Design principles for High-Capacity Wireless Access Networks

IK2514 Wireless Infrastructure Deployment and Economics
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Outline

• Requirements for future system, Do we need 5G?
  • Some key trends
  • Transparency & mobile data tsunami
  • The internet of things and senses

• Design principles for scalable Infrastructure
  • Key trade-offs: Cost, Energy, Spectrum
  • The two worlds – or are they three?

• What about the internet of things??
Is it a bird? .. a plane?

No, it’s 5G!
Key trend

Transparency eats efficiency for breakfast
A lessons from History - Dominant designs

● From infrastructures driven by "killer apps" and "one-trick ponies"
  → general IP-based access infrastructures

● Internet access = dominant design for ALL services (fixed & mobile)
  ● Marginalizes other technical solutions – e.g. Wireless P2P, Mesh, ...
  ● Story sounds familiar ...?

"IP is the answer - now, what was the question?"
The price tag for transparency – the Mobile Data avalanche

Cisco forecast: 2015 - 26x
Extrapolation: 2020 - 1000x

Exponential growth (now slowing down somewhat)
Assumes **zero marginal cost** for access
How long can this be sustained?

VolP traffic forecasted to be 0.4% of all mobile data traffic in 2015.
Source: Cisco VN Mobile, 2011
Operator dilemma: More for less money

- Spending capability of user increases with GNP growth (<10% annually)
- Capacity requirements increase by 80-100% annually

\[ C_{SYS} = c_{BS} N_{BS} \]

Challenge: 1000x lower cost/bit
Key trend 2: Things that communicate & the Internet of Senses
Things that communicate

Internet of Things

- Billions of devices
- Low power
- Low cost
- High reliability
- Low delay

4G not a scalable solution
SIM-cards in every device?
"The internet of senses"
("Tactile Internet")

IP Cloud

< 1 ms delay

Speed of light: 300 km/ms
Mission critical communication
(Super real-time, super reliable...)

Source: The Economist, April 20th, 2013
Design principles for Scalable Wireless Infrastructures
Design principles for Scalable Wireless Infrastructures
Key Design Constraints

\[ C_{tot} = C_{spectrum} + C_{infra} + C_{energy} \]
How to increase capacity?

$$R_{tot} \approx \frac{\eta}{A} N_{BS} W_{sys}$$  \hspace{1cm} C_{SYS} = c_{BS} N_{BS} + c_{sp} W_{sys}$$

- Increase $\eta$, spectral efficiency (signal processing)
  - Close to theoretical limits
  - More power (in processing – receiver limitation!)
- More base stations, $N_{BS}$
  - Expensive
  - More power?
- More spectrum, $W_{SYS}$
  - Shortage?
Energy consumption modelling

Power consumption

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

Proportional to #base stations

Independent of #base stations
Energy consumption modelling (2)

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

\[ P_{rx}(d) = \frac{c'GP_{tx}}{d^\alpha} \]

\[ P_{tx} = \left[ \frac{R}{2W} - 1 \right] \frac{N_0W}{cG} R_{cell}^\alpha \]

Average spectral efficiency

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

\[ P_c = \left( N_{BS} \left\{ a \left\{ \frac{N_0W}{cG} \left( \frac{R_{tot}}{2N_{BS}W} - 1 \right) \left( \frac{A}{\pi N_{BS}} \right)^{\alpha/2} \right\} + b_{radio} + b_{backhaul} + y \frac{R_{tot}}{N_{BS}} \right\} + d \right) / A \]
What cell size to use?

\[
\overline{R} \approx c_0 W \log_2 \left( 1 + \frac{c' P_{\text{tot}}}{N_0 r^{-\alpha-2}} \right)
\]

Energy

\[
P_{\text{tot}} \approx c_1 r^{-\alpha-2} \left( \frac{\overline{R}}{2^{c_0 W}} - 1 \right)
\]

Required total power

Infra cost

Spectrum
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;
Spectrum / Infrastructure tradeoff

\[
C_{\text{sys}} \approx c_{BS} N_{\text{BS}} = c_{BS} \frac{B_{\text{tot}}}{\eta W_{\text{SYS}}} \\
B_{\text{tot}} \approx \frac{C_{\text{sys}}}{c_{BS}} \eta W_{\text{sys}} = \eta N_{\text{BS}} W_{\text{sys}}
\]

\[
B_{\text{tot}} + \Delta B \approx \eta N_{\text{BS}} W_{\text{sys}} + \eta \Delta N W_{\text{sys}} + \eta N_{\text{BS}} \Delta W
\]

\[
C_{\text{sys}} + \Delta C \approx C_{\text{sys}} + c_{BS} \Delta N + \left(\Delta c_{BS} N_{\text{BS}} + c_{sp}\right) \Delta W
\]

\[
\min \Delta C = \min \left( c_{BS} \frac{\Delta B}{\eta W_{\text{SYS}}}, \left(\Delta c_{BS} N_{\text{BS}} + c_{sp}\right) \frac{\Delta B}{\eta N_{\text{BS}}} \right)
\]

\[
c_{sp}^* = \frac{c_{BS}}{W_{\text{SYS}}} - \Delta c_{BS} N_{\text{BS}} \quad \text{Engineering value of spectrum}
\]
Discussion 2: The street light analogy

Why are parts of Sweden dark at night?
• Technical limitations?
• User demand?
• Economical limitations?
The Light Analogy II: HET NETs

- Indoor – Short Range

Outdoor – Wide Area
How to lower the cost:

”HET NET”s – deploy according to demand

Traffic distribution

Indoor/ Hot Spot | Urban | Suburban | Rural

”Blanket coverage”

Het Net Deployment
A World Divided

The coverage world

Public operators
- Access any-time, anywhere
- "Insurance" – guaranteed access at moderate datarates (1-2 Mbit/s)
- Monthly fee
- Power/Site/Backhaul
- Exclusive spectrum licensing – spectrum sharing

The capacity world

Facility owners
- Local access - "off-loading"
- Sanitary requirement / no charge
- User experiences – high data rates
- Ultra dense deployment – Interference
- (Low power, no site cost, existing backhaul)
- Post-code licensing – infrastructure sharing

The coverage world vs. The capacity world

A World Divided
Is there enough capacity?

<table>
<thead>
<tr>
<th>Intersite</th>
<th>Spectrum</th>
<th>No BS</th>
<th>Cap/Site</th>
<th>Area cap</th>
</tr>
</thead>
<tbody>
<tr>
<td>Macro</td>
<td>300 m</td>
<td>500 MHz</td>
<td>10 /km²</td>
<td>1 Gb/s</td>
</tr>
<tr>
<td>WiFi - today</td>
<td>30m</td>
<td>500 MHz</td>
<td>1000/km²</td>
<td>1 Gb/s</td>
</tr>
<tr>
<td>WiFi - ideal</td>
<td>1/room</td>
<td>2 GHz</td>
<td>50K/km²</td>
<td>4 Gb/s</td>
</tr>
</tbody>
</table>

Simple area-based calculation – outdoor/indoor wall penetration not included

Spectrum: There is potentially lots of spectrum < 20 GHz for indoor short range use (on secondary basis)
Can the Things use the same infrastructure?
## Very diverse requirements

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Human centric</th>
<th>Machine Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity</td>
<td>Very Large</td>
<td>Small</td>
</tr>
<tr>
<td>Number of devices</td>
<td>Moderate</td>
<td>Very large</td>
</tr>
<tr>
<td>Wide area coverage</td>
<td>Important</td>
<td>(Sometimes) Important</td>
</tr>
<tr>
<td>Reliability</td>
<td>Moderate</td>
<td>(Sometimes) High</td>
</tr>
<tr>
<td>Cost</td>
<td>Moderate</td>
<td>(Sometimes) Very low</td>
</tr>
<tr>
<td>Power consumption</td>
<td>Moderate</td>
<td>Sometimes) Very low</td>
</tr>
<tr>
<td>Delay</td>
<td>Moderate</td>
<td>Sometimes) Very low</td>
</tr>
</tbody>
</table>
Distribution of resources critical

IP Cloud

Edge cloud "Fog"

< 1 ms delay

Speed of ligth: 300 km/ms
Everything under one roof?  
Transparancy vs Efficiency

The IP-access world
• Large volumes of standardized equipment, unified platforms
• Low efficiency, overprovisioning of resources
• Willingness to pay for flexibility

The MTC world
• Large volumes
• Very diverse requirement on power, delay, cost…
• Non-standardized equipment, no unified platforms
• Rational decisions based on savings
Who will provide infrastructure and services?
Mobility Foresight

- High complexity of market structure
- The Technoclan
- The Flash Mob
- Machine centric design
- The Red Queens Army
- The Harmonious Empire
- Human centric design
- Low complexity of market structure
Alternative (Technical) Mapping of MobFor scenarios

Best effort IP infrastructure for all?

Internet of small Things

Ultra Dense

Internet of "Important" Things

Wide-area M2M

Mobile Data

Coverage world (Wide Area)

1000 times more capacity

Capacity world (Local Area)

Single infrastructure = traditional operator model?
In Summary

5G is

- Not technically needed to contain the ”Data Tsunami” (can be managed by evolved 4G+WiFi)
- Addressing new challenges in large scale, wide-area infrastructure for M2M applications
- Not only about connectivity but a computational platform to manage generic resources like processing and storage
- Important to the incumbent industry to show renewal and claim (exclusive) spectrum to sustain current business modell