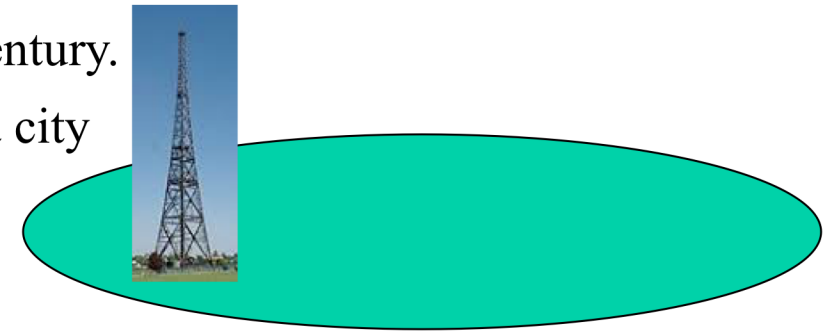
Cellular Systems, 5G Systems and Beyond

Path loss < coverage :(
Capacity :)

History of Mobile Phones

Radio bourdcasting

- Wireless Telegraphy by Marconi in early 1896
  - Significance: able to carry out long distance wireless communications
- Wireless Telephony around early 20th century.
  - Able to deliver wireless voice over a city



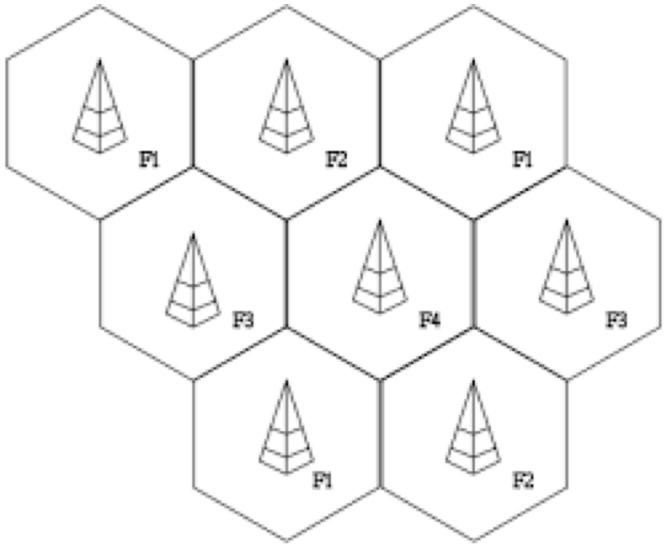
- Yet, the first generation mobile phone appeared in 1973!
- What is the missing piece for mobile phone systems?

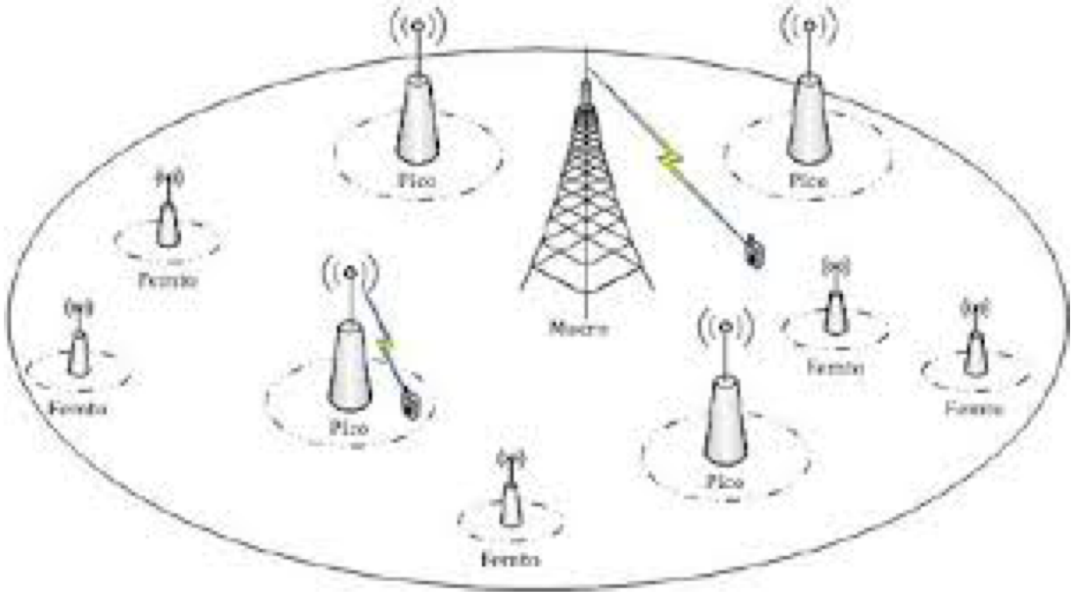
capacity

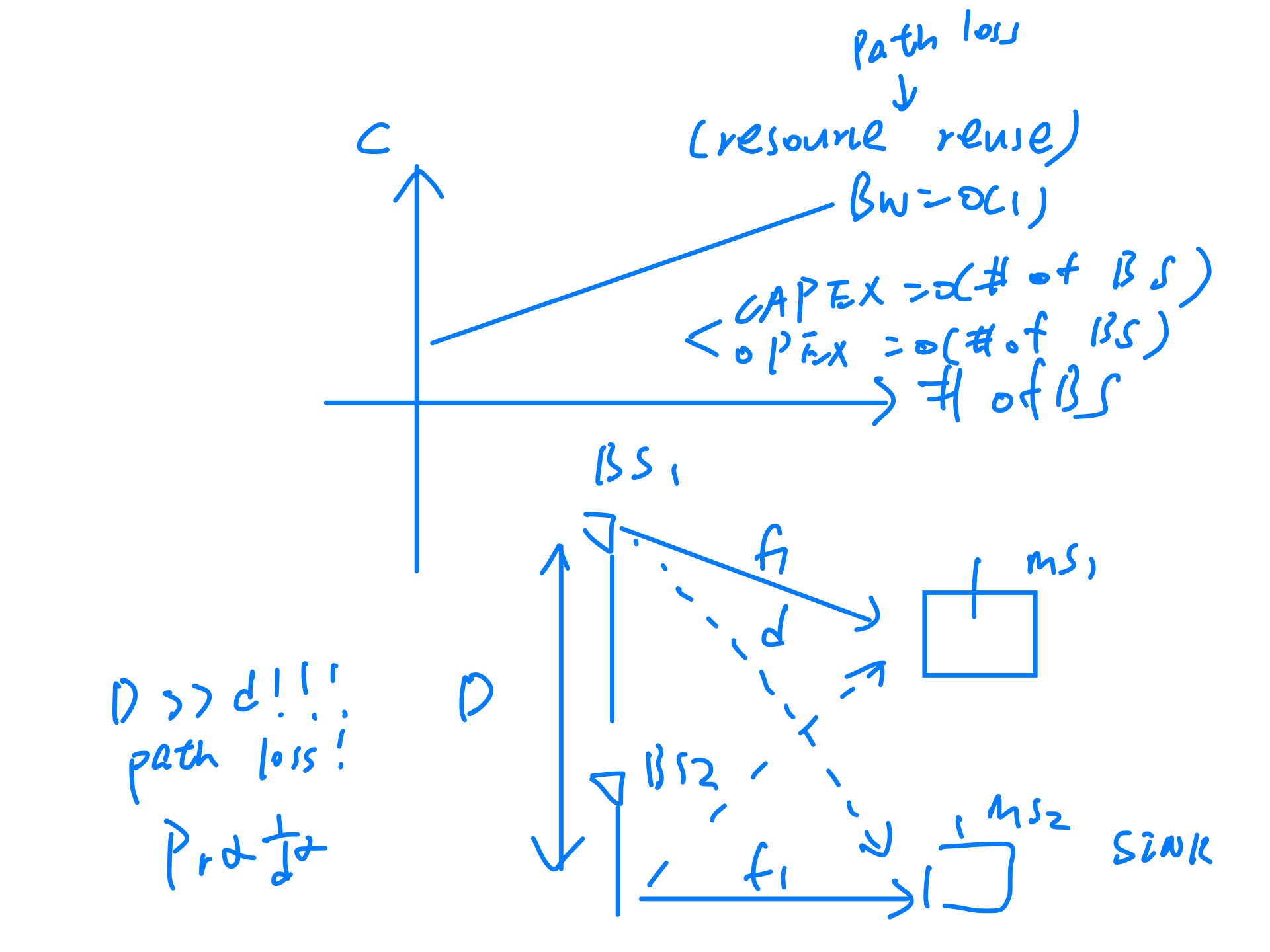
how can we service tons of people?

Mobile Phone Systems

- Key issue is "Capacity" due to limited radio spectrum
- The solution is Cellular Architecture (invented by Bell Labs)

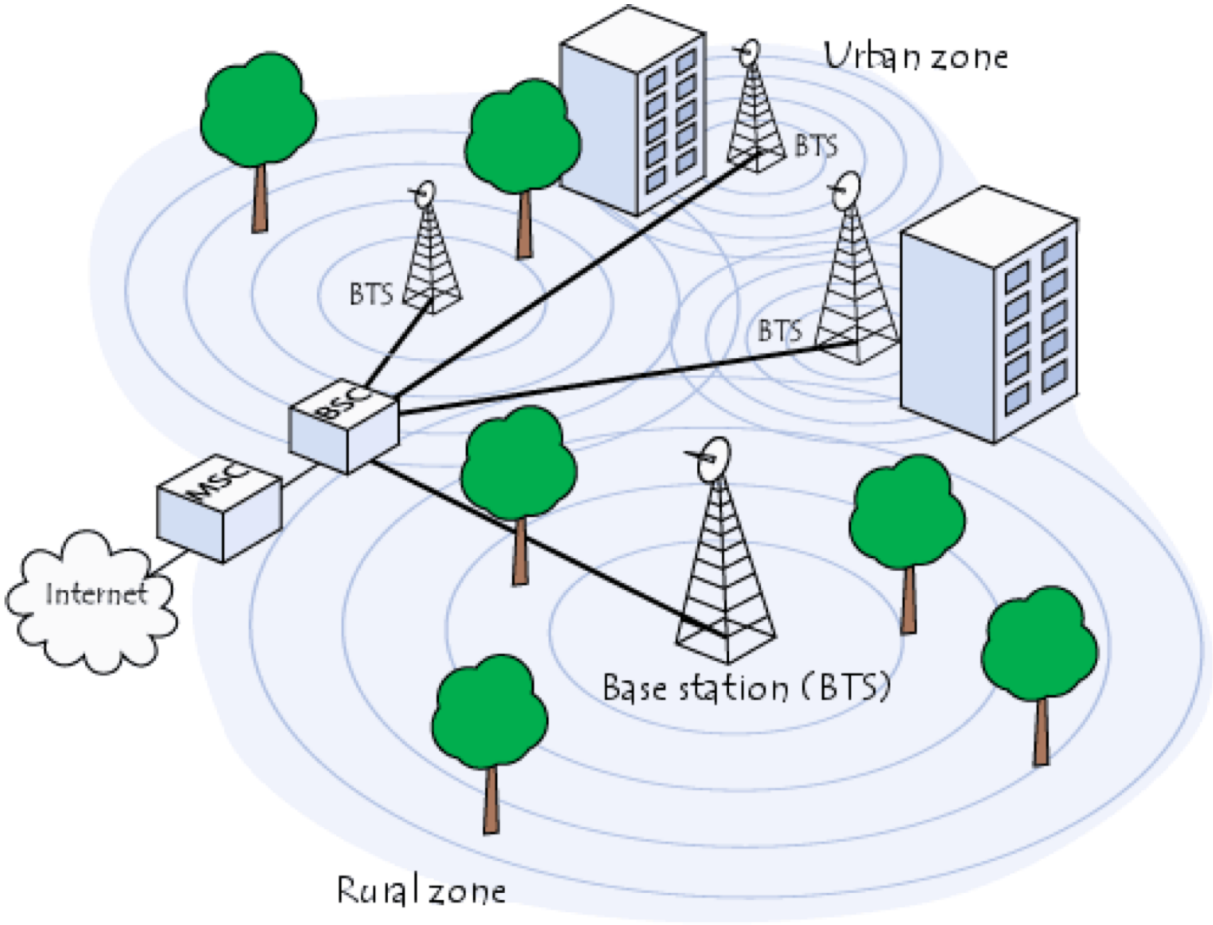





path loss
(resource reuse)
C
BW = O(1)
CAPEX = O(# of BS)
OPEX = O(# of BS)
# of BS
BS1
f1
MS1
d
D >> d!!!
path loss!
Pr ∝ 1/d²
D
BS2
MS2
SINK
f1

Architecture of Cellular System

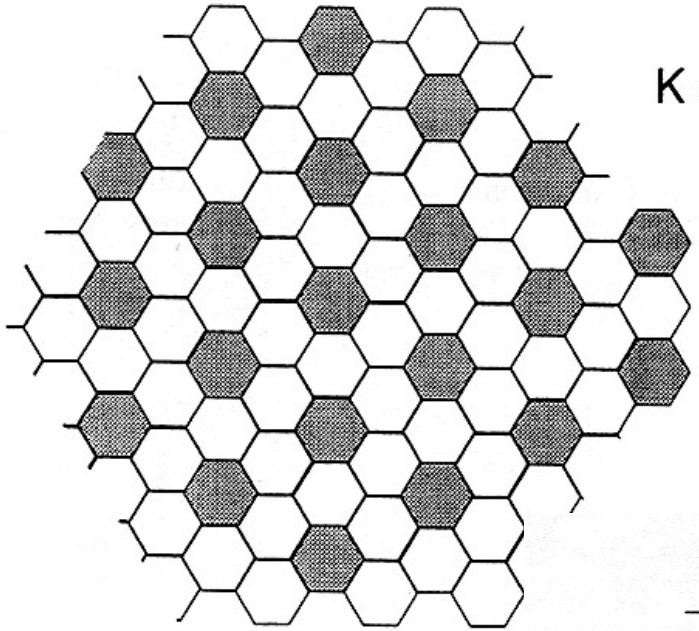
- Mobile users connect with the network via a base station (BTS). This refers to the radio interface
- A number of base stations (BTS) are connected to a base station controller (BSC) via backhauls
- A number of BSCs are connected to the core network (Mobile Switching Center)
- The MSCs form the core network of the cellular system and interface to the PSTN (for voice) and internet (for data)



Which interface is the capacity bottleneck in a cellular network?

X

Multi-cell Capacity Comparisons



7 different frequencies

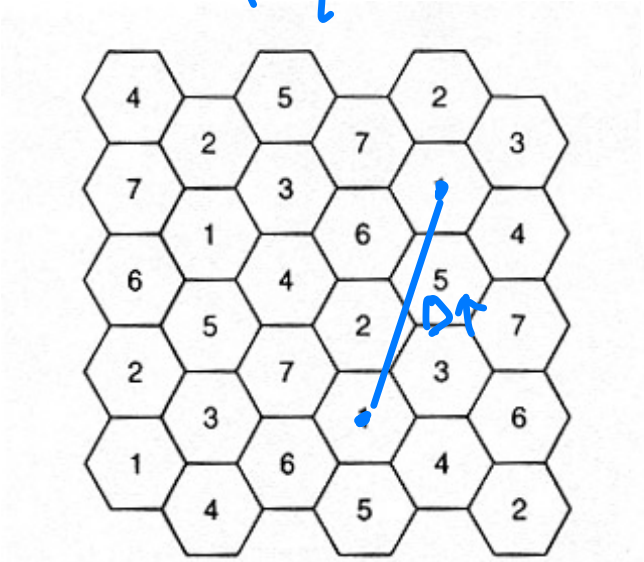
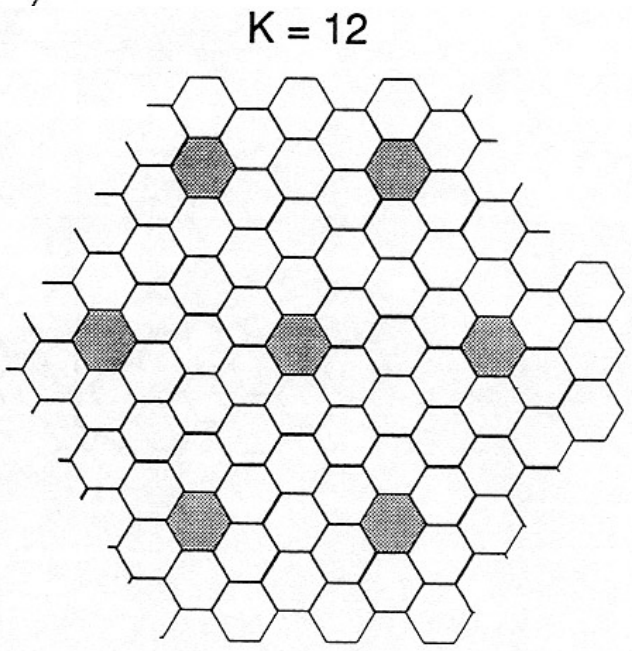


Figure 16.15 A cell layout based on $N = 7$.

$$C = \frac{600}{\text{slope}} \times BS$$

if stepper slope, ↓



Why Cellular Architecture?

- Frequency Reuse
  - Scenario II (no reuse)
    - All the N channels are divided into B distinct sets.
    - Each set is allocated to a cell.
    - Total capacity = (N/B) x B = N —> poor system capacity
    - No 2 users could interfere --> good quality.
  - General Resource Reuse
    - need a flexible resource reuse scheme
    - allow a graceful tradeoff between signal quality and capacity.
- The key is that signal will attenuate (path loss) as it transverse certain distance.
- Interference could be controlled if we make sure co-channel cells are far apart.

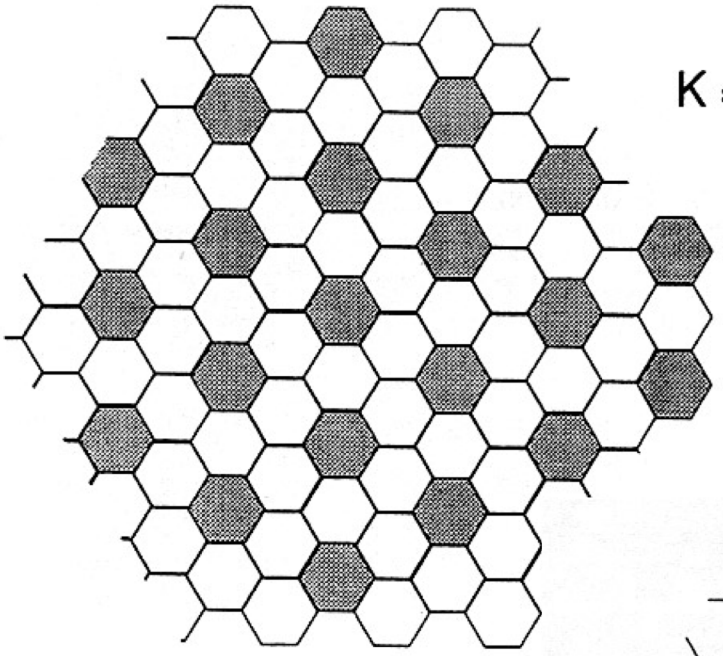
① Phy design
e.g. FM. non-linear amplification
min SIR = 18dB
N = 7
N = 4
digital tx
SIR = 13dB
↓
2G higher voice capacity than 1G

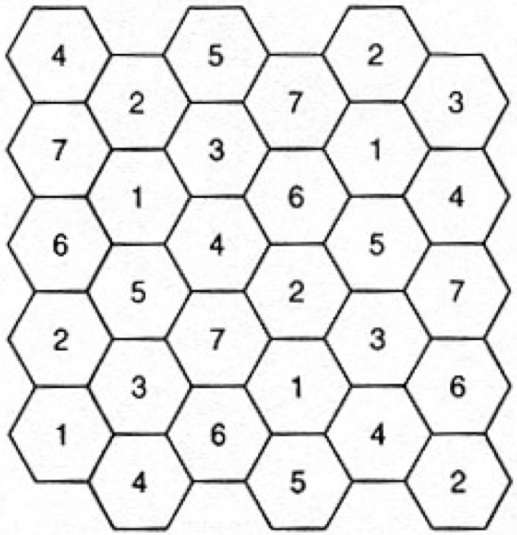
② Path loss environment

$\alpha = 2$ (remote) $\alpha = 4$ (urban)

$[N = 7]$ $[N = 4]$

Why Cellular Architecture





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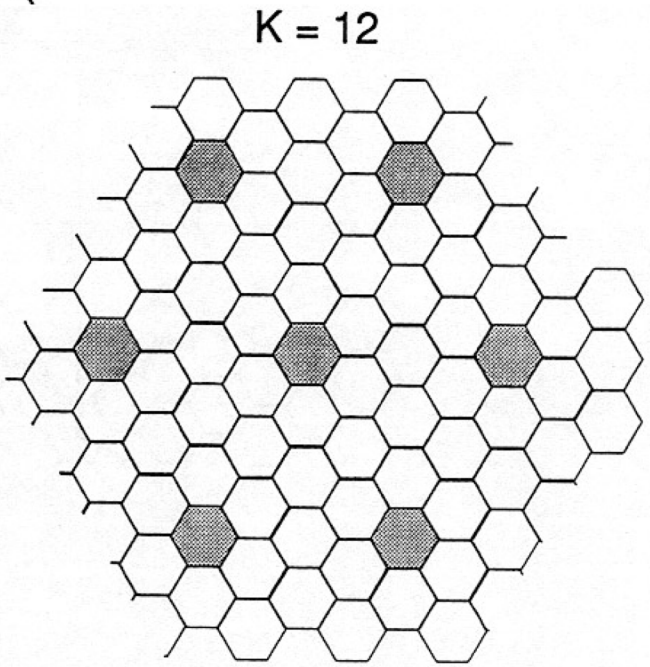


Evolution of Cellular Systems

1st Generation Systems: - Review

- Analog Voice Transmission (FM 30kHz), digital signaling (FSK).
- Support voice communication only.
- Capacity is the primary concern.
- Numerous incompatible standards around the world.
- AMPS (Advanced Mobile Phone System) in the US and TACS in UK as 1G system examples.
- Signals from different users are separated by FDMA (frequency division multiple access).
- the total number of distinct channels is limited.

– FM transmission--> the required SIR ~18dB.

– reuse pattern K=7

Evolution of Cellular Network

Cell Size and Coverage

- Initial deployment stage,
  - the bottleneck of the system is coverage than capacity.
  - macro-cells are deployed to minimize number of base stations.
- Growth stage,
  - the number of subscribers gradually increases.
  - Densely populated areas --> the overall subscriber loading may exceed the cell's capacity.
  - Cell splitting / sectorization is applied to relief the capacity loading.
- Mature stage
  - system capacity becomes the bottleneck.
  - system capacity could not be further enhanced by system engineering approach.

Evolution of Cellular Networks

2G Systems:

- The major driving force:
  - to enhance the cellular network voice capacity.
  - utilizing the limited frequency spectrum more effectively.
- Spectrum:
  - New 2G Cellular Spectrum + PCS spectrum
  - Europe/HK: 900 MHz cellular + 1.8 GHz PCS
  - US: 800MHz cellular + 1.9 GHz PCS
- Digital transmission technologies are employed
  - Robust transmission through error correction coding
  - increase immunity to noise and interference.
  - Reduce the K factor

Evolution of Cellular Systems

2G Systems:

- Source Coding

– compress digitized speech.
– Each user occupies less bandwidth.
– E.g. Digital AMPS --> one 30kHz carrier contains 3 users.

- Wireless Data Service:

– circuit switched mode.
– air interface and the associated resources are dedicated to the user throughout the session.
– The transmission speed is quite low, from 9.6kbps to 14.4kbps.

Evolution of Cellular Systems

2G Systems:

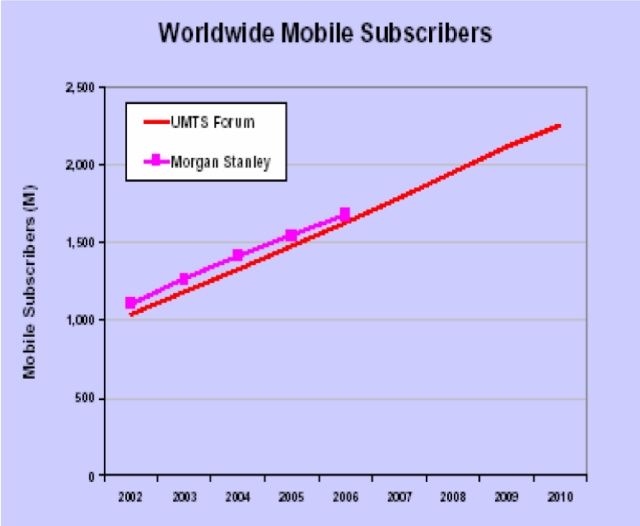
- European Markets:
  - Revolutionary approach.
  - Scrap all 1G investments.
  - Replace with a unified standard (GSM).
  - This is mainly because of the incompatibility of the existing 1G systems in Europe.
  - GSM captures the over 90% of the worldwide cellular market.
- US Markets:
  - Evolutionary approach.
  - Backward compatible with 1G (AMPS).
  - We have Digital-AMPS (IS54) and CDMA (IS95).
  - This is because the penetration of the AMPS system is large and the local US market for cellular communication is huge enough.

Evolution of Cellular Systems

3G Systems:

• 2G systems could satisfy the huge capacity requirement by utilizing the limited spectrum more effectively.

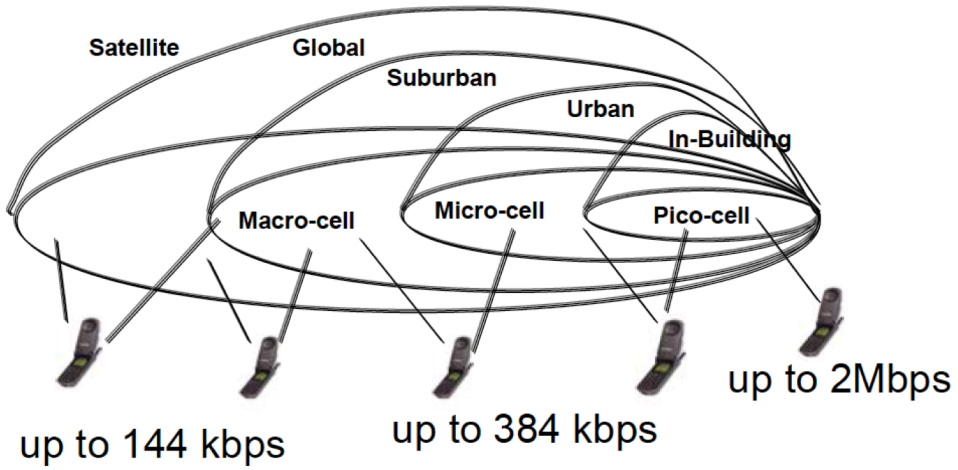
• The motivation behind 3G systems is the need for high-speed wireless data communication.

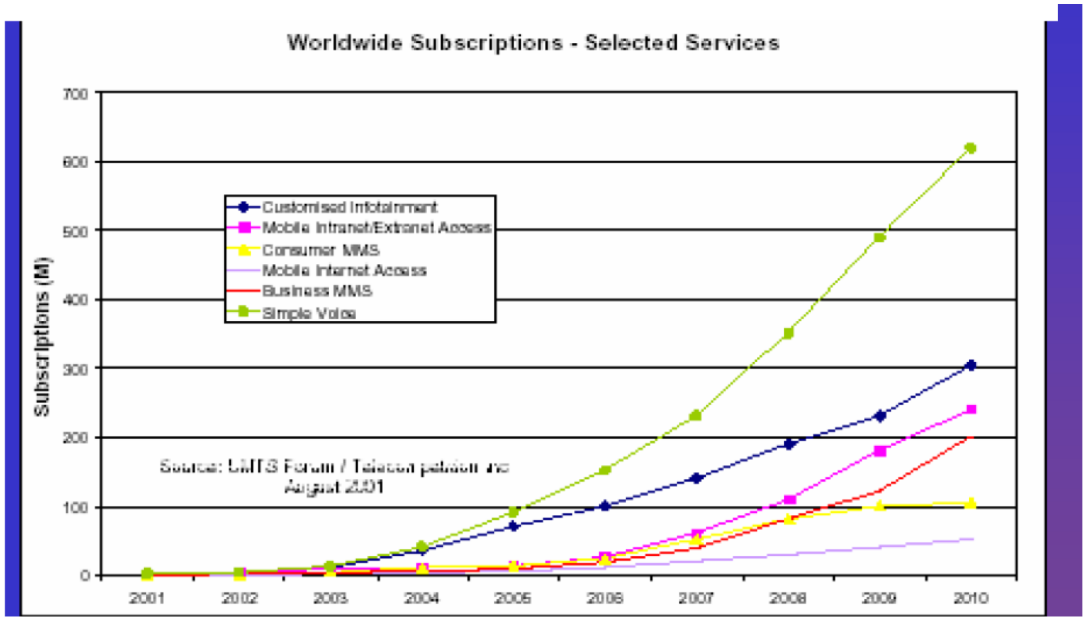


- Focus on data service and value added applications
  - Mobile Internet Access
  - Mobile Intranet/Extranet Access
  - Personalized Infotainment
    - Video, audio, interactive games, TV, etc.
  - Multimedia Message Service (MMS)
  - Location Based Services (LBS)
  - Rich Voice (video telephony, text + audio, etc.)
- Theme
  - Multi-mode (multi-media) service
  - Community and identity

Evolution of Cellular Systems

Seamless End to End Service with different data rates





X

Evolution of Cellular Systems

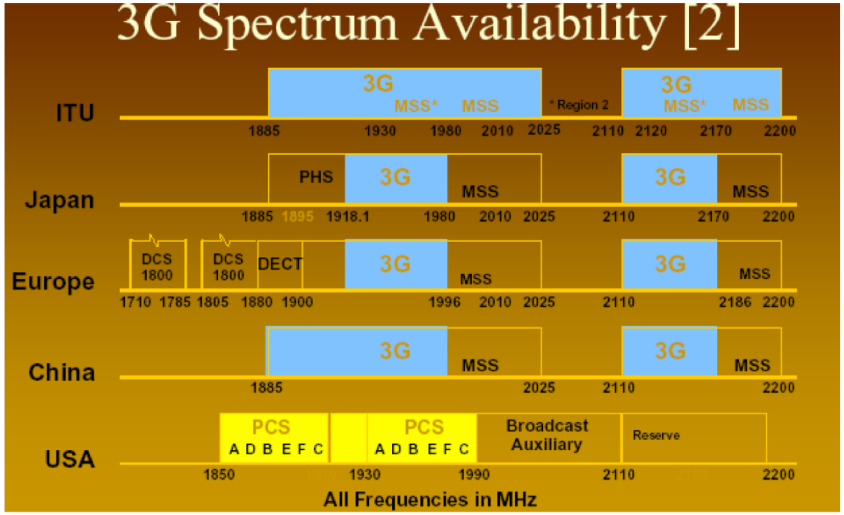
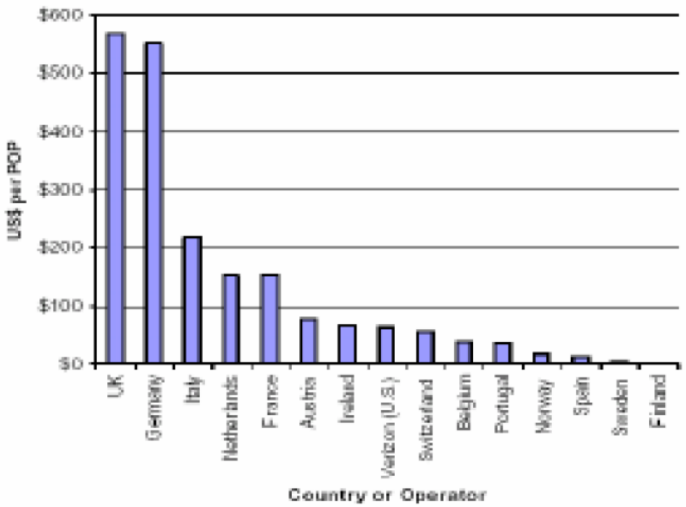


Exhibit 1.11

COST OF 3G FREQUENCY PER POP

Country or Operator	Spectrum Cost / POP
UK	$570
Germany	$551
Italy	$218
Netherlands	$153
France	$152
Austria	$77
Ireland	$65
Verizon (U.S.)	$63
Switzerland	$55
Belgium	$39
Portugal	$36
Norway	$18
Spain	$12
Sweden	$5
Finland	$0



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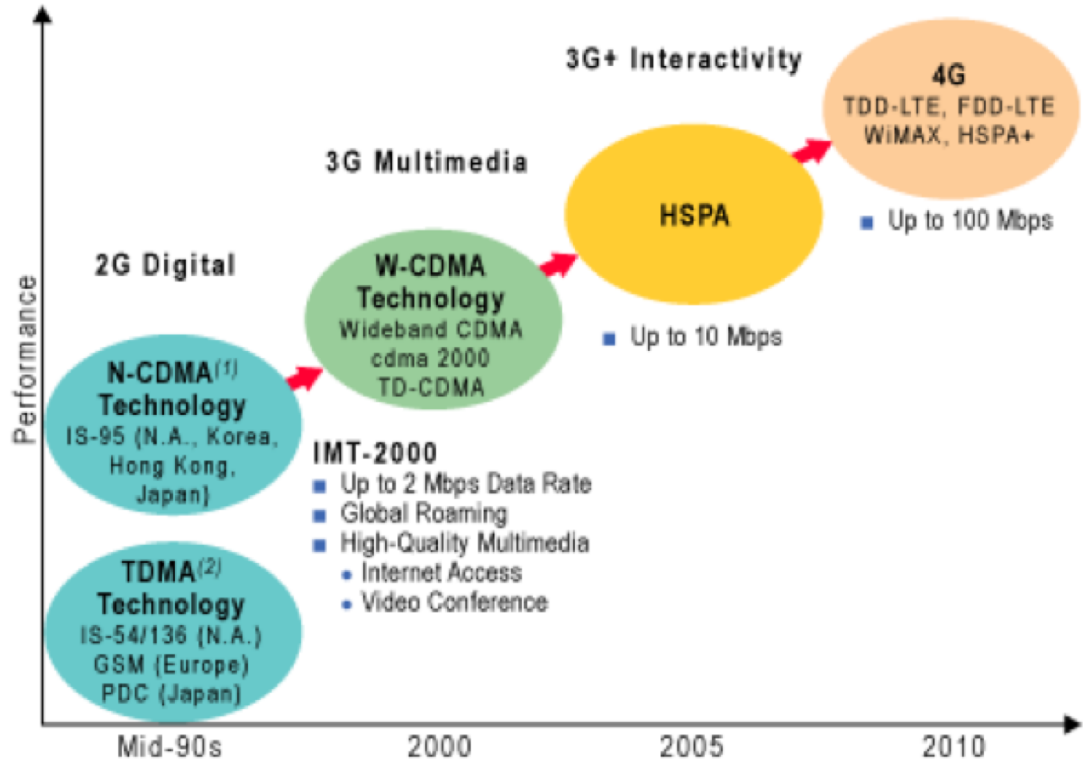
Evolution of Cellular Systems



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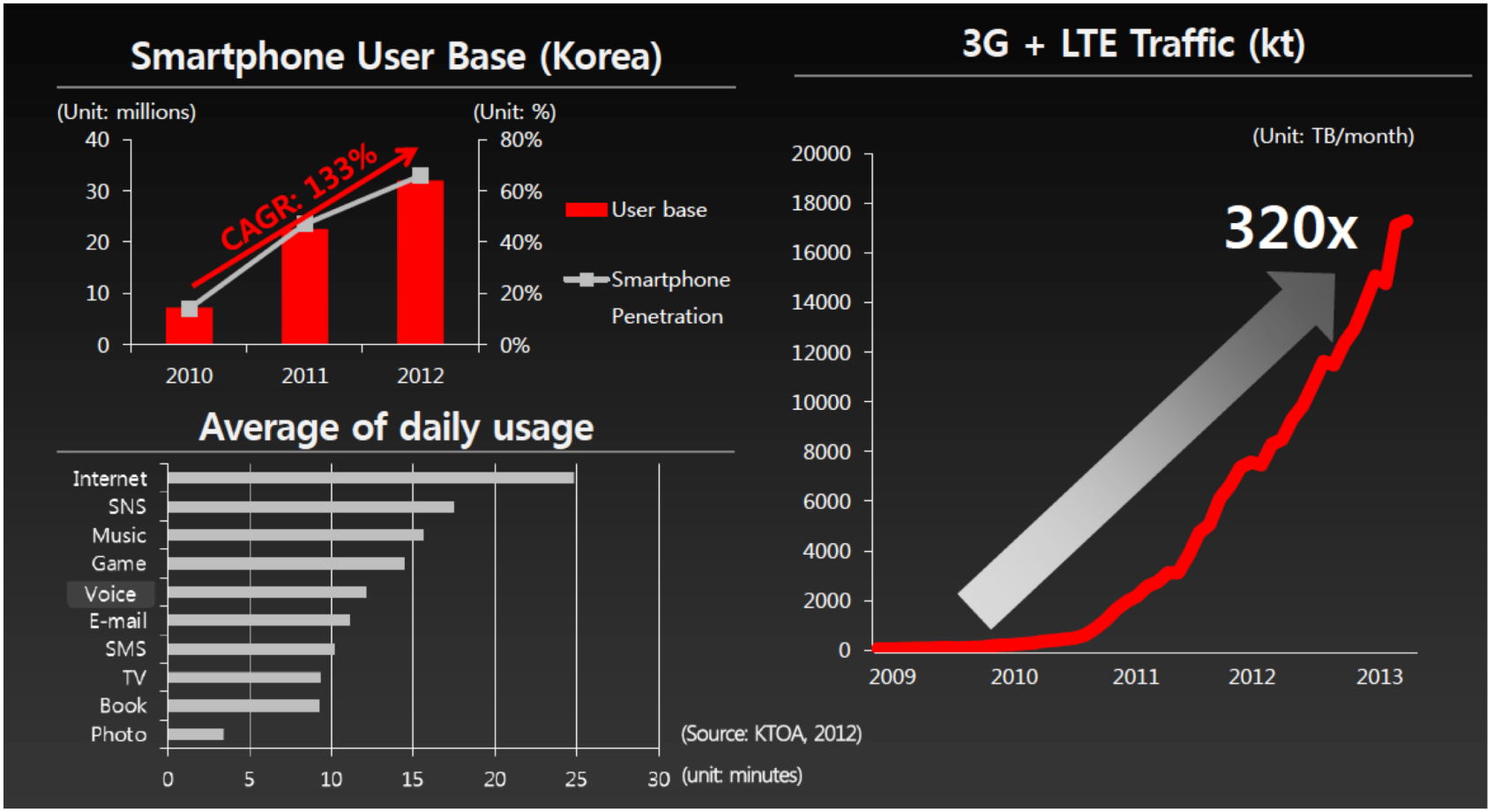
Evolution of Cellular Systems



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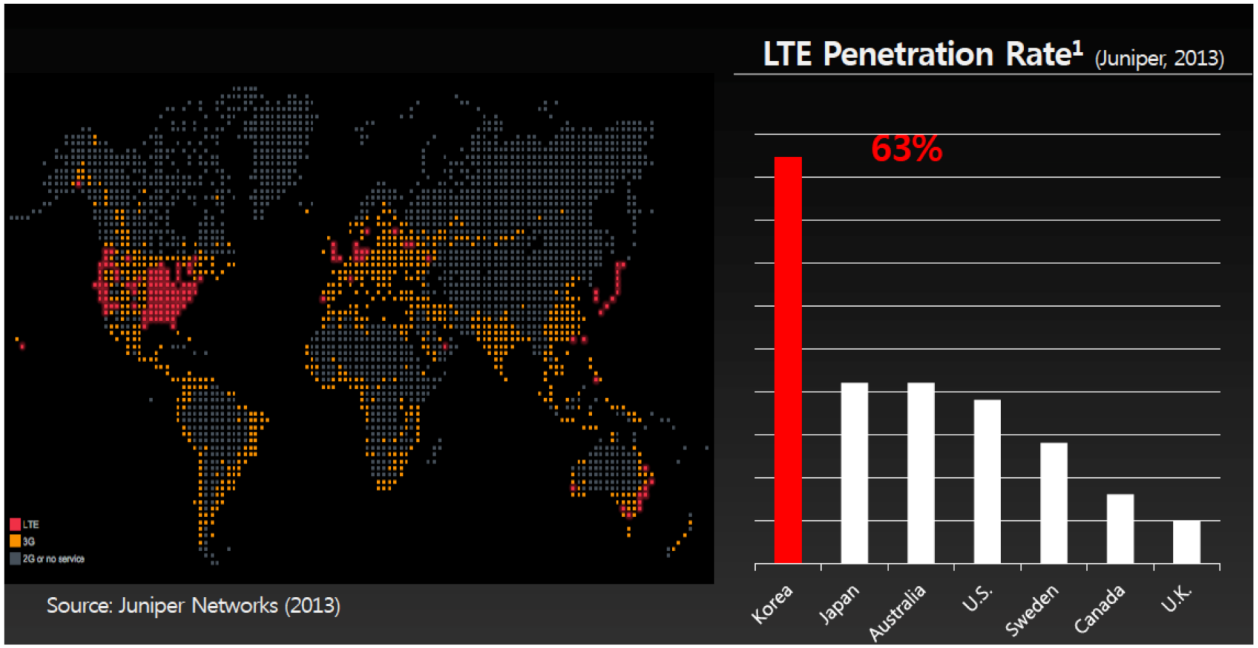
Evolution of Cellular Systems



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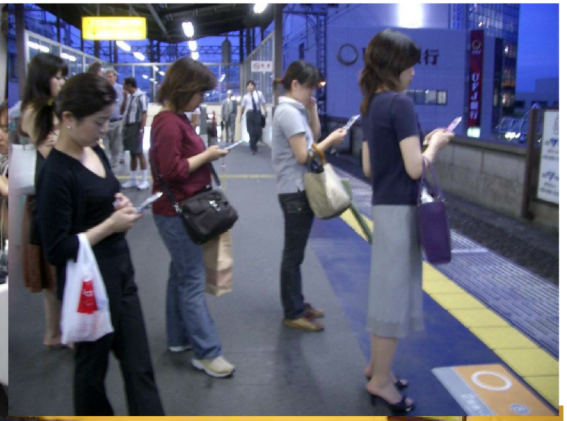
5G Cellular Systems



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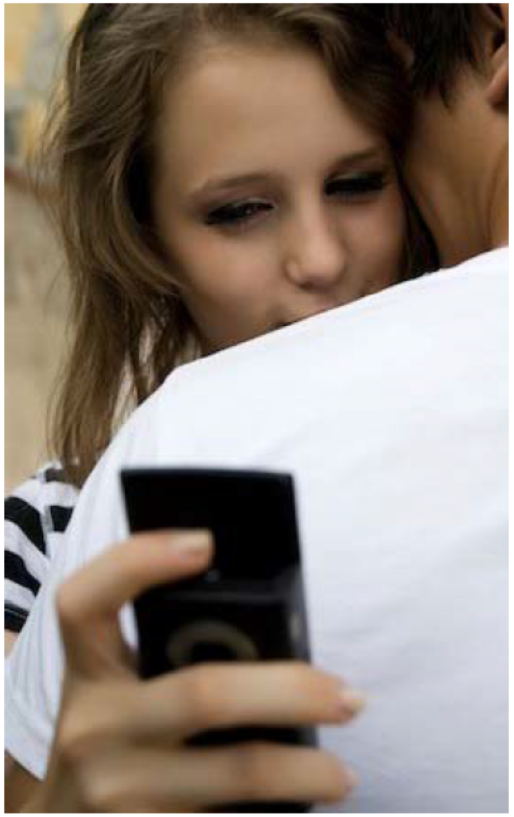
5G Cellular Systems



5G Cellular Systems

X

5G Cellular Systems

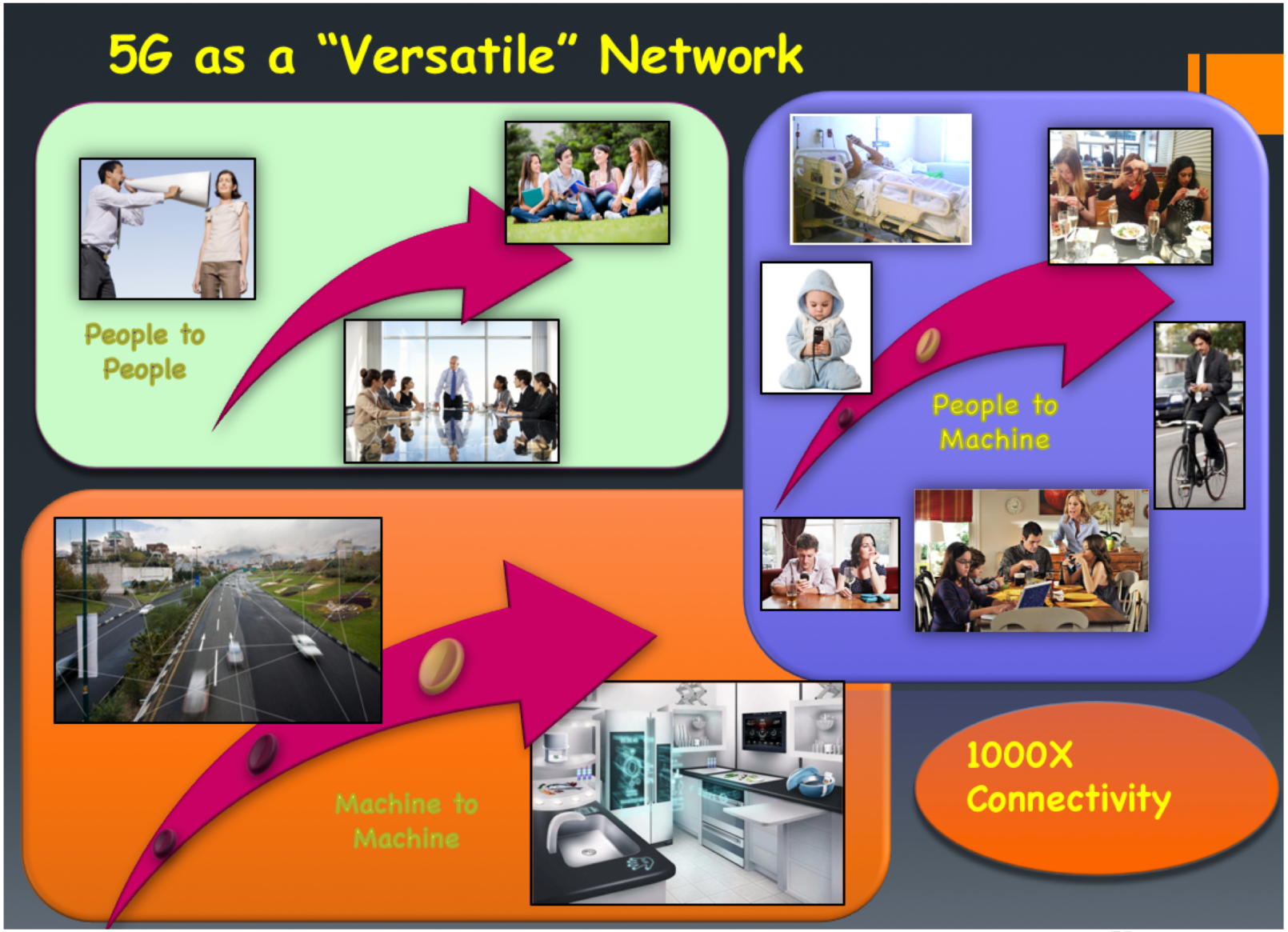
2005

5G Cellular Systems

2013

x

5G Cellular Systems



5G as a "Tactile" Wireless Network

Communications Networks Today

- Targets for delivery of content and information
- Latency ~ 50ms (VoIP)

Communications Networks Tomorrow (Tactile Wireless Network)

- Machine Type Communications
- Real-time Control / Interactive Gaming Applications
- **Latency is the KEY** (Target Latency < 1ms)
- Very Challenging

5G Cellular Networks

Where are these 1000X coming from?

Advanced Radio Resource Management

Physical Layer Techniques

Increase SINR
FEC, Diversity, Interference Coordination, CoMP, Advanced RRM

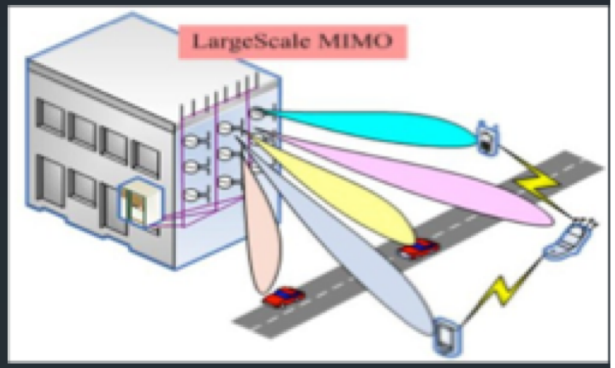
$$C = \sum_{Channels} B_i \log_2(1 + P_i / N)$$

More Spatial Channels
Massive *MIMO*,
Spatial Reuse (Small Cells, HetNet)

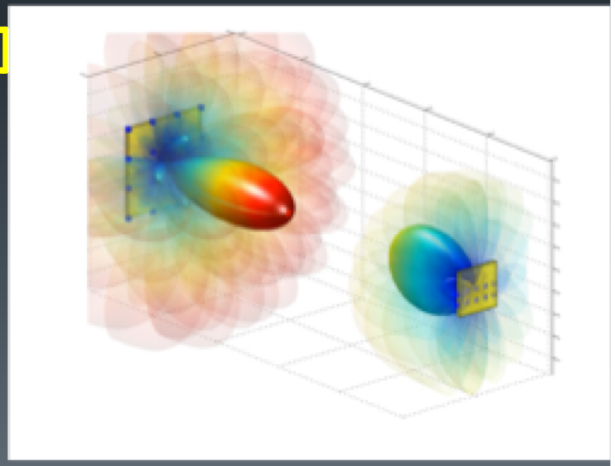
More Bandwidth
Carrier Aggregation, Unlicensed LTE, mmWave

(I) Large MIMO, HetNet, Small Cells and mmWave

- "More Channels" [Massive MIMO Network]:
  - Opportunities:
    - Bandwidth is always limited ➔ Should scale up the number of antennas!
  - Challenges
    - **Insufficient Pilot Symbols**: Pilot training overhead does not scale with # of antennas
    - **Enormous Number of RF Chains**:- Expensive and Power Issues
    - **Intercell Interference Mitigation Requires Global Real-time CSI** ➔ Sensitive to Backhaul Signaling Latency



- "More BW" [mmWave @ 28GHz, 60GHz]
  - Opportunities
    - Huge Bandwidth Available
  - Challenges
    - LOS propagation
    - Beamforming is needed to overcome the path loss
    - **Beam Tracking** is needed to support Access Applications.



Example 1: QoE Aware RRM for Video Streaming

- **QoE of Video Streaming = Playback Interruption:** when the playback buffer underflows during the transmission → highly undesirable for the end user experience.

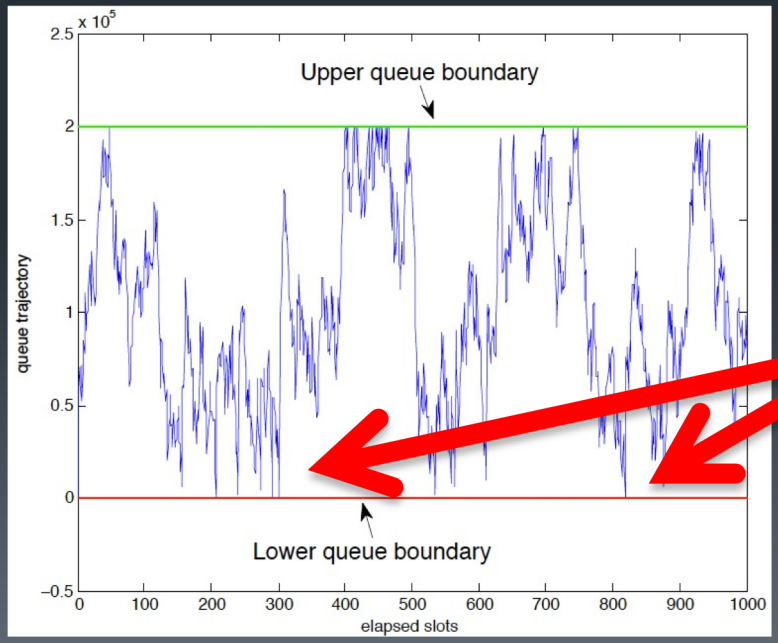


Fig. Illustration of a queue trajectory of the playback queue at the mobile user.

playback interruption occurs

Video Streaming QoS Requirements

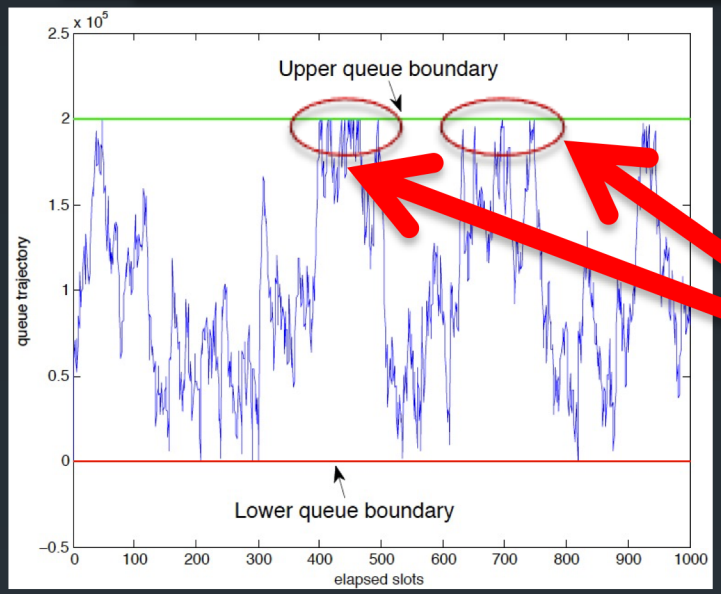
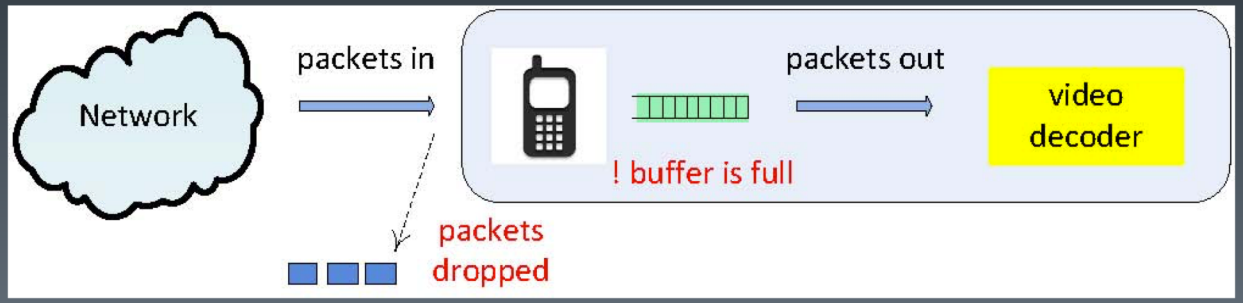


Fig. Illustration of a queue trajectory of the playback queue at the mobile user.

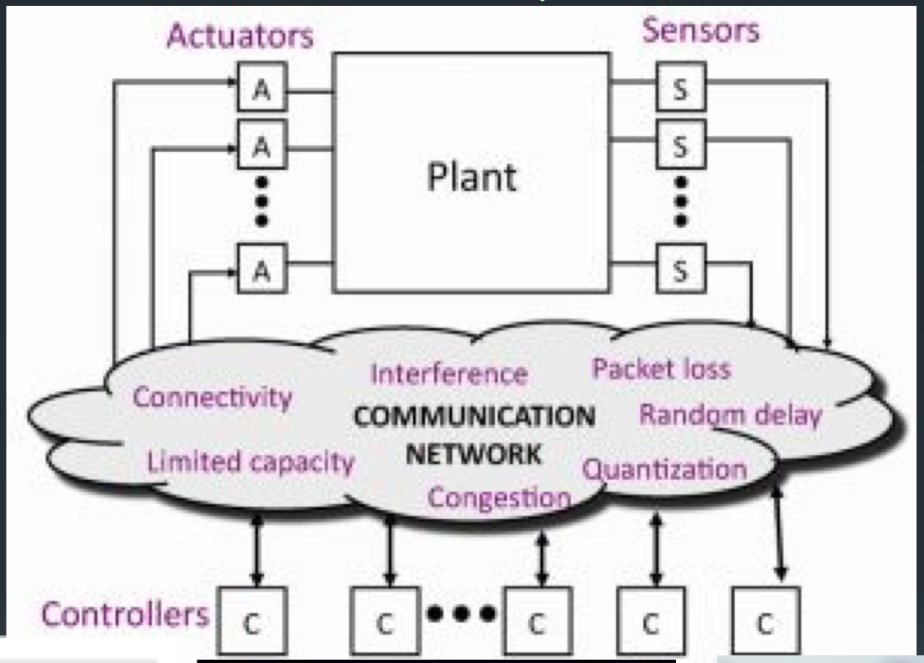
buffer overflow occurs

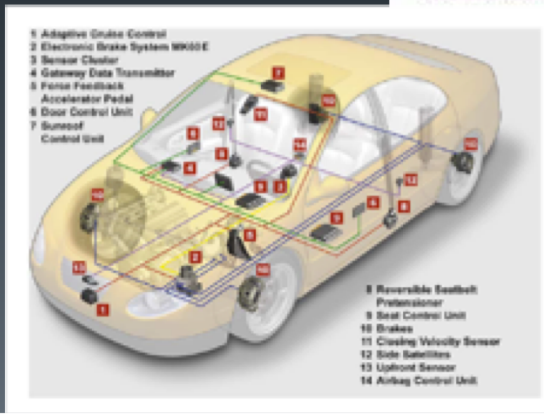
- **Buffer overflow:** it causes incoming video packets dropped and results in wastage of wireless resource used to transmit these dropped packets.

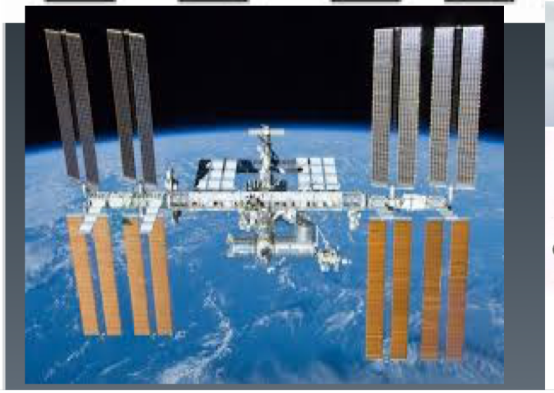


Example 2: Networked Control Systems

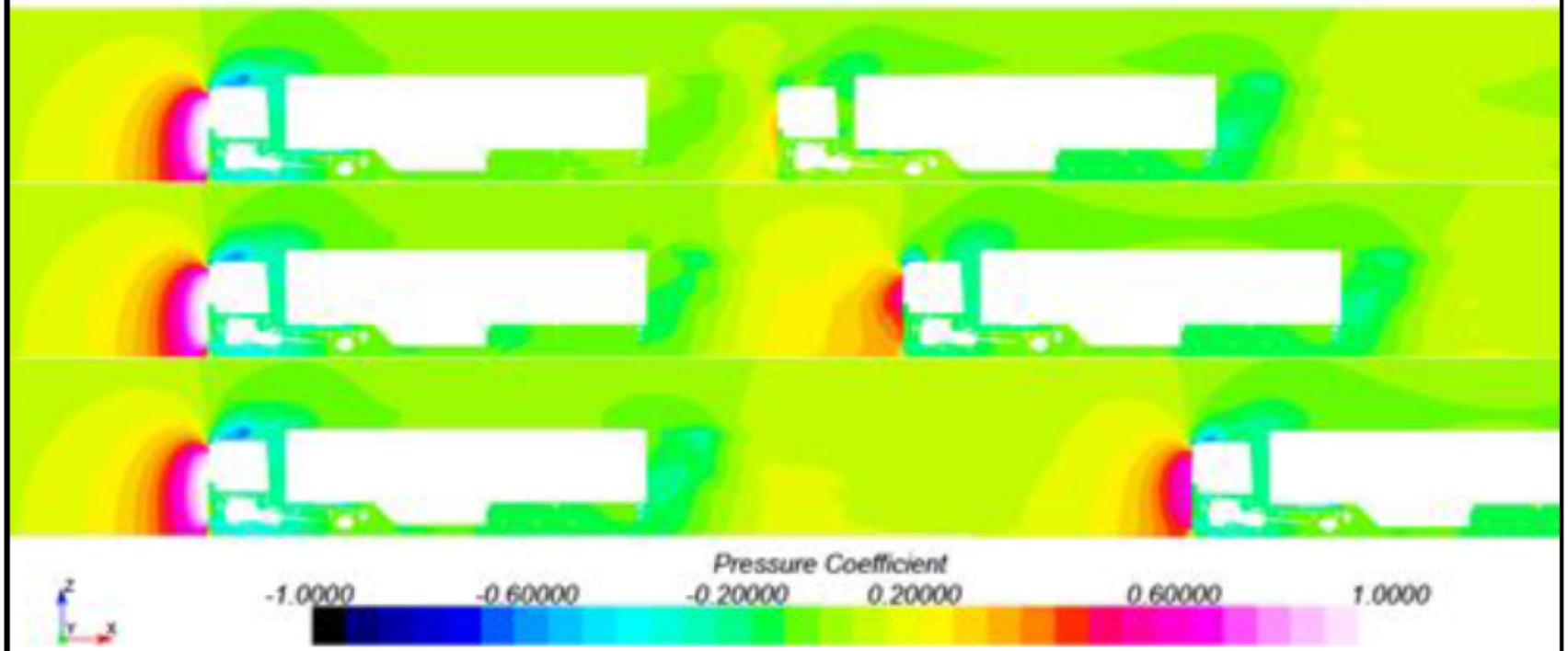
Interplay between Control Theory and Communication Theory







The Physics



Norrby (2014), Liang (2016)