Challenge 2020:

1000 times more capacity at today's cost & energy

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Mobile Data avalanche

VolP traffic forecasted to be 0.4% of all mobile data traffic in 2015.
Source: Cisco VNI Mobile, 2011

Cisco forecast: 2015 - 26x
Extrapolation: 2020 - 1000x
Computing & Communication Paradigms

- Bandwidth cost
  - Fixed
  - Mobile
- Computing, switching cost
- Computing demand
- Leased lines
- Computer centers
- Cloud computing
- Mobile Services everywhere
- Packet switching
- PC, server-client


Wireless@KTH
### World wide proliferation of Mobile Data

<table>
<thead>
<tr>
<th>Key Global Telecom Indicators for the World Telecommunication Service Sector in 2011 (all figures are estimates)</th>
<th>Global</th>
<th>Developed nations</th>
<th>Developing nations</th>
<th>Africa</th>
<th>Arab States</th>
<th>Asia &amp; Pacific</th>
<th>CIS</th>
<th>Europe</th>
<th>The Americas</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mobile cellular subscriptions (millions)</strong></td>
<td>5,981</td>
<td>1,461</td>
<td>4,520</td>
<td>433</td>
<td>349</td>
<td>2,897</td>
<td>399</td>
<td>741</td>
<td>969</td>
</tr>
<tr>
<td><strong>Per 100 people</strong></td>
<td>86.7%</td>
<td>117.8%</td>
<td>78.8%</td>
<td>53.0%</td>
<td>96.7%</td>
<td>73.9%</td>
<td>143.0%</td>
<td>119.5%</td>
<td>103.3%</td>
</tr>
<tr>
<td><strong>Fixed telephone lines (millions)</strong></td>
<td>1,159</td>
<td>494</td>
<td>665</td>
<td>12</td>
<td>35</td>
<td>511</td>
<td>74</td>
<td>242</td>
<td>268</td>
</tr>
<tr>
<td><strong>Per 100 people</strong></td>
<td>16.6%</td>
<td>39.8%</td>
<td>11.6%</td>
<td>1.4%</td>
<td>9.7%</td>
<td>13.0%</td>
<td>26.3%</td>
<td>39.1%</td>
<td>28.5%</td>
</tr>
<tr>
<td><strong>Active mobile broadband subscriptions (millions)</strong></td>
<td>1,186</td>
<td>701</td>
<td>484</td>
<td>31</td>
<td>48</td>
<td>421</td>
<td>42</td>
<td>336</td>
<td>286</td>
</tr>
<tr>
<td><strong>Per 100 people</strong></td>
<td>17.0%</td>
<td>56.5%</td>
<td>8.5%</td>
<td>3.8%</td>
<td>13.3%</td>
<td>10.7%</td>
<td>14.9%</td>
<td>54.1%</td>
<td>30.5%</td>
</tr>
<tr>
<td><strong>Fixed broadband subscriptions (millions)</strong></td>
<td>591</td>
<td>319</td>
<td>272</td>
<td>1</td>
<td>8</td>
<td>243</td>
<td>27</td>
<td>160</td>
<td>145</td>
</tr>
<tr>
<td><strong>Per 100 people</strong></td>
<td>8.5%</td>
<td>25.7%</td>
<td>4.8%</td>
<td>0.2%</td>
<td>2.2%</td>
<td>6.2%</td>
<td>9.6%</td>
<td>25.8%</td>
<td>15.5%</td>
</tr>
</tbody>
</table>

Source: **International Telecommunication Union (November 2011)**

via: mobiThinking

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**Wireless @ KTH**
More for less money

- Spending capability of user increases with GNP growth (<10% annually)
- Capacity requirements increase by 100% annually
- but will operators keep up?

- Excess capacity when 3G was deployed to meet coverage constraints
- "Hidden traffic" ("App-App", "Cloud based") causes severe problems ("Control plane overload")
- Rapid LTE Deployment – medium term solution since terminal market still dominated by WCDMA/HSPA terminals
How can we achieve the target?
Some fundamental design
Constraints

IEEE Wireless Communications, October 2011.
Candidate Technologies

• Improved Spectral Efficiency (Moore’s Law)
  – PHY-layer (Modulation, MIMO)
  – Interference Management (COMP/ICIC)
• Denser infrastructure
• More Spectrum
In search for 5 G
1000 times more capacity ..but how?

What does the “market” think?

<table>
<thead>
<tr>
<th>Company</th>
<th>Spectrum</th>
<th>Spectral efficiency</th>
<th>Densification</th>
<th>Total capacity increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nokia Siemens</td>
<td>10x</td>
<td>10x</td>
<td>10x</td>
<td>1000x</td>
</tr>
<tr>
<td>Huawei</td>
<td>3x</td>
<td>3.3x</td>
<td>10x</td>
<td>100x</td>
</tr>
<tr>
<td>NTT Docomo</td>
<td>2.8x</td>
<td>24x</td>
<td>15x</td>
<td>1000x</td>
</tr>
</tbody>
</table>

What does capacity mean?

\[ R_{tot} = N_{user} R_{user} \]
Spectral efficiency & PHY Layer improvements

- Operation today almost at Shannon limit
  \[ R = nW \log \left( 1 + \frac{P}{I_0W} \right) \]

- Increased peak rates have limited effect on average or guaranteed rate if BS density is too small
- Too high \( \frac{R}{W} \) leads to poor energy efficiency
- Conclusion:
  - Further increase in spectral efficiency not feasible/desirable
  - Multiple antenna (MIMO) gain feasible (factor \( n \) in peak rate)

Capacity and Peak Rate are not simply related

Capacity ≠ Peak Rate
Moore’s law not applicable to concrete and steel
• Edge rates dominate
• High peak rates make sense only in dense deployment
• Cost/Tech drivers:
  - Peak rates: Replace base station equipment
  - Edge rate: More Base stations sites
Interference Management

- Ideal COMP/ICIC ("Crazy COMP")
  - Completely Noise limited
  - Some additional diversity gain
  - Theoretical gains 3-4 (?) in SE (reduced reuse factor)
- Practically achievable gains significantly less
  - CSI estimation errors/quantization
  - CSI feedback capacity & processing

Source: 3GPP TSG RAN WG1, R1-100855
"Performance evaluation of intra-site DL CoMP"
Cooper’s law

- 1,000,000 times more capacity over last 45 years
  - 25x more spectrum
  - 25x better modulation/signal processing
  - 1600x densification (more base stations)

Source: http://www.arraycomm.com/technology/coopers-law
Cost for densification

\[ C_{\text{infra}} \propto C_{BS} \frac{N_{\text{user}} R_{\text{user}} A_{\text{service}}}{\eta W_{\text{sys}}} \]

"Zander’s Law"

\[ C_{BS} = C_{\text{site}} + C_{\text{backhaul}} + C_{\text{Equipment}} \]
Densification: Technology shift

- Industry grade eq
- High power
- 24-7 availability
- High **system** complexity
- **COST** = equipment, site, spectrum, energy

- Consumer grade eq
- Low power/Short range
- Low **system** complexity (P&P, SON)
- Massive deployment – mainly indoor
- Reliability through redundancy
- Deploy where backhaul available
- **COST** = Deployment
Sharing infrastructure: A new ways to low-cost capacity

• Technology: Not an issue!
• Business model: Cooperation!

"HET NETs"
Infrastructure sharing

- Multiple competing parallel infrastructures

- Multimode shared infrastructure
  - Explicit sharing
  - Coopetition
Why do we need more spectrum?

- More data rate / Capacity?
  - For very high data rates (>100 Mbit/s user rate)
- Lower deployment cost (fewer base stations)
- Lower energy consumption (lower spectral efficiency)

### Spectrum options?

<table>
<thead>
<tr>
<th></th>
<th>Exclusive &lt;6 GHz</th>
<th>Shared &lt; 6 GHz</th>
<th>Secondary &lt;6 GHz</th>
<th>Exclusive &gt; 10 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Availability</strong></td>
<td>Very Low</td>
<td>Low (100 MHz)</td>
<td>Good (&gt;1 GHz)</td>
<td>Very good</td>
</tr>
<tr>
<td><strong>Advantages</strong></td>
<td>• Guaranteed QoS</td>
<td>• Spectrum available</td>
<td>• Spectrum available</td>
<td>Very high capacity</td>
</tr>
<tr>
<td></td>
<td>• Long-term investments</td>
<td>• Low cost equipment/deployment</td>
<td>• Low cost equipment/deployment</td>
<td>Low interference</td>
</tr>
<tr>
<td><strong>Disadvantages</strong></td>
<td>High deployment cost</td>
<td>• No QoS guarantees</td>
<td>• Limited QoS guarantees</td>
<td>LOS propagation, antennas</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Low availability</td>
<td>• Regulatory uncertainty</td>
<td>Dedicated Deployment</td>
</tr>
</tbody>
</table>
Commercial Feasibility of Secondary Spectrum Use (FP7 QUASAR)

- Plenty of spectrum for secondary use, in particular short range indoor
- Availability very scenario & location specific
- Sensing useless in many popular scenarios – yields very low utilization
- Key challenges in business scalability:
  - Assessing impact of multiple interferers
  - Strong Coupling to infrastructure lifetime
Some conclusions

• Moore Law is not going to save the day (not this time either)

• Denser infrastructure – still the key to higher capacity
  - Infrastructure sharing – ”disruptive” business model
  - Cost dominated by deployment & fixed infrastructure – not equipment, spectrum
  - Challenge: Ad-hoc, Out-of-the-box deployment (P&P, SON)

• More **low-band** spectrum → lower cost, lower energy consumption

• Several new spectrum options available
Additional slides
Cellular Design for Power/Total Cost minimization
Energy consumption modelling

- **Assumptions:**
  - Homogenous network, (real network - composed of homogeneous “islands”)

- **Power consumption**

\[ P = N_{BS} \left[ aP_{tx} + b_{radio} + b_{backhaul} + y \frac{R_{tot}}{N_{BS}} \right] + d \]

- Proportional to #base stations
- Independent of #base stations
Energy consumption modelling (2)

- Spectrum-Infrastructure Cost-Power Trade-off (Shannon Bound)

\[ P_{rx}(d) = \frac{c' GP_{tx}}{d^\alpha} \quad P_{tx} = \left[ \frac{R}{2W} - 1 \right] \frac{N_0W}{cG} R_{cell}^\alpha \]

- Average spectral efficiency

\[ S = \frac{R}{W} \]

\[ P_c = \left( N_{BS} \right) \left[ a \left( \frac{N_0W}{cG} \left( 2 \frac{R_{tot}}{N_{BS}W} - 1 \right) \left( \frac{A}{\pi N_{BS}} \right)^{\alpha/2} \right) + b_{radio} + b_{backhaul} + y \frac{R_{tot}}{N_{BS}} \right] + d \right) / A \]
“Green” Architecture

- If power/energy is the dominant constraint:

\[
\lim_{{N_{BS} \to \infty}} P_c (N_{BS}) \to \alpha > 2
\]

There is always a non-null and finite value that minimizes the areapower consumption.
Green Architecture

- Idle power

\[ \text{Area Power Consumption (Watt/km}^2\text{)} \]

\[ R_{\text{tot}} = 20 \text{Mbps/km}^2 \]

\[ R_{\text{tot}} = 5 \text{Mbps/km}^2 \]
Deployment of Minimal Total Cost

- Total Network Cost as a function of main drivers of the network:

\[
\text{Cost} = c_0 \cdot N_{BS} + c_1 \left\{ N_{BS} \left[ a \left( \frac{N_o W}{cG} \left( \frac{2 \bar{R}_{tot}}{N_{BS} W} - 1 \right) \left( \frac{A}{\pi N_{BS}} \right)^{\alpha / 2} \right) \right] + b_{\text{radio}} + b_{\text{backhaul}} + y \frac{\bar{R}_{tot}}{N_{BS}} \right\} + d \right\} + c_2 W
\]

- \( c_0 [\text{€/BS}] \): Annual cost per base station
- \( c_1 [\text{€/Energy Unit}] \): Annual energy cost
- \( c_2 [\text{€/Mhz}] \): Annualized spectrum cost
• Minimum total cost now occurs at a much lower number of base stations than in the energy-only minimization.
• Spectrum cost constant – provides only a level shift of the total cost;
Increasing infrastructure cost

- Total cost increases
- Optimal number of base station is not that much affected.
As the spectrum cost increases, optimum spectrum expenditure moves closer to the “energy asymptote”
Cost drivers

Greenfield deployment

QUASAR  Technical findings
QUASAR Key technical findings

- Plenty of spectrum available – but very scenario & location specific - commercial success is where we can live with this
- Aggregate interference critical for the scalability – massive use of secondary spectrum
  - Both co-channel & and adjacent channel interference has to be considered
- "Cognitive" sensing is not very effective in most popular scenarios – geolocation based techniques are preferable
  - Limited knowledge of victim receiver location
  - Difficult to assess aggregate interference
  - Sensing interesting to improve/calibrate database propagation models
Co-channel & Adjacent channel interference
Aggregate interference due to “massive” use

TV coverage area, TV test points and secondary deployment area

Density of the households
Each household $\rightarrow$ 1 transmitter
(Un-)Reliability of sensing

- Opportunity (not signal) Detection problem
- Even with “perfect” signal detection uncertainty remains about
  - Primary receiver location
  - Primary system path loss
  - Aggregate interference
- Maps into high interference margins and (very) inefficient spectrum use

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Standard deviation</th>
<th>IM (95%)</th>
<th>IM (99%)</th>
<th>Rate (IM=95%)</th>
<th>Rate (IM=99%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low detection correlation ( =0)</td>
<td>23,0</td>
<td>37,8</td>
<td>53,5</td>
<td>1,66E-04</td>
<td>4,51E-06</td>
</tr>
<tr>
<td>High detection correlation ( =1)</td>
<td>21,5</td>
<td>35,4</td>
<td>50,1</td>
<td>2,86E-04</td>
<td>9,75E-06</td>
</tr>
<tr>
<td>Known primary receiver position</td>
<td>11,3</td>
<td>18,6</td>
<td>26,3</td>
<td>1,38E-02</td>
<td>2,33E-03</td>
</tr>
<tr>
<td>Known path gain</td>
<td>8,0</td>
<td>13,2</td>
<td>18,6</td>
<td>4,83E-02</td>
<td>1,38E-02</td>
</tr>
<tr>
<td>Genie aided access (full knowledge)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>