Introduction to Cellular Communications

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Computer Engineering
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Outline of this part of the course

• **Introduction to wireless communications**

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

• **Fundamentals of cellular standards**
  o 3G communications
  o 4G communications
  o 5G communications

• **Discussion and perspectives**
Introduction to modern wireless communications
In 2019, the number of mobile users is around **7 billions** worldwide (out of 7.7 Ginhabitants!)

In Italy, the count is about **100,000,000 connections** for a population of **59.3 Minhabitants** (December 2018)
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 5 hours of videos are uploaded worldwide to Youtube
Fixed vs. mobile broadband subscriptions

Global ICT developments, 2001-2018*

- Mobile-cellular telephone subscriptions
- Individuals using the Internet
- Fixed-telephone subscriptions
- Active mobile-broadband subscriptions
- Fixed-broadband subscriptions

Per 100 inhabitants

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)
A brief history of wireless communications (2/3)

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
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
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

**End of 1950s/beginning of 1960s:**

- **Introducing cells** to provide **seamless** coverage
- **Cluster with size (reuse factor) K=4**
- **Co-channel (intercell) interference**
- **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
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)
Time division multiple access (TDMA)

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:
Code division multiple access (CDMA) (2/2)

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, 4G LTE makes use of a combination of FDMA and TDMA:
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
- ...
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 \( K \),

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

$$\gamma = \frac{S}{I + N} \approx \frac{S}{I}$$

where $S$ represents the useful signal power, $I$ is the multiple-access interference (both inter- and intra-cell) and $N$ is the additive noise. Cellular systems are usually interference-limited.

To provide a good signal quality, we must ensure $\gamma \geq \gamma_{\text{min}}$, where the minimum SINR $\gamma_{\text{min}}$ 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.
Choosing the reuse factor $K$ (4/6)

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

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

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

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

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.

$K = \{19, 21\}$

$K = \{7, 9\}$
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

http://www.inwit.it/mappa-dei-siti?field_region_value=16

http://opensignal.com/index.php?lat=44.7775&lng=14.2561&initZoom=6&isHeatMap=1
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)**
  - GPRS: 171.2 kb/s
  - 1G
  - GSM: 9.6 kb/s

- **2G (1995)**
  - EDGE: 384 kb/s

- **3G (2005)**
  - UMTS: 2 Mb/s
  - HSPA: 5.76/14.4 Mb/s

- **4G (2015)**
  - HSPA+: 22/168 Mb/s
  - LTE-A: 100 Mb/s / 1 Gb/s

- **5G (2030)**
  - LTE-A: 100 Mb/s / 1 Gb/s

- **300 ms**
- **150 ms**
- **15 ms**
0G systems

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

- 1979: Nippon Telegraph and Telephone (NTT)
- 1981: Nordic Mobile Telephone (NMT)
- 1983: Advanced Mobile Phone System (AMPS)
- 1983: Total Access Communication System (TACS)

- analog cellular systems
- FM + FDMA + FDD
- carrier frequencies: 450 MHz, 900 MHz
- channel spacing: 12.5 ÷ 30 kHz
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2G systems

- **digital cellular systems**
- **GMSK+ FDMA/TDMA + FDD (GSM)**
- carrier frequencies: 900 MHz, 1800 MHz
- channel spacing: 200 kHz (GSM)

1991:
Global System for Mobile communications (GSM)

1993:
Pacific Digital Cellular (PDC)

1994:
Interim Standard 54 (IS-54, a.k.a. DAMPS)

1995:
Interim Standard 95 (IS-95, a.k.a. cdmaOne)

1997:
GPRS (2.5G), to support packet switching

2003:
EDGE (2.75G), to support higher rates
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3G systems

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

- 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**: small cell, mmWave, massive MIMO
  - full duplex?


