Wireless Communications
Lecture 3: Fundamentals of Cellular Communications

Module Representative: Prof. Dr.-Ing. Hans D. Schotten
schotten@eit.uni-kl.de

Lecturer: Dr. Vincenzo Sciancalepore
vincenzo.sciancalepore@neclab.eu

Institute of Wireless Communication (WiCon)
Department of Electrical and Computer Engineering
TU Kaiserslautern

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Outline

• Overview of cellular networks
• Radio Spectrum and propagation models
• Cell dimensioning
• Coverage and capacity planning
• Frequency reuse
• Dynamic channel allocation
Telecommunications means
Cellular Communications Evolution
The business of the Mobile Networks

**Mobile Subscriptions to Outnumber the World’s Population**
World population vs. estimated number of worldwide mobile subscriptions

- **World Population**
- **Mobile Subscriptions**

<table>
<thead>
<tr>
<th>Year</th>
<th>World Population</th>
<th>Mobile Subscriptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>7.3b</td>
<td></td>
</tr>
<tr>
<td>2011</td>
<td>7.4b</td>
<td></td>
</tr>
<tr>
<td>2012</td>
<td>7.5b</td>
<td></td>
</tr>
<tr>
<td>2013</td>
<td>7.6b</td>
<td></td>
</tr>
<tr>
<td>2014</td>
<td>7.7b</td>
<td></td>
</tr>
<tr>
<td>2015</td>
<td>7.8b</td>
<td></td>
</tr>
<tr>
<td>2016</td>
<td>7.9b</td>
<td></td>
</tr>
<tr>
<td>2017</td>
<td>8.0b</td>
<td></td>
</tr>
<tr>
<td>2018</td>
<td>8.1b</td>
<td></td>
</tr>
<tr>
<td>2019</td>
<td>8.2b</td>
<td></td>
</tr>
<tr>
<td>2020</td>
<td>8.3b</td>
<td></td>
</tr>
</tbody>
</table>

**Landline Phones Are a Dying Breed**
% of U.S. household with and without a working landline telephone*

- **Landline Phone**
- **Cell Phone Only**

<table>
<thead>
<tr>
<th>Year</th>
<th>Landline Phone</th>
<th>Cell Phone Only</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004</td>
<td>92.7%</td>
<td>5.0%</td>
</tr>
<tr>
<td>2005</td>
<td>91.9%</td>
<td>5.0%</td>
</tr>
<tr>
<td>2006</td>
<td>91.2%</td>
<td>5.0%</td>
</tr>
<tr>
<td>2007</td>
<td>90.6%</td>
<td>5.0%</td>
</tr>
<tr>
<td>2008</td>
<td>89.9%</td>
<td>5.0%</td>
</tr>
<tr>
<td>2009</td>
<td>89.2%</td>
<td>5.0%</td>
</tr>
<tr>
<td>2010</td>
<td>88.6%</td>
<td>5.0%</td>
</tr>
<tr>
<td>2011</td>
<td>88.0%</td>
<td>5.0%</td>
</tr>
<tr>
<td>2012</td>
<td>87.4%</td>
<td>5.0%</td>
</tr>
<tr>
<td>2013</td>
<td>86.7%</td>
<td>5.0%</td>
</tr>
<tr>
<td>2014</td>
<td>86.0%</td>
<td>5.0%</td>
</tr>
<tr>
<td>2015</td>
<td>85.3%</td>
<td>5.0%</td>
</tr>
<tr>
<td>2016</td>
<td>84.6%</td>
<td>5.0%</td>
</tr>
</tbody>
</table>

* based on the CDC’s biannual National Health Interview Survey of ~20,000 U.S. households

Source: Centers for Disease Control and Prevention, NCHS

Statista
Cellular network architecture

Communications for connecting people

+ Communications for connecting things

Communication speed has increased by around 10,000 times over the past 30 years

5G is not only ultra high speed...

Increased capacity by introduction of OFDMA & MIMO

Increased capacity by shifting from TDMA $\rightarrow$ CDMA
Radio spectrum

- Wave length \[ \lambda = \frac{c}{f} \]
- Light speed \[ c = 3 \cdot 10^8 \text{ m/s} \]
- Frequency \( f \) \[ s(t) = \cos(2\pi ft + \varphi) \]

<table>
<thead>
<tr>
<th>Frequency Band</th>
<th>Description</th>
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<tbody>
<tr>
<td>ELF</td>
<td>&lt;3 KHz</td>
</tr>
<tr>
<td>VLF</td>
<td>3-30 KHz</td>
</tr>
<tr>
<td>LF</td>
<td>30-300 KHz</td>
</tr>
<tr>
<td>MF</td>
<td>300 KHz - 3 MHz</td>
</tr>
<tr>
<td>HF</td>
<td>3-30 MHz</td>
</tr>
<tr>
<td>VHF</td>
<td>30-300 MHz</td>
</tr>
<tr>
<td>UHF</td>
<td>300 MHz - 3 GHz</td>
</tr>
<tr>
<td>SHF</td>
<td>3-30 GHz</td>
</tr>
<tr>
<td>EHF</td>
<td>30-300 GHz</td>
</tr>
<tr>
<td>IR</td>
<td>300 GHz – 400 THz</td>
</tr>
<tr>
<td>Light</td>
<td>400-900 THz</td>
</tr>
</tbody>
</table>

Remote control, Voice, analog phone
Submarine, long-range
Long-range, marine beacon
AM radio, marine radio
Amateur radio, military, long-distance aircraft/ships
TV VHF, FM radio. AM x aircraft commun.
Cellular, TV UHF, radar
Satellite, radar, terrestrial wireless links, WLL
Experimental, WLL
LAN infrared, consumer electronics
Optical communications
Radio spectrum

• Mobile Radio networks
  • Bandwidth range 900-2200 MHz (VHF-UHF)
  • Antenna design is simple, size is small (up to few cm)
  • Emitted powers around 1W to cover up to few kilometers so as to penetrate building walls

• Point-to-point and satellite links
  • Bandwidth range 3-30 GHz (SHF)
  • Plenty of bandwidth available but strong attenuation due to meteorological effects (such as rain, fog)

• Data wireless networks (WLAN, WPAN, etc.)
  • Bandwidth range 2.4 GHz e 5GHz (ISM band)
  • Interference with other systems (such as microwave ovens, remote controls)
  • In the highest frequency (5 GHz) attenuation due to rain

• High frequencies
  • High bandwidth availability
  • Less interference as the spectrum is less crowded
  • Propagation is impaired by the obstacles

• Low frequencies
  • Low bandwidth availability
  • Big antennas required
  • Many interference sources in this bandwidth spectrum
Cellular network

• Network is divided into several cells where the base station (BTS) is placed in the center: users connect to a single BTS (Serving BTS)

• Cells conventionally have an hexagonal shape to better tesselate but in reality they have a circular coverage (in case of isotropic antennas)

• In real deployments the base station is provided with 3-sector-antennas

• Cell-edge users experience high interferences from adjacent BTSs

• How to dimension a single cell?
Empirical models

• Recall that the maximum pathloss is \( L_p = P_t - P_r \)

• Empirical models can be used to calculate attenuation due to distance with approximated formulas based on general characteristics of the propagation area

• Reference scenarios and parameters
  • Urban areas (big-medium-small cities), rural areas
  • Combinations of basic models (such as LOS, reflected ray)
  • Frequency, distance, antenna heights
  • Environmental characteristics (such as lakes, streets)

• Okumura-Hata: urban area
  \[
  L_p = 69.55 + 26.16 \log f - 13.82 \log h_T - a(h_R) + \left( 44.9 - 6.55 \log h_T \right) \log d
  \]

• Simple model
  \[
  L_p(d) = 10\eta \log_{10} \left( \frac{d}{d_0} \right)
  \]
Dimensioning the cell coverage

• The propagation model is not accurate due to the shadowing effect
• This is taken into account while dimensioning the cell radius by adding a fading margin to prevent edge-users from receiving very low channel quality \( M \)

• **Fading margin**
  \( M = \text{cell-edge power} - \text{receiver threshold} = \bar{P}_{dB}(R) - P_r \)

• **Homework**
  Received power at 10 m = 100mW
  Receiver threshold = -50 dBm
  Propagation factor \( \eta = 3.7 \)
  Log-normal shadowing with \( \sigma_{dB} = 4 \) dB
  Fading margin \( M = 6 \) dB
  Cell Radius \( R = ? \)
Dimensioning the cell coverage

• Outage probability

\[ f_{P_{dB}}(r)(x) = \frac{1}{\sqrt{2\pi} \sigma_{dB}} e^{-\frac{(x-P_{dB}(r))^2}{2\sigma_{dB}^2}} \]

\[ \text{Pr}_{out}(r) = \int_{-\infty}^{\infty} f_{P_{dB}}(r)(x)dx = \frac{1}{2} \text{erfc} \left( \frac{P_{dB}(r) - P_r}{\sqrt{2}\sigma_{dB}} \right) \]

where \( P_{dB}(r) = P_{dB}(R) - 10\eta \log_{10} \left( \frac{r}{R} \right) \)

that yields

\[ \text{Pr}_{out}(r) = \frac{1}{2} \text{erfc} \left( \frac{P_{dB}(R) - P_r - 10\eta \log_{10} \left( \frac{r}{R} \right)}{\sqrt{2}\sigma_{dB}} \right) = \frac{1}{2} \text{erfc} \left( \frac{M - 10\eta \log_{10} \left( \frac{r}{R} \right)}{\sqrt{2}\sigma_{dB}} \right) \]

and \( \text{Pr}_{out}(R) = \frac{1}{2} \text{erfc} \left( \frac{M}{\sqrt{2}\sigma_{dB}} \right) \)

Remind that \( \varphi(x) = \frac{1}{2} \left[ 1 + erf \left( \frac{x}{\sqrt{2}} \right) \right] \), where \( \varphi(x) \) is the CDF of the normal distribution and then \( \text{erfc}(x) = 2[1 - \varphi(x\sqrt{2})] \)
Dimensioning the cell coverage

- Outage area

\[
\Pr_{\text{out}}^A (R) = \frac{1}{\pi R^2} \int_0^R \Pr_{\text{out}}(r) 2\pi r \, dr = \int_0^R \frac{r}{R} \text{erfc} \left( \frac{M - 10\eta \log_{10}(r)}{\sqrt{2\sigma_{dB}}} \right) \frac{dr}{R}
\]

\[
= \int_0^1 x \text{erfc} \left( \frac{M - 10\eta \log_{10} x}{\sqrt{2\sigma_{dB}}} \right) dx = \int_0^1 x \text{erfc} \left( \frac{\ln(m) - \eta \ln x}{\sqrt{2\sigma}} \right) dx
\]

where \( \sigma = \frac{\sigma_{dB} \ln 10}{10} \) and \( m = 10^{\frac{M}{10}} = \frac{\overline{P}(R)}{P_{th}} \)

Assuming \( K_1 = \frac{\ln(m)}{\sqrt{2}\sigma} \) and \( K_2 = \frac{\sqrt{2}\sigma}{\eta} \)

\[
\Pr_{\text{out}}^A (R)
= \int_0^1 x \text{erfc} \left( K_1 - \frac{\ln(x)}{K_2} \right) dx = K_2 \int_{K_1}^{+\infty} e^{2K_2(K_1-z)} \text{erfc}(z) \, dz = \left[ -\frac{1}{2} e^{2K_2(K_1-z)} \text{erfc}(z - K_2) - \frac{1}{2} e^{2K_2(K_1-z)} \text{erfc}(z) \right]_{K_1}^{+\infty}
\]

\[
= \frac{1}{2} \text{erfc}(K_1) - \frac{1}{2} e^{2K_2K_1-K_2^2} \text{erfc}(K_1 + K_2)
\]

\[
\text{erfc}(x) = \frac{2}{\sqrt{\pi}} \int_x^{+\infty} e^{-t^2} \, dt = 1 - \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2} \, dt
\]

\[
D[\text{erfc}(x)] = -\frac{2}{\sqrt{\pi}} e^{-x^2}
\]

\[
\int \text{erfc}(x) \, dx = x \text{erfc}(x) - \frac{1}{\sqrt{\pi}} e^{-x^2}
\]
Radio planning

- BTS positioning and configuration adjustments are challenging problems
- Considered aspects: signaling propagation, traffic estimation, antenna positioning, antenna configuration, inter-cell interferences
- Traffic distribution is provided using a discrete set of points, namely test points (TPs), i.e., centroids of traffic
- BTSs can be placed only in candidate sites
- **Coverage and capacity planning**
Coverage and capacity planning

- Traffic generated is served only if the quality of the connection good enough

- Signal-to-interference-noise ratio (SINR) \( \frac{P_r}{N_0 + \sum_{i \in I} P_{i,r}} \)

- Power control mechanisms
  - Power-based
  - SINR-based

- **Cell breathing effect**: coverage change
  Increasing traffic leads to an increasing interference that results in channel degradation at the cell-edge
Coverage and capacity planning

• How to optimally select a set of candidate sites (to place BTSs), and assign test points to BTSs so that the total cost is minimized while the minimum channel quality level is still guaranteed.

\[
\text{maximize } \sum_{i \in I} \sum_{j \in S} \phi(a_i)x_{i,j} - \lambda \sum_{j \in S} c_j y_j
\]

subject to

\[
\frac{P_{\text{tar}}}{\sum_{h \in I} \phi(a_h)g_{h,j} \sum_{t \in S} \frac{P_{\text{tar}}}{g_{h,t}} x_{h,t} - P_{\text{tar}} \geq \text{SINR}_{\text{min}} y_j}
\]

\[
\sum_{j \in S} x_{i,j} \leq 1
\]

\[
x_{i,j} \leq y_j
\]

Power-based power control

\[
\frac{P_{\text{tar}}}{g_{i,j}} \leq P_{\max}
\]
Inter-cell interference mitigation

• Inter-cell interferences significantly impair the channel condition and the user data rate

• Different frequency channels might be assigned to distinct cells to alleviate the interference problem

• Not enough available channels: they can be assigned to multiple cells sufficiently apart each other

• The hexagonal shape helps to properly make the frequency assignment
Frequency reuse

• Frequencies can be reused as much as possible while still guaranteeing the SINR constraints

• Assuming hexagonal cells and homogeneous traffic, frequencies are divided into $K$ groups and assigned to a group of $K$ cells, namely *cluster*

• The cluster is regularly repeated in the whole system area

• Cluster size ($K$) admits only certain values (1,3,4,7,9,12,...) due to the hexagonal shape

• Assuming same antennas and same power

\[
SINR = \frac{P_t G d^{-\eta}}{\sum_{i=1}^{6} P_t G d_i^{-\eta}} = \frac{d^{-\eta}}{\sum_{i=1}^{6} d_i^{-\eta}}
\]

\[
SINR \approx \frac{r^{-\eta}}{6D^{-\eta}} = \frac{1}{6} \left( \frac{1}{R} \right)^{-\eta} \text{ where } d = r \text{ and } d_i \approx D
\]
Cluster dimensioning

• SINR strictly depends on the reuse factor \( R = \frac{D}{r} \)

• Assuming that \( K = \frac{R^2}{3} \), the minimum cluster size is \( K_{\text{min}} \approx \frac{(6\text{SINR})^2}{3\eta} \)

• Homework

\[ \text{SINR}_{\text{min}} = 18 \text{ dB} \]

Propagation factor \( \eta = 3.9 \)
Cluster size \( K = ? \)

• Fading margins can be considered to account for fast fading and shadowing effects
Clustering with sectorial antennas

- Directive antennas are commonly used to reduce the angle of the main lobe up to 120°
- Three-sectorial antennas are provided to the same BTS site
- Frequency reuse is applied to any single sector
- Recalling the SINR formula, we can rewrite
  \[ SINR \approx \frac{r^{-\eta}}{MD^{-\eta}} = \frac{1}{M} \left( \frac{1}{R} \right)^{-\eta} \]
  - This yields
  \[ K_{min} \approx \frac{(M \cdot SINR)^{\eta}}{3} \]
  - Adjacent frequencies should not be assigned to multiple sectors of the same BTS site

\[ M = \frac{6}{s sectors} \]
Frequency assignment problem

• The problem can be designed as a graph coloring problem known to be **NP-Hard**

• Vertices are BTS site and edges define two BTS that cannot use the same frequency due to high interference

• Each color defines a different frequency channel to be assigned

• Frequency Assignment Problem (FAP): edges have 3 different values (0, 1 and 2) specifying whether the two vertices (BTSs) can use the same frequency (0), cannot use the same frequency (1), cannot use adjacent frequencies (2)

• Heuristics are defined, such as greedy solution
Dynamic channel allocation

- Frequency assignment is performed during the planning phase.
- Dynamic channel allocation may help while assigning different channels based on the current traffic load.
- Available channels are gathered into a common pool of resources and are dynamically assigned based on event occurrences, such as call arrivals.
- BTSs are aware about the channel assigned to the adjacent cells so as to avoid inter-cell interference while occupying new channels.
- Game-theory paradigm can be used to design distributed algorithms.