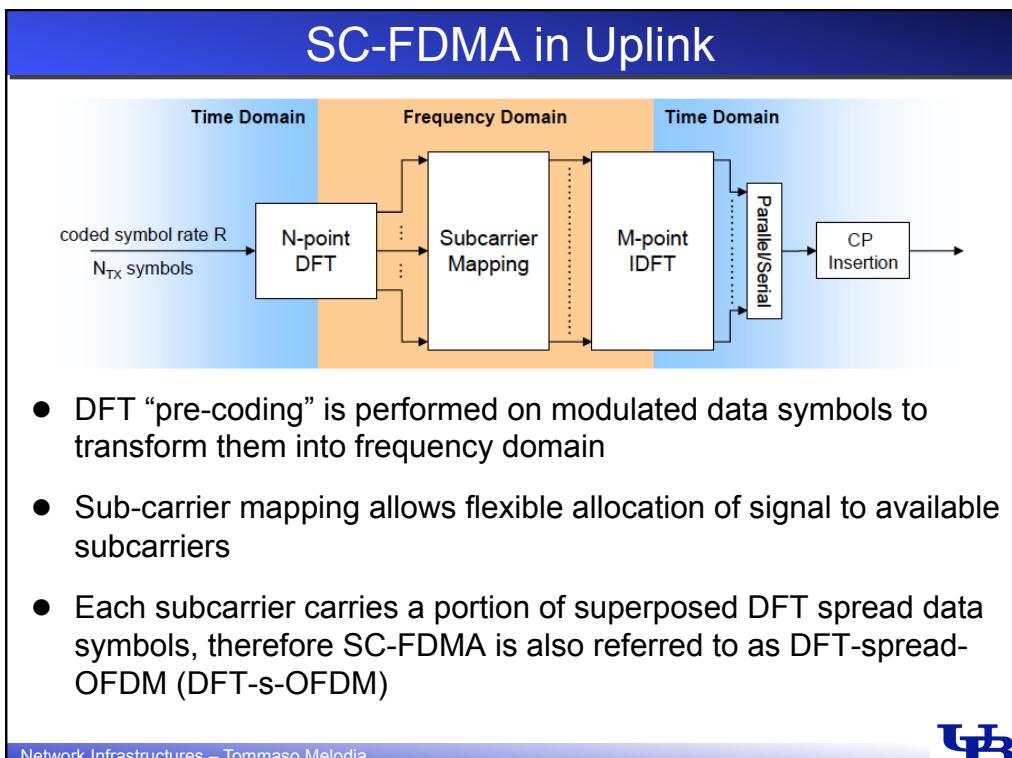
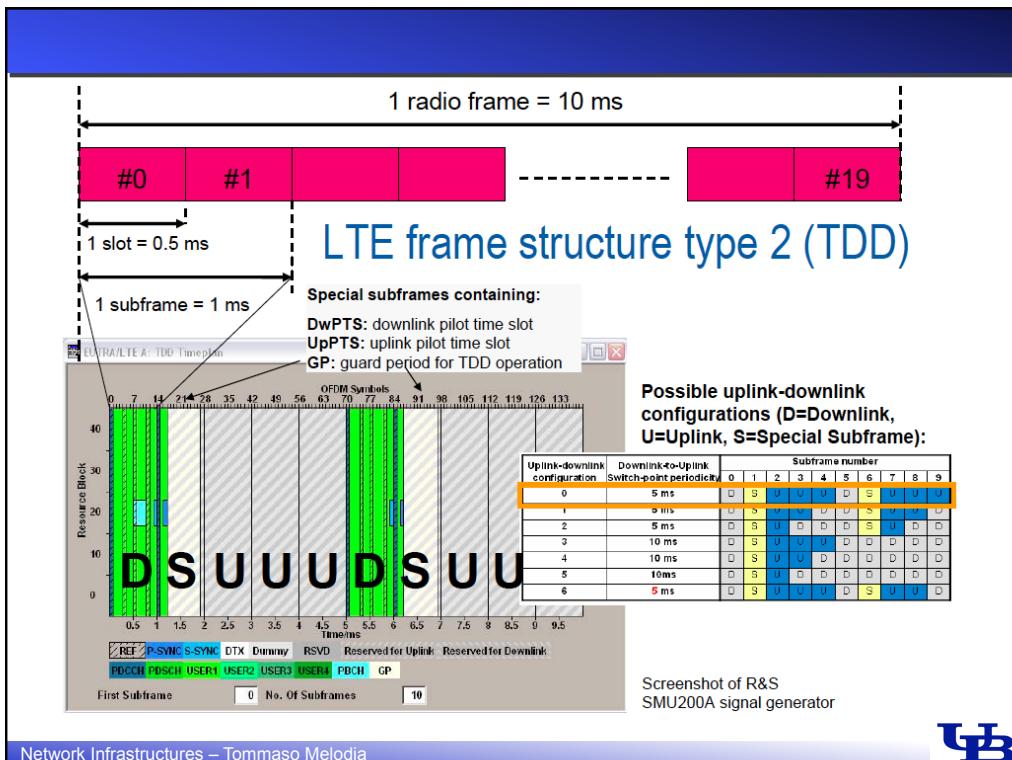


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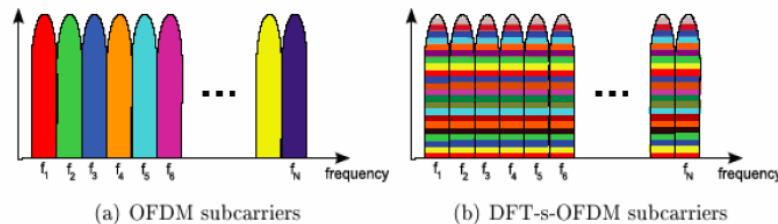
- $10 \text{ MHz} = 50 \text{ RB} \rightarrow$   
 $50 \text{ RB} * 180 \text{ kHz} = 9.0 \text{ MHz} + 1 \text{ unused DC subcarrier}$   
 $= 9.015 \text{ MHz}$
- 1 subframe has 2 time slots.
- With normal (extended) cyclic prefix (CP) we got 7 (6) OFDM symbols per time slot



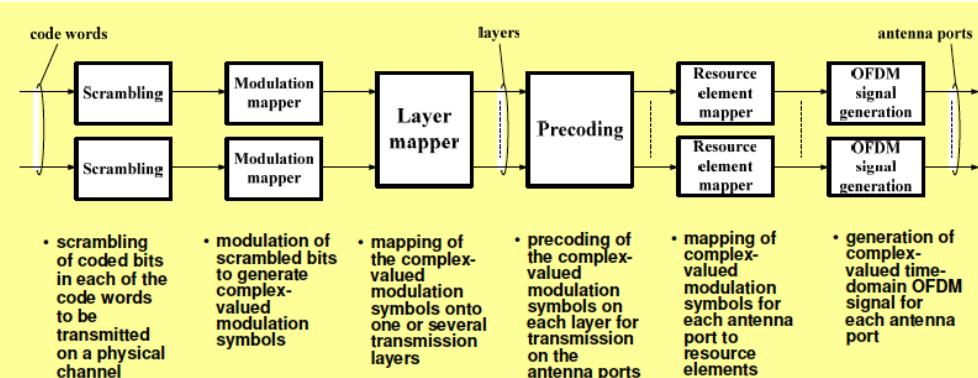


## OFDMA vs SC-FDMA

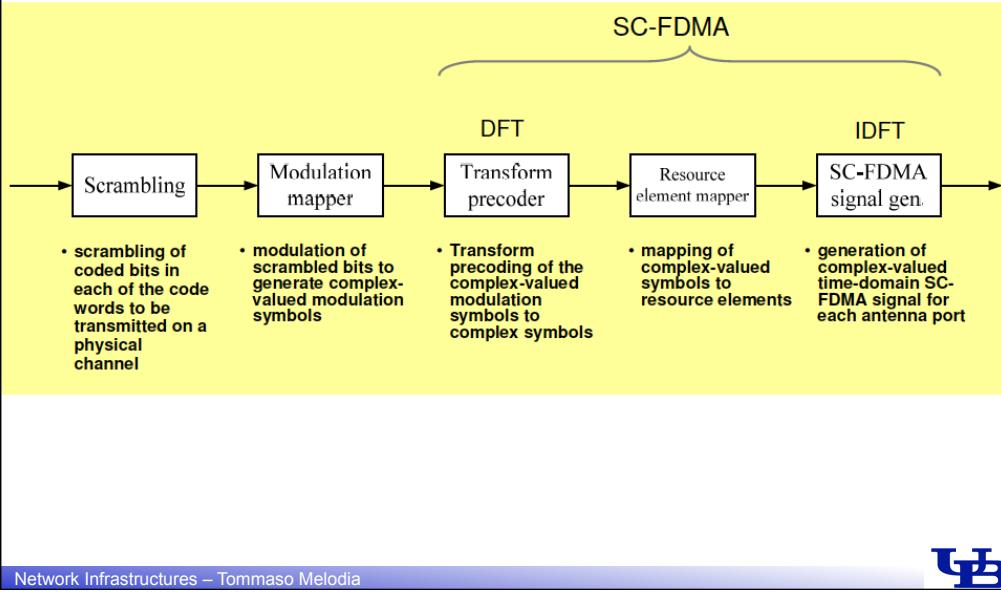
- In OFDMA, each sub-carrier only carries information related to one specific symbol
- In SC-FDMA, each sub-carrier contains information of ALL transmitted symbols



## Downlink Physical Channel Processing



## Uplink Physical Channel Processing



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## Contents

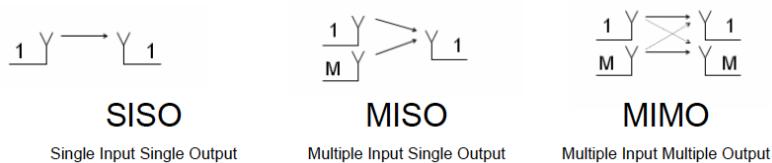
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## MIMO Transmission

- 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



## 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

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## Transmit Diversity

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

↑  
Time-spread  
↓  
Channel Time-variance
- With suitable choices of array geometry and antenna element patterns,  

$$H(\tau) = H$$
 which is an  $MR \times MT$  matrix with complex Gaussian i. i. d random variables
- Accurate for NLOS rich-scattering environments, with sufficient antenna spacing at transmitter and receiver with all elements identically polarized

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## 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  $\text{trace}(Q) < P$  according to the power constraint

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

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

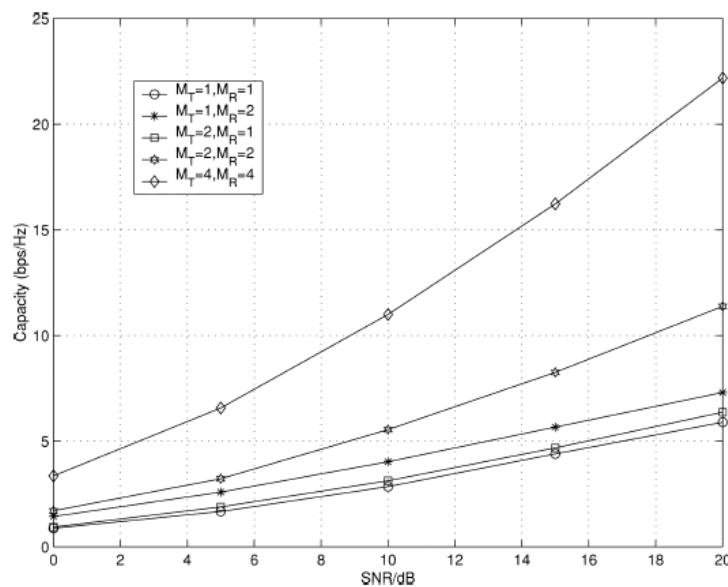
The optimal choice for *blind* transmission

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

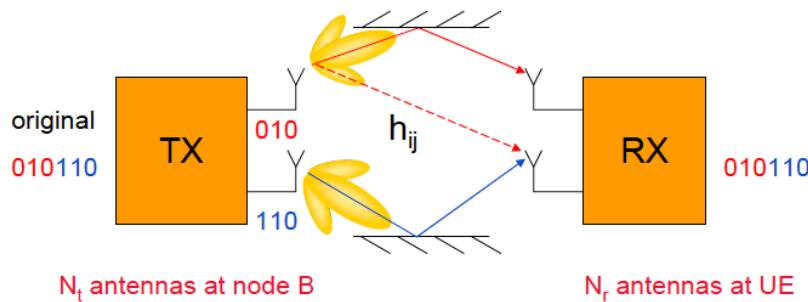
$$C_{EP} = \min(M_T, M_R) \log_2 (P/M_T) + \text{constant b/s/Hz}$$



## Capacity of MIMO Channels



## Increasing Data Rate with Spatial Multiplexing

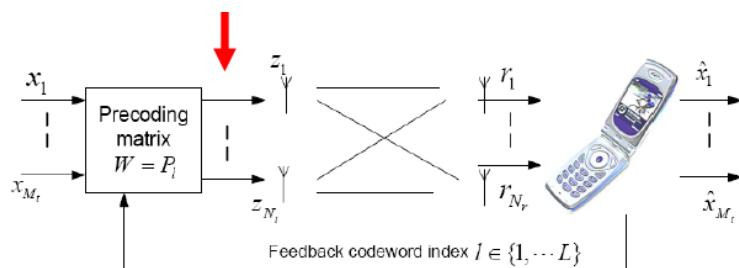


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## LTE Downlink Spatial Multiplexing

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

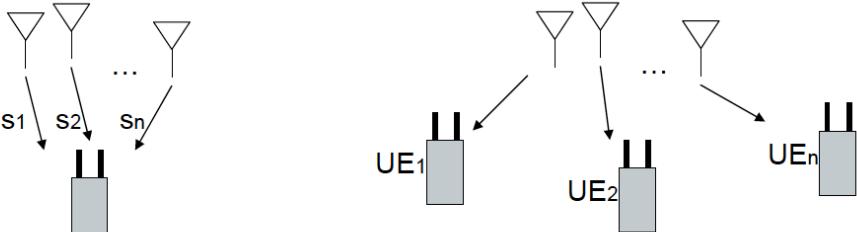


- Optimum precoding matrix is selected from predefined “codebook” known at both eNB and UE
- UE estimates the channel, selects the best precoding matrix at the moment and sends back its index

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## SU-MIMO versus MU-MIMO



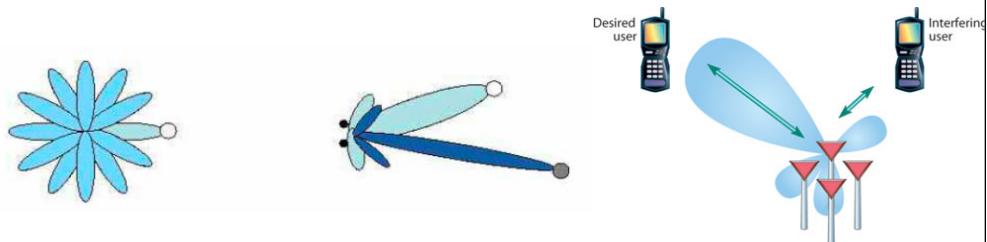
|  |  |
|--|--|
| <p><b>I SU (Single User)-MIMO</b></p> <ul style="list-style-type: none"> <li>─ Goal: to increase user data rate</li> <li>─ Simultaneous transmission of different data streams to 1 user</li> <li>─ Efficient when the user experiences good channel conditions</li> </ul> | <p><b>I MU (Multiple User)-MIMO</b></p> <ul style="list-style-type: none"> <li>─ Goal: to increase sector capacity</li> <li>─ Selection of the users experiencing good channel conditions</li> <li>─ Efficient when a large number of users have an active data transmission simultaneously</li> </ul> |
|--|--|

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**UB**

## 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

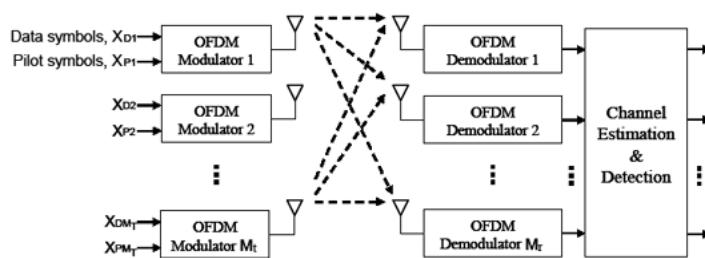


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**UB**

## 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



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## Contents

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

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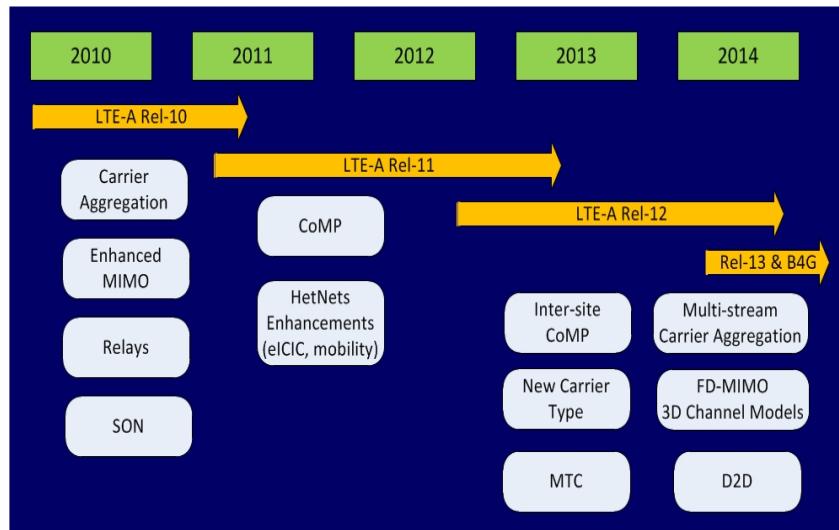
## LTE vs LTEA

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

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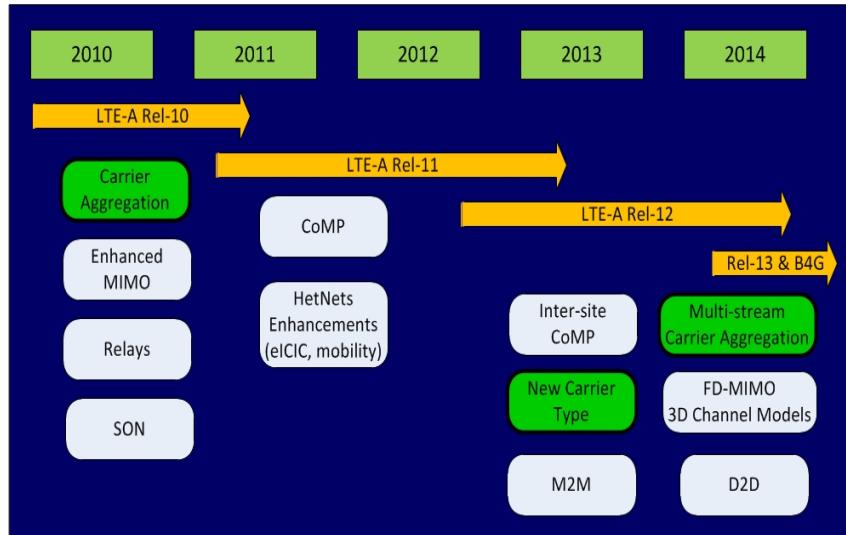
## Key Technologies in LTEA



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## Key Technologies in LTEA



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## 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

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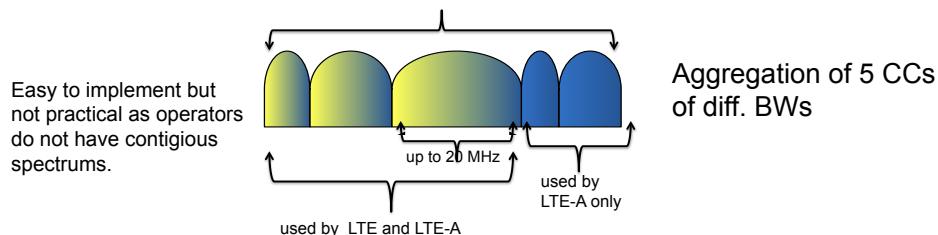
## Carrier aggregation

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



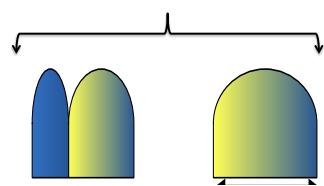
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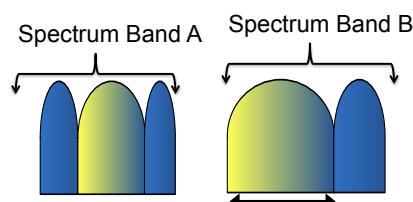
## Carrier aggregation

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.

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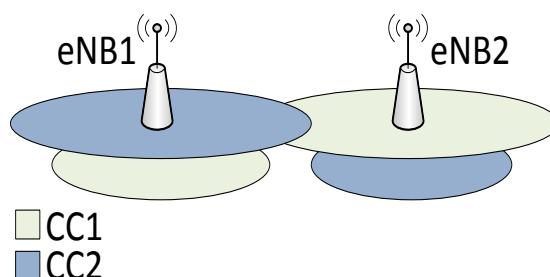


## Carrier aggregation: current status

- 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

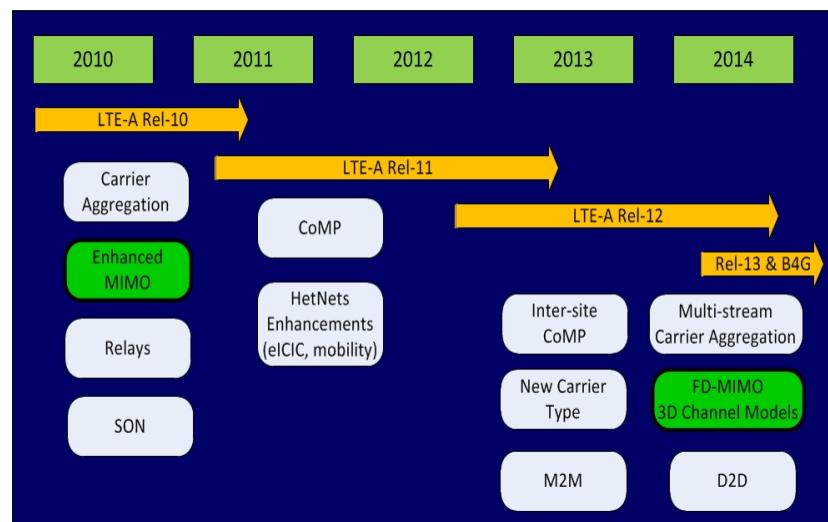
- Higher Throughput
  - Wider BWs lead to very high bit rates (up to 1Gbps)
- Inter-Cell Interference and Mobility Improvements:
  - Continuous and non-interfering coverage is provided by power adjustments for each carrier



## 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

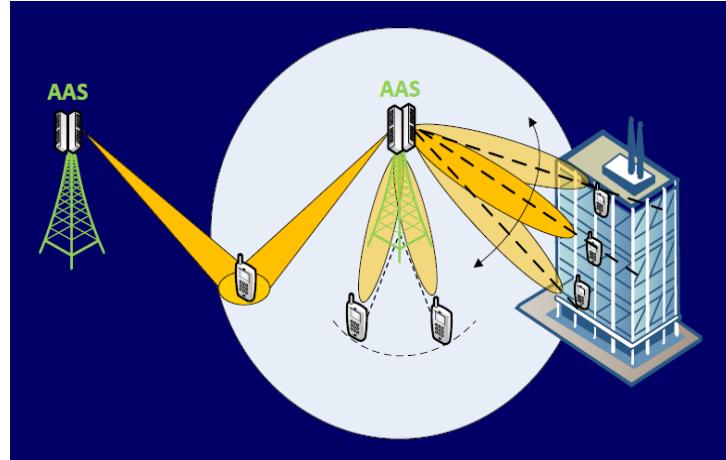


## Full Dimension (FD) MIMO

- 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.



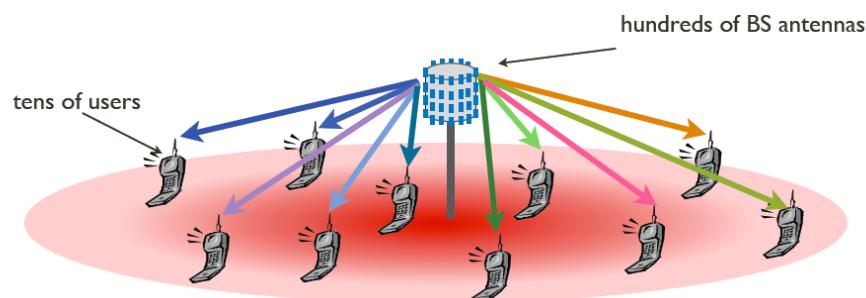
## Full Dimension (FD) MIMO



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## Massive MIMO

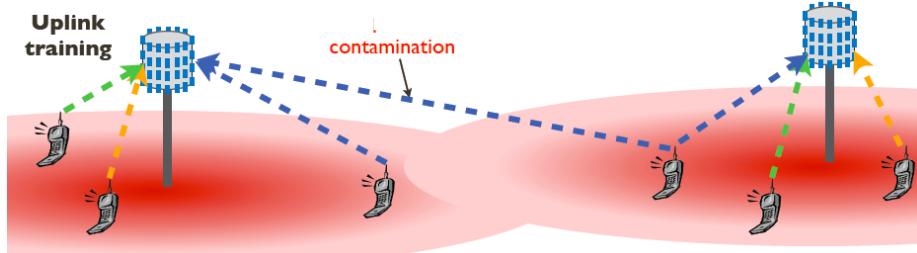


- A very large antenna array at each base station
  - An order of magnitude more antenna elements in conventional systems
- A large number of users are served simultaneously
- An excess of base station (BS) antennas

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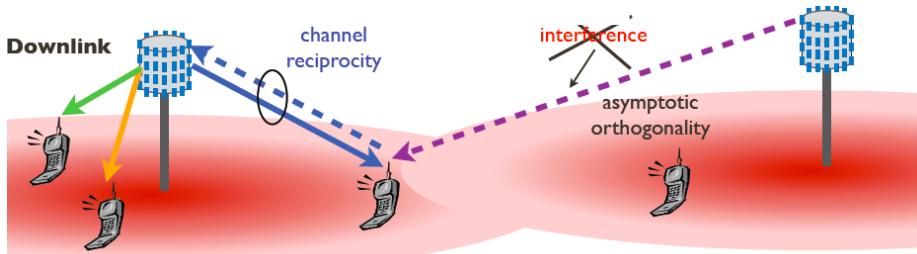
## Massive MIMO



- 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

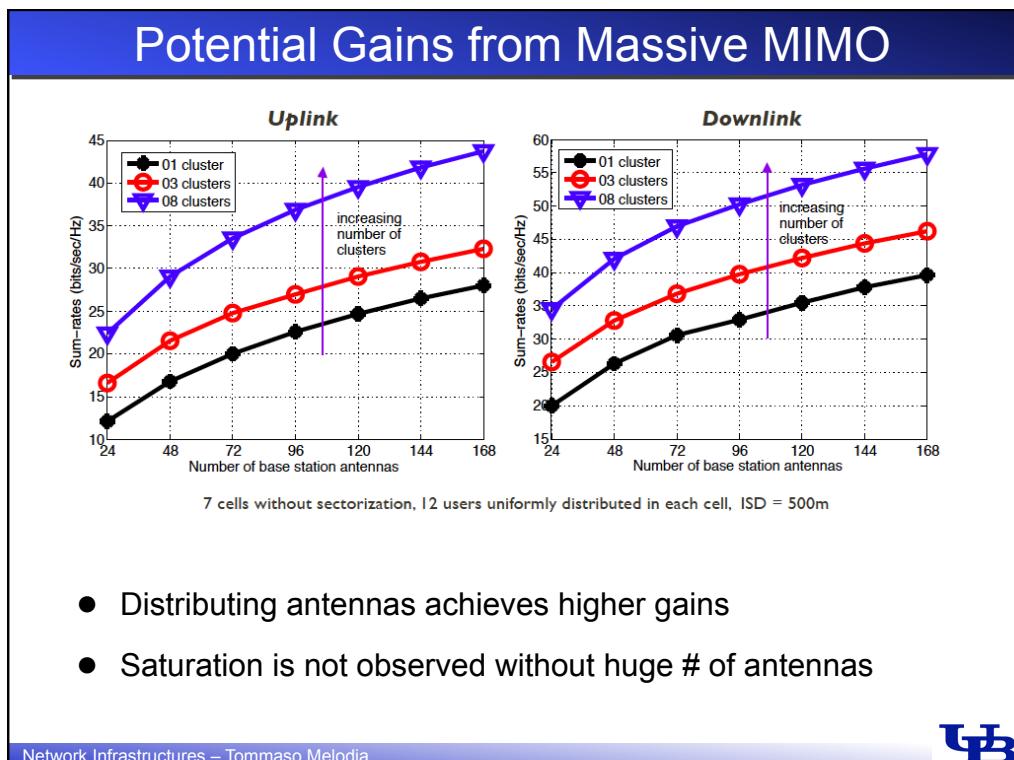
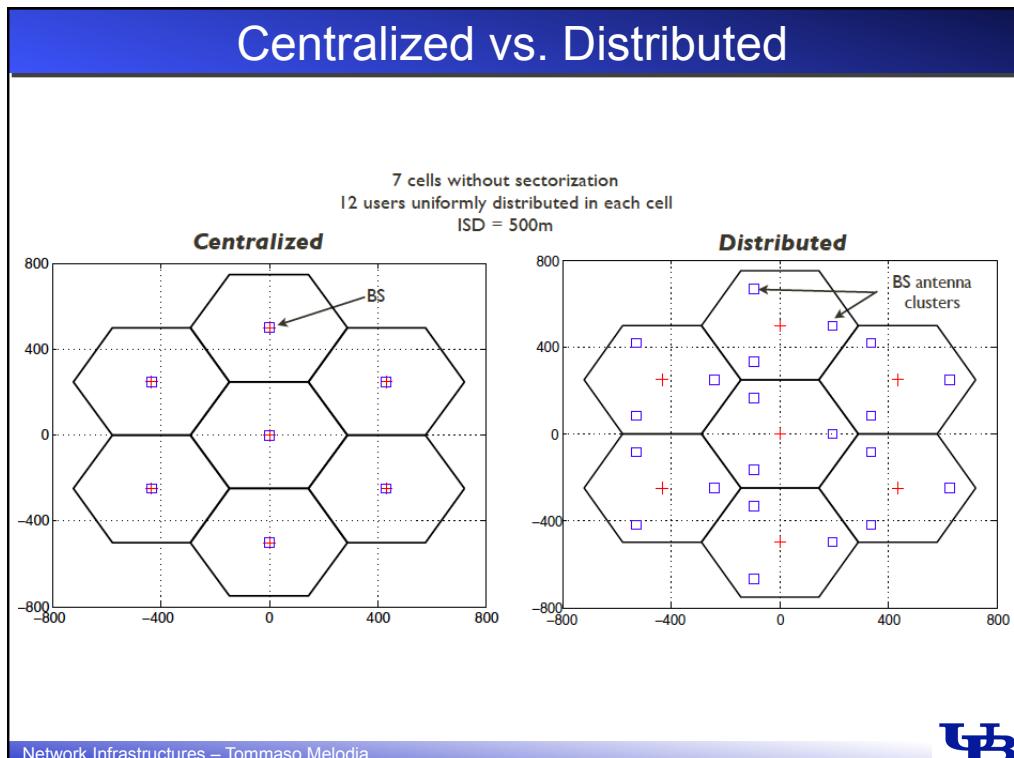


## Massive MIMO

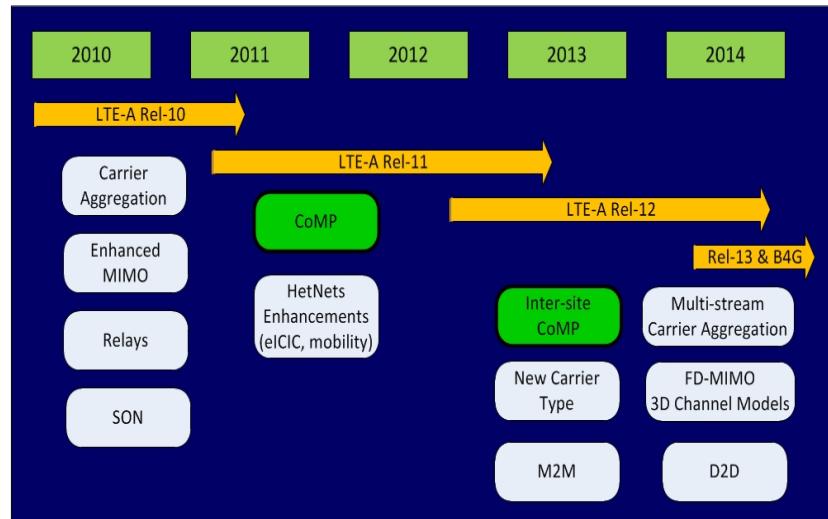


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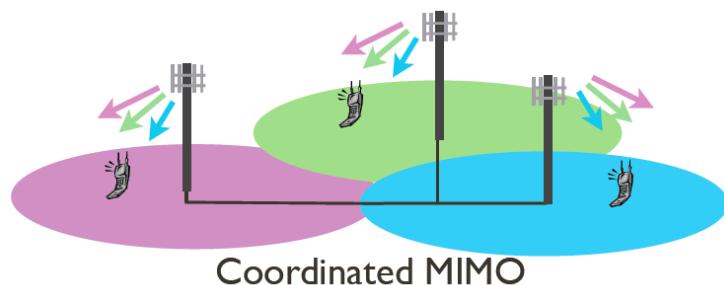
## Key Technologies in LTEA



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## Coordinated MIMO & CoMP



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

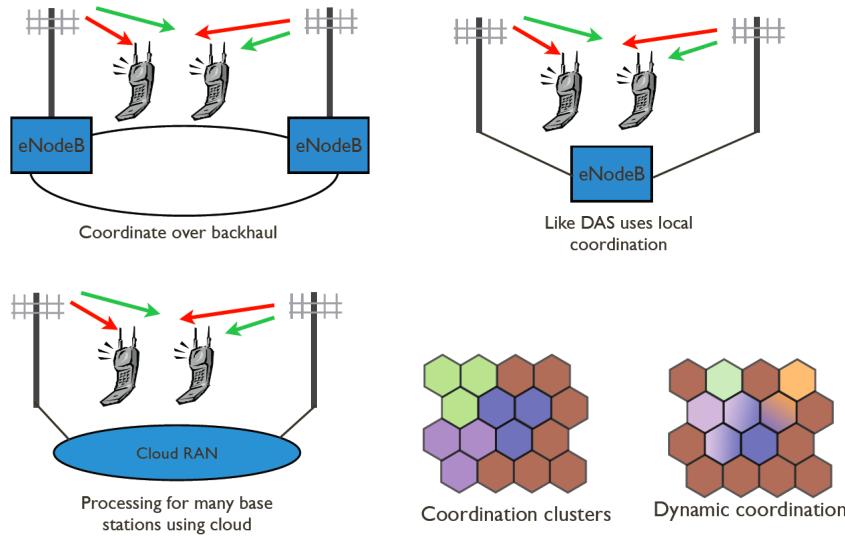
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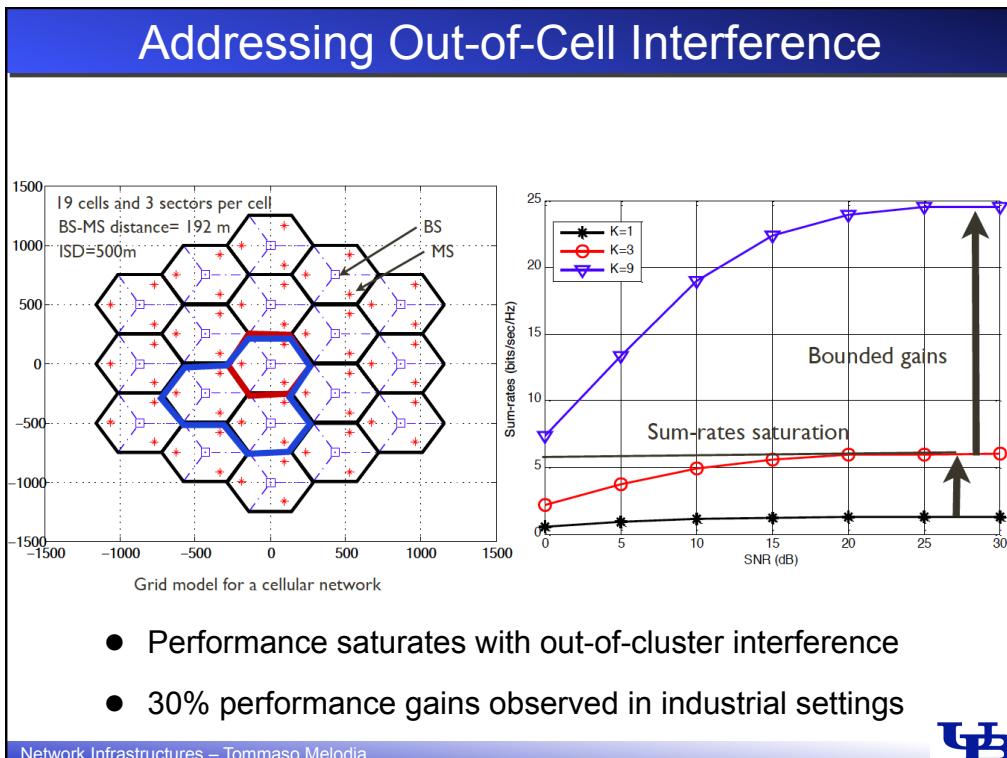
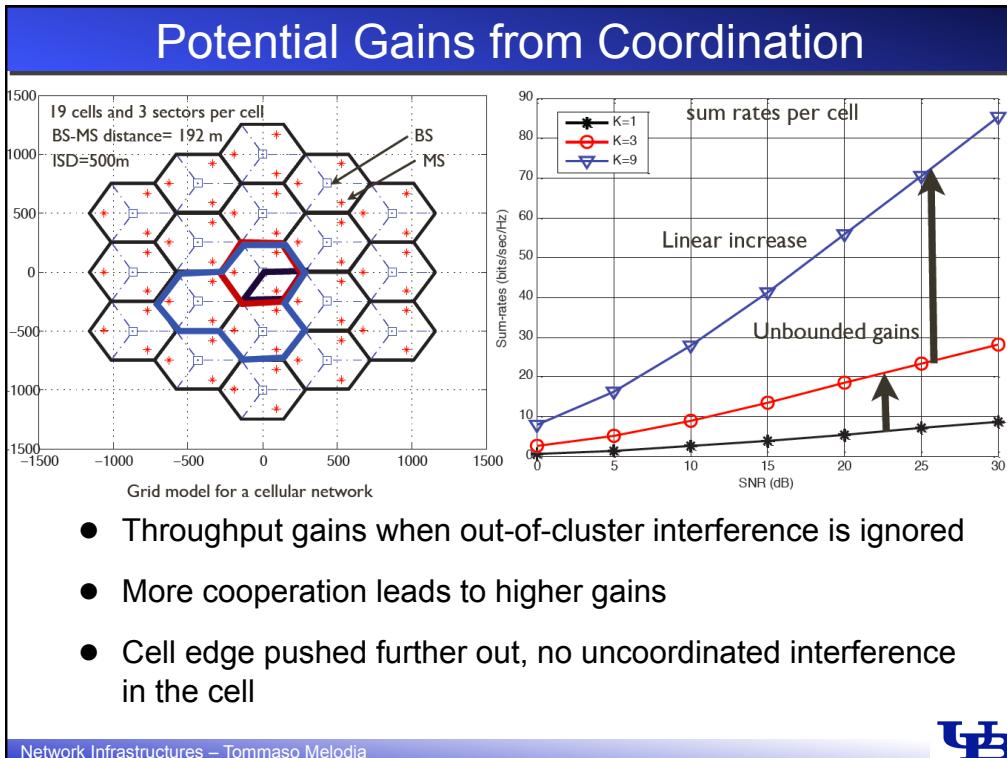


## Coordinated MIMO & CoMP

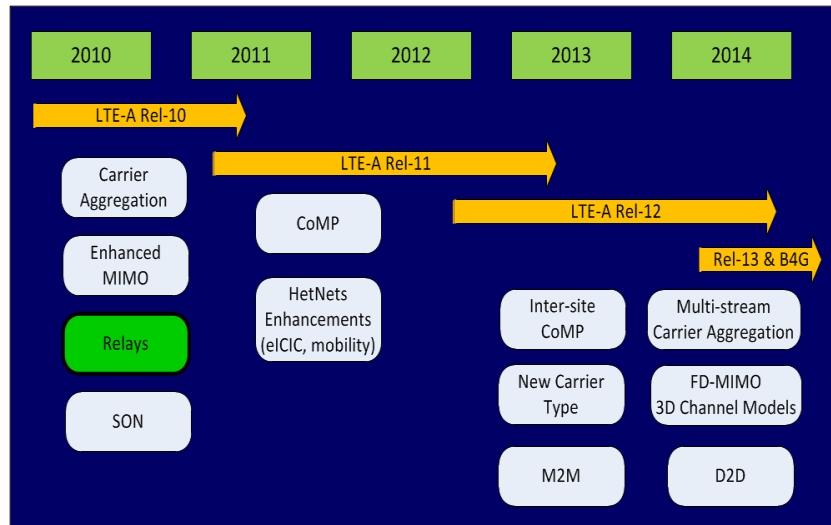
- Set of techniques to improve coverage, cell-edge throughput and system efficiency.
- Principle: UEs at the cell-edge can communicate with several cell sites, both for the DL and UL.
  - Also viewed as Distributed MIMO
  - Coordination can be simple (e.g. signaling to avoid interference) or complex.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

## CoMP Architecture





## Key Technologies in LTEA

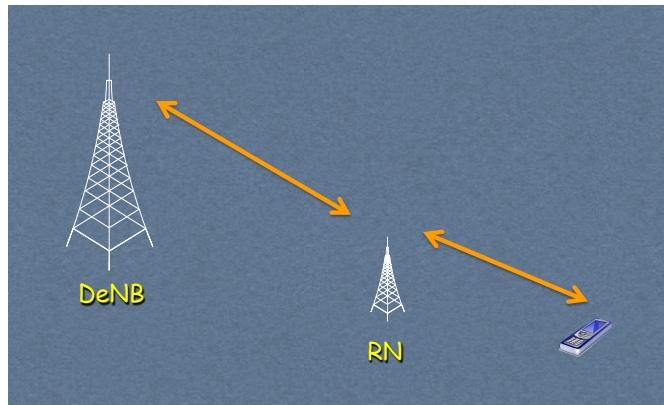


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## Relays

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



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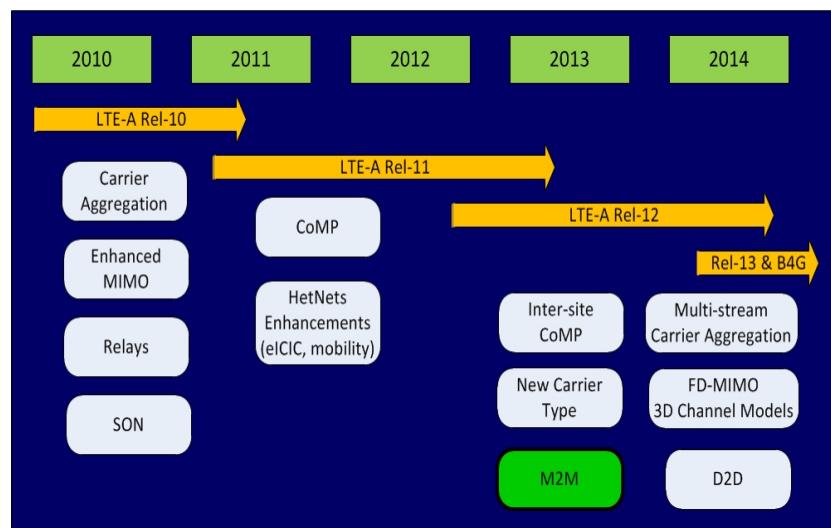
## Benefits of Relays

- 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

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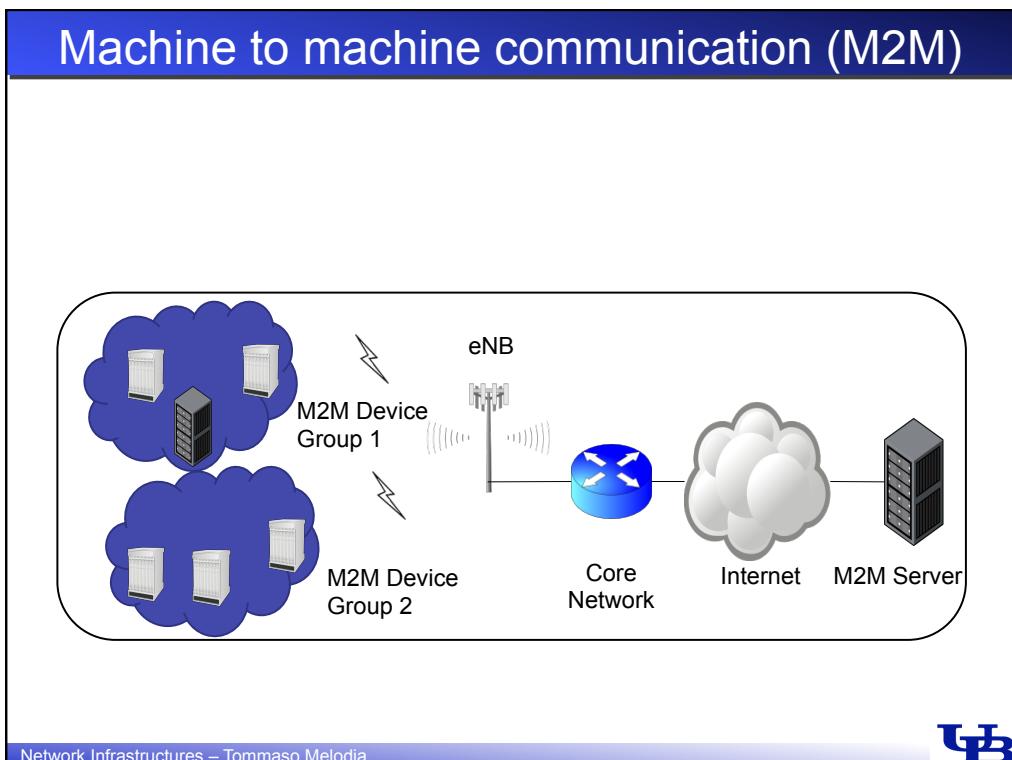
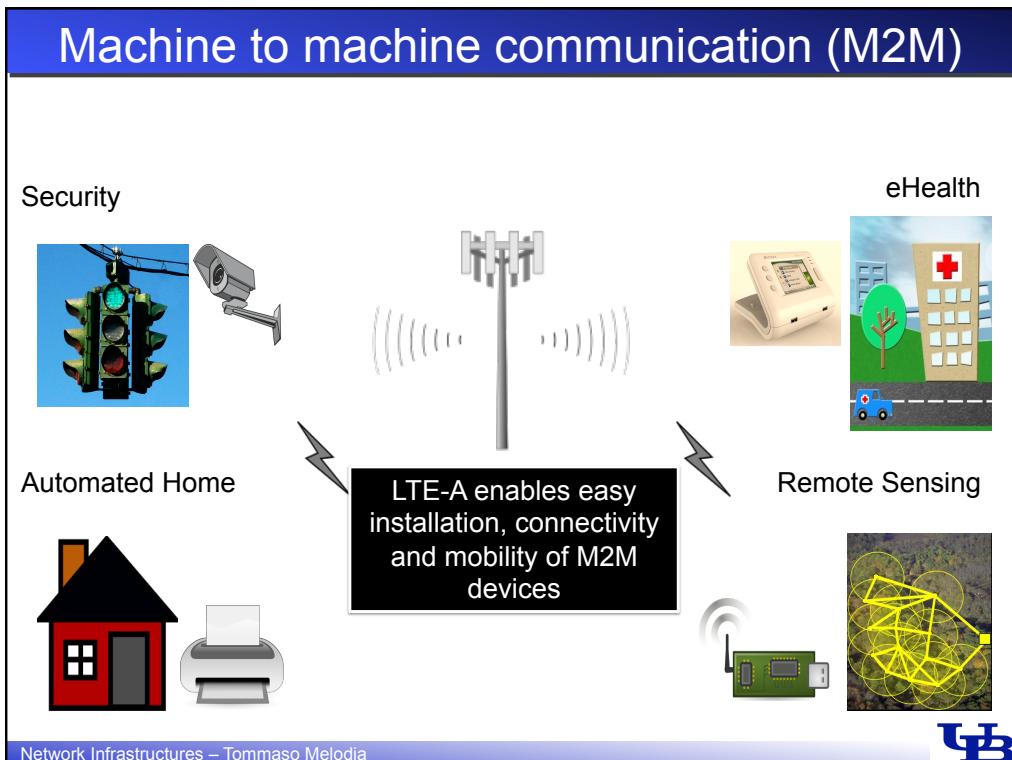


## Key Technologies in LTEA



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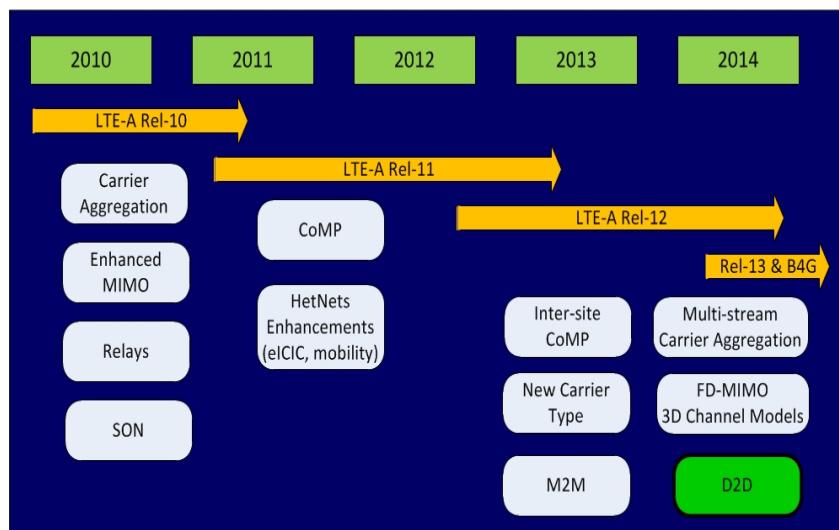


## M2M Key Issues

- 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.

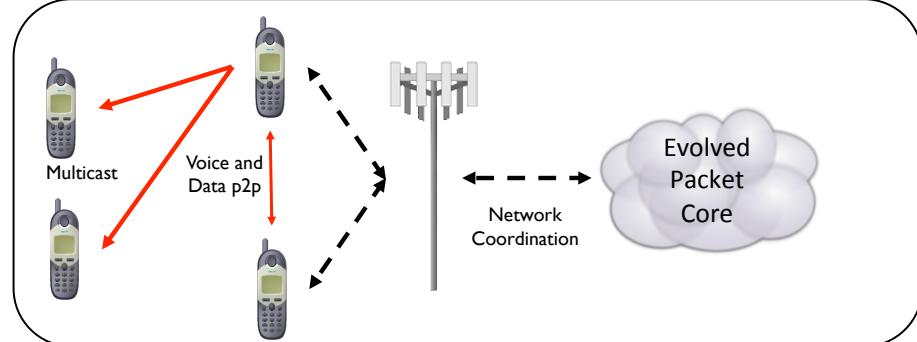
## Key Technologies in LTEA



## 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)

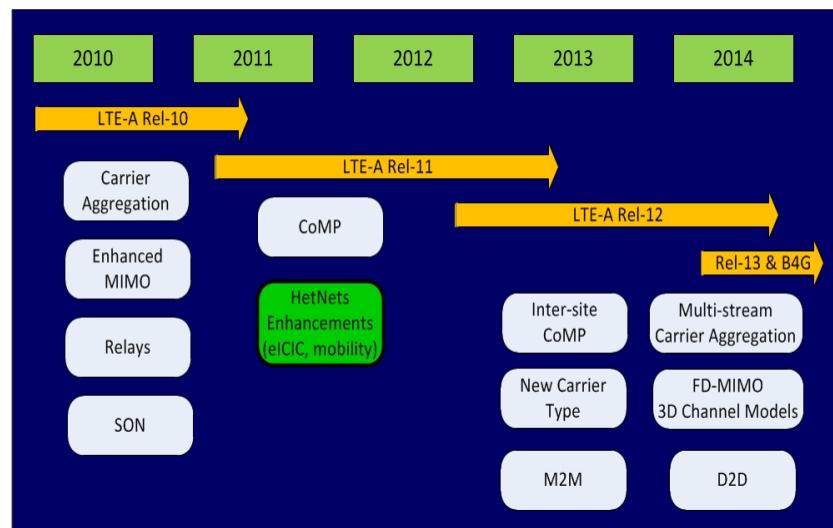
## D2D

- 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

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## Key Technologies in LTEA

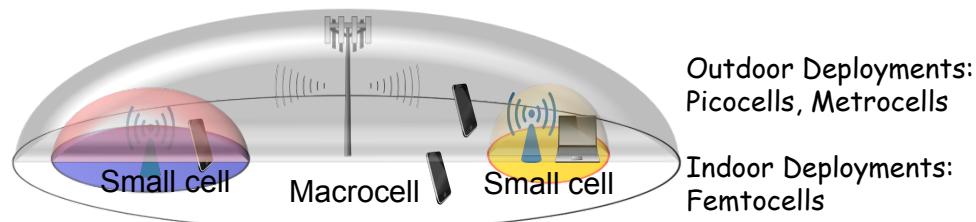


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## Heterogeneous Networks (HetNets)

- 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:

High UL data rate

High load

Low Load

### Association Policy:

BS with minimum pathloss

Offload to small cells

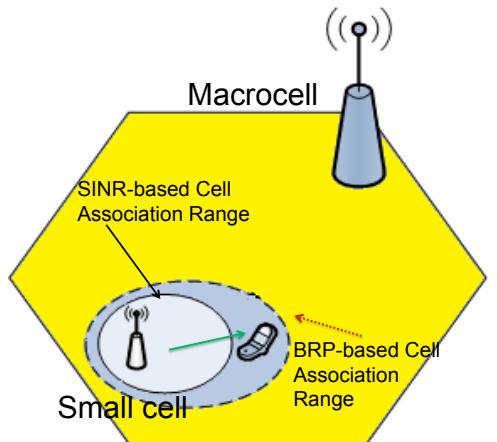
BS with best DL SINR

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

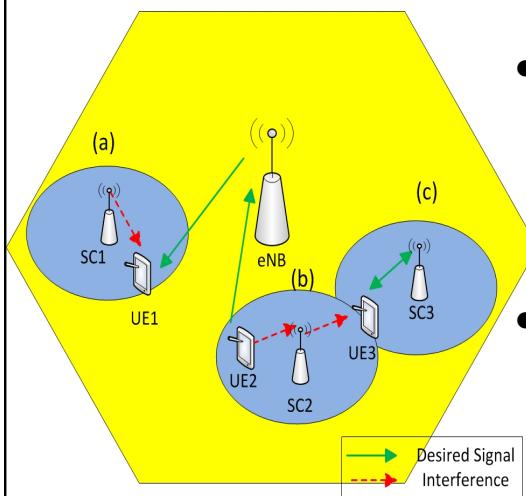
**Disadvantage:**

- \* Low per-user throughput (due to interference)

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## 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

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## 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 Aggregation)
  - Time-domain based schemes
  - Frequency domain based schemes