Computer Engineering
Electronics and Communications Systems

Introduction to Cellular Communications

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Outline of this part of the course

- **Introduction to wireless communications**

- **Basics of wireless propagation:**
  - Large-scale and small-scale fading
  - Time and frequency selectivity
  - Methods to combat channel impairments

- **Fundamentals of cellular standards**
  - 3G communications
  - 4G communications
  - 5G communications

- **Discussion and perspectives**
Introduction to modern wireless communications
Some (whopping) facts (1/2)

- In 2014, the number of mobile users reach around 7 billion users worldwide!
- In Italy, there are 88,580,000 mobile phones for a population of 60,090,400 inhabitants (December 2013): **147.4% penetration**

Note: * Estimate
Source: ITU World Telecommunication/ICT Indicators database
Some (whopping) facts (2/2)

- The number of people with access to mobile communications is higher than those with access to working toilets (around 4.5 billions)

- The number of people that owns a mobile phone is larger than the one that owns/uses a toothbrush (around 4 billion)

- Every second, more than an hour of videos is uploaded to Youtube
fixed (wired) subscriptions

- Developed
- World
- Developing

mobile subscriptions

- Developed
- World
- Developing

Note: * Estimate
Source: ITU World Telecommunication/ICT Indicators database
A brief history of wireless communications (1/3)

• 1864: Maxwell proves the existence of electromagnetic waves
• 1887: Hertz sends and receives wireless waves, using a spark transmitter and a resonator receiver
• 1895: Guglielmo Marconi sends a radio signal over more than a mile, from the Isle of Wight to a tugboat 18 miles away
• 1904: Fleming patents the diode
• 1906: DeForest patents the triode amplifier; first speech wireless transmission, by Fessenden
• WW I: Rapid development of communications intelligence, intercept technology, cryptography
• 1920: Marconi discovers short-wave radio, with wavelengths between 10 and 100 meters
• 1935: Armstrong invents the frequency modulation (FM)
Mobile wireless systems ensure the **communications** between **mobile** nodes

In the last eighty years, wireless technology has **evolved** over many aspects:

- increased coverage distance
- increased quality (throughput, error rate performance, spectral efficiency)
- improved availability of services (broadband communications)
- decreased energy consumption (energy efficiency)
- reduced costs (for both service providers and subscribers/users)
- reduced device sizes and costs
A brief history of wireless communications (3/3)

0G
1960

1G
1985

2G
1995

3G
2005

4G
2015

Introduction to modern wireless communications systems
Basics of wireless communication systems

**Infrastructure network**
- higher rates
- lower latencies

**Examples:**
- cellular networks
- WLANs
- paging systems

**Infrastructure-less, ad-hoc network**
- lower deployment costs
- useful in impaired environments

**Example:**
- Bluetooth
An elementary wireless system

Note: This is not a cellular system, it can be labeled as a 0G system (1940s)

Constraints:
- limited frequency range (due to licensed spectrum)
- limited coverage area (due to power masks)

Features:
- low density of users (per unit of area)
- discontinued service when exiting the coverage area
End of 1950s/beginning of 1960s: introducing **cells** to provide **seamless** coverage

- **co-channel (intercell) interference**
- **cluster with size (reuse factor) K=4**
- **handover**

**Available channels**
With the advent of 4G systems, we also have **fractional frequency reuse (FFR)**
Medium access techniques

- radio transceiver configuration *(duplexing)*

- multiple access scheduling
Duplexing

- **frequency division duplexing (FDD):** uplink and downlink take place at the same time on different frequencies
  - 1G, 2G

- **time division duplexing (TDD):** uplink and downlink take place on the same frequency at different times
  - 3G, 4G

- **full duplex (FD):** uplink and downlink take place at the same time on the same frequency
  - 5G
Multiple access techniques

Since the wireless channel is a shared medium, some multiple access techniques are needed to schedule multiple users over a dedicated channel.

We can exploit several degrees of freedom: frequency, time, space, codes, etc.
Frequency division multiple access (FDMA)

The available bandwidth $B$ is subdivided into $M_F$ non-overlapping subchannels (in the frequency domain):

- FDMA is suitable to both analog and digital systems (used since the early days of analog radios)
The bandwidth $B$ is assigned to the $M_T$ users using a round-robin scheduling: each user makes use of the whole bandwidth for its assigned time slot:

TDMA can be used only in digital systems.
To accommodate more users in the same cell, we can assign each user a different **spreading code**:
There exist different techniques to implement CDMA for spread spectrum (SS) communications:

- **frequency hopping (FH)**

- **direct sequence (DS):**
  - orthogonal codes
  - non-orthogonal codes (causing intercell interference)
Multiple antennas at both the transmit and the receive sides can generate independent signals, thus achieving spatial multiplexing:
As an example, the global system for mobile communications (GSM) makes use of a combination of FDMA and TDMA:
Planning of a cellular network

Some key performance indicators:

- spectral efficiency [b/s/Hz]
- energy efficiency [b/J]
- area spectral efficiency [b/s/Hz/m²]
- handover rate
- capital expenditure (CapEx) and operating expenditure (OpEx) costs
- …
Area spectral efficiency (1/4)

For the sake of simplicity, let us neglect considerations about modulations and other PHY details, and let us focus on the density of users (per unit area):

\[ u = \frac{M}{A} \]

number of channels
coverage area

In the case of a 0G system, \( u \) is upper-bounded by:

- a limited number of subchannels \( M \), due to a finite licensed spectrum
- a minimum area \( A \), that ensures a sufficient coverage region for the users
To address a **continuous** coverage across the bidimensional space, we make use of a **cellular** network, in which:

\[ u = \frac{M_{\text{cell}}}{A_{\text{cell}}} \]

Using a cluster with reuse factor \( K \),

\[ M_{\text{cell}} = \frac{M}{K} \]

\( K = 7 \)
Let us consider a *hexagonal* cell with radius $R$:

Using simple geometrical notions,

$$A_{\text{cell}} = 6 \cdot \frac{1}{2} \cdot R \cdot \frac{\sqrt{3}}{2} R = \frac{3\sqrt{3}}{2} R^2$$
As a consequence,

\[ u = \frac{M_{\text{cell}}}{A_{\text{cell}}} = \frac{2M}{3\sqrt{3}} \cdot \frac{1}{KR^2} \]

The radius \( R \) represents a tradeoff between:

- CapEx and OpEx costs (\( R \) as high as possible, to reduce the number of BTSs)
- power consumption budget (\( R \) as low as possible, to save the energy expenditure at the cell edge)

\( R \) ranges from a hundred meters (highly-populated urban scenarios) to some kilometers (poorly-populated rural areas)

The minimum \( K \) must be chosen according to INTERFERENCE ISSUES.
Choosing the reuse factor $K$ (1/6)

Although a low $K$ is desirable to increase $u$, good system performance is guaranteed by a minimum signal-to-interference-plus-noise ratio (SINR), with the SINR defined as:

\[
\gamma = \frac{S}{I + N} \approx \frac{S}{I}
\]

cellular systems are usually interference-limited

To provide a good signal quality, we must ensure $\gamma \geq \gamma'$, where the minimum SINR $\gamma'$ depends on the system parameters, such as:

- modulation
- bandwidth
- channel coding
- multiple access technique
Rule of thumb: the larger $K$ is, the smaller is intercell interference, and the better the SINR is!

\[
\gamma = \frac{S}{I + N} \approx \frac{S}{I}
\]

Cellular systems are usually interference-limited.
Choosing the reuse factor $K$ (3/6)

How is $\gamma$ impacted by the network parameters?

Let us focus on the downlink, and let us make some simplifying assumptions:

- Each BTS is placed in the cell center
- Both the BTSs and the MSs have omnidirectional antenna patterns
- Only the first interfering tier is considered
- All BTSs use the same transmit power $P_T$
- All received powers can be computed using

$$P_R(d) = \chi \cdot \frac{P_T}{d^n}$$

where $d$ is the distance between the transmitter and the receiver, $n$ is the path-loss exponent, and $\chi$ is a scaling factor.
Choosing the reuse factor $K$ (3/6)

The **useful** signal power received at the MS is

$$S = \chi \cdot \frac{P_T}{R^n}$$

The **interfering** power caused by the $k$-th co-channel BTS is

$$I_k = \chi \cdot \frac{P_T}{d_k^n}$$

where $d_k$ is the distance between the $k$-th BTS and the MS
To determine $d_k$, we need to compute the reuse distance $D$:

Using the Carnot theorem, we get $D = \sqrt{3K} \cdot R$.
Choosing the reuse factor $K$ (5/6)

In practice, when $K \gg 1$, we can make the approximation

$$d_k \approx D$$

and thus

$$I_k \approx \chi \cdot \frac{P_T}{\left(\frac{R}{\sqrt{3K}}\right)^n}$$

In the worst-case scenario (when all interfering BTSs are active),

$$I = \sum_{k=1}^{K-1} I_k = \chi (K - 1) \cdot \frac{P_T}{\left(\frac{R}{\sqrt{3K}}\right)^n}$$

To sum up,

$$\gamma \approx \frac{(3K)^{n/2}}{K - 1}$$
Choosing the reuse factor $K$ (6/6)

As an example, let’s consider $n=4$ (urban scenario):

We can then plug this value back to $u = \frac{2M}{3\sqrt{3}} \cdot \frac{1}{KR^2}$ to compute the density of users.
More on area spectral efficiency

Since the user density is given by

$$u = \frac{M_{\text{cell}}}{A_{\text{cell}}} = \frac{2M}{3\sqrt{3}} \cdot \frac{1}{KR^2}$$

the service providers can fix $K$ and $u$, so that the actual cell size (i.e., $R$) depends on the density of population.

A more realistic BTS deployment on an actual urban scenarios can look like the picture on your right side.
Interference reduction methods

There exist some additional techniques to increase the SINR. Just to mention a few examples, we can use:

- **cell sectoring**
- **frequency hopping**
- **multiuser detection**
The wireless standards across time

0G

1960

GSM: 9.6 kb/s

1G

1985

GPRS: 171.2 kb/s

2G

1995

EDGE: 384 kb/s

3G

2005

UMTS: 2 Mb/s

4G

2015

HSPA: 5.76/14.4 Mb/s

HSPA+: 22/168 Mb/s

LTE-A: 100 Mb/s / 1 Gb/s

300 ms

150 ms

15 ms

Introduction to modern wireless communications systems
0G systems

- analog single-cell systems
- frequency modulation (FM)
- FDMA
- FDD
- channel spacing:
  - 1940s: 120 kHz
  - 1960s: 60 kHz
  - 1970s: 25 kHz
1G systems

- analog cellular systems
- FM + FDMA + FDD
- carrier frequencies: 450 MHz, 900 MHz
- channel spacing: 12.5 ÷ 30 kHz
Introduction to modern wireless communications systems

2G systems

- digital cellular systems
- GMSK+ FDMA/TDMA + FDD (GSM)
- carrier frequencies: 900 MHz, 1800 MHz
- channel spacing: 200 kHz (GSM)
- 1997: GPRS (2.5G), to support packet switching
- 2003: EDGE (2.75G), to support higher rates

GSM

Global System for Mobile communications (GSM)

Interim Standard 54 (IS-54, DAMPS)

Interim Standard 95 (IS-95, a.k.a. cdmaOne)

Pacific Digital Cellular (PDC)
3G systems

- **2002:**
  - 3G, IS-95 (a.k.a. cdma2000)
  - UMTS
  - Freedom of Mobile Multimedia Access (FOMA)
- **2002:**
  - Universal Mobile Telecommunications System (UMTS)

**Key Points**

- **digital cellular systems**
- **QPSK + CDMA + FDD/TDD**
- **carrier frequencies:** 2 GHz
- **channel spacing:** 5 MHz (UMTS/FOMA)

- **2006:** HSPA (3.5G), to support asymmetric rates
- **2008:** HSPA+ (3.75G), to support higher rates

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4G systems

- digital cellular systems
- QAM + OFDMA + FDD/TDD
- carrier frequencies: 2.5, 3.5, 5.8 GHz
- channel spacing: 3.5 \(\div\) 20 MHz
The challenging requirements set by the IMT-2020 for 5G systems include:

- **data rates:**
  - 1000× aggregate data rate increase with respect to (wrt) 4G
  - 100 Mb/s edge rate (100× wrt 4G)

- **latency:** 1 ms (10× wrt 4G)

- **energy efficiency:** 100× wrt 4G
Generation shift highlights

- **0G → 1G**: cellular deployment
- **1G → 2G**: digital systems
- **2G → 3G**: wideband signals (using CDMA)
- **3G → 4G**: even wider bandwidths (using OFDMA)
- **4G → 5G**: network densification, mmWave, massive MIMO, full duplex?


