Technology vs. Topology

Can WiMAX, HSPA+ or LTE Address the Wireless Capacity Crunch?

Moray Rumney
Agilent Technologies
Agilent Technologies
The World’s Premier Measurement Company

$5.8 billion FY08 revenue

18,500 employees

Customers in over 110 countries

69-year heritage of innovation
# Agilent Businesses – FY’08 Revenue $5.8B

<table>
<thead>
<tr>
<th>Electronic Measurement</th>
<th>Life Sciences and Chemical Analysis</th>
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<tr>
<td>$3.6B</td>
<td>$2.2B</td>
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<table>
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<tr>
<th>Wireless BU</th>
<th>Networking &amp; Digital Solutions BU</th>
<th>Electronic Instruments BU</th>
<th>Life Sciences Solutions Unit</th>
<th>Chemical Analysis Solutions Unit</th>
<th>Materials Science Solutions Unit</th>
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<tr>
<td>$2.1B</td>
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<td>$700M</td>
<td>$900M</td>
<td>$1.2B</td>
<td>$100M</td>
</tr>
</tbody>
</table>

**Sales, Services, and Support**

Agilent Laboratories – Applied research, existing and new businesses
Peak vs. Average
Which is the best car?

Answer: Both! It depends on the problem you are trying to solve
Cooper’s law on wireless capacity growth

Dr. Martin Cooper of Motorola - “father” of the modern mobile phone - has observed:

*The number of simultaneous voice and data connections has doubled every 2.5 years since wireless began (1900)*

Cooper’s Law

Dr. Martin Cooper in 1982 with the DynaTAC
Descriptions can be completely accurate but not tell the full story

QUIZ #1: What do you get when:

You scrape a horse’s tail

Across dried sheep intestine?

For about half an hour?
Answer:

The Elgar Cello Concerto!

Sometimes sheep intestines are referred to as cat gut:
ITU recommendation ITU-R.1645
Also known as the “van” diagram

But what does this look like when probability of coverage is considered?

Voice and SMS are near 100%

Data becomes less probable with increased mobility and rate
What is enabling this apparent exponential growth in wireless communications?

The capacity of a system to deliver services is defined by three main factors:

- The bandwidth of the available radio *spectrum* – in MHz
- The *efficient use* of that spectrum – bits / second / hertz
- The *number of cells* – this equates to *spectrum reuse*
Growth to date dominated by increasing cell count

If we apply Cooper’s law over the last 50 years we are looking at a growth in wireless capacity of perhaps 1,000,000

Allocating this growth between the axes of capacity looks roughly like this:

Growth has historically been dominated by the increase in the number of cells.
Cellular wireless peak data rates appear to be on track to grow by 100,000 between 1985 and 2015

<table>
<thead>
<tr>
<th>Date</th>
<th>System</th>
<th>Peak data rate</th>
<th>Channel Bandwidth</th>
<th>Frequency reuse</th>
<th>Peak Spectral efficiency</th>
<th>Normalized efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>1985</td>
<td>AMPS</td>
<td>9.6 kbps</td>
<td>30 kHz</td>
<td>7 / 21</td>
<td>0.015</td>
<td>1</td>
</tr>
<tr>
<td>1992</td>
<td>GSM</td>
<td>9.6 – 14.4 kbps</td>
<td>200 kHz</td>
<td>4 / 12</td>
<td>0.032 - 0.048</td>
<td>2.1 – 3.2</td>
</tr>
<tr>
<td>1997</td>
<td>GPRS</td>
<td>171 kbps</td>
<td>200 kHz</td>
<td>4 / 12</td>
<td>.07</td>
<td>4.7</td>
</tr>
<tr>
<td>2000</td>
<td>EDGE</td>
<td>474 kbps</td>
<td>200 kHz</td>
<td>4 / 12</td>
<td>0.2</td>
<td>13.3</td>
</tr>
<tr>
<td>2003</td>
<td>W-CDMA</td>
<td>2 Mbps</td>
<td>5 MHz</td>
<td>1</td>
<td>0.4</td>
<td>26.6</td>
</tr>
<tr>
<td>2006</td>
<td>HSDPA</td>
<td>14 Mbps</td>
<td>5 MHz</td>
<td>1</td>
<td>2.8</td>
<td>187</td>
</tr>
<tr>
<td>2009</td>
<td>HSDPA+ 64QAM &amp; 2x2 MIMO</td>
<td>42 Mbps</td>
<td>5 MHz</td>
<td>1</td>
<td>8.4</td>
<td>560</td>
</tr>
<tr>
<td>2011</td>
<td>LTE</td>
<td>100 Mbps</td>
<td>20 MHz</td>
<td>1</td>
<td>5</td>
<td>333</td>
</tr>
<tr>
<td>2012</td>
<td>LTE 2x2 MIMO</td>
<td>172.8 Mbps</td>
<td>20 MHz</td>
<td>1</td>
<td>8.6</td>
<td>576</td>
</tr>
<tr>
<td>2013</td>
<td>LTE 4x4 MIMO</td>
<td>326.4 Mbps</td>
<td>20 MHz</td>
<td>1</td>
<td>16.3</td>
<td>1087</td>
</tr>
<tr>
<td>2015</td>
<td>IMT-Advanced targets</td>
<td>1 Gbps</td>
<td>100 MHz</td>
<td>1</td>
<td>10</td>
<td>667</td>
</tr>
</tbody>
</table>

With such peak data rates the demand for capacity could be huge
With today’s cellular densities, average data rates (i.e. capacity) falls behind peak data rates by 10x.

Efficiency, spectrum and capacity are normalized to single-band GSM in 1992.

A 10x capacity gap has opened up today!

Improvements in average efficiency and spectrum are not keeping up with peak rates.

Cambridge Wireless Technology vs. Topology
Moray Rumney 29th Jan 2009
Growth in peak / average spectral efficiency by technology

Peak efficiency lies around this line

Average efficiency and hence capacity growth of deployed systems lags well behind and will level off due to inter-cell interference

Peak efficiency drives up air interface cost & complexity

You pay for the peak but experience the average
This plot shows the variation in geometry factor across a typical outdoor urban cell.

Very high spectral efficiency is only seen when the geometry factor is above 15 dB, which is an environment that 90% of the user population will not experience.

In-building penetration loss will degrade performance further.

This puts a finite and very low limit on indoor performance when using outdoor transmission systems.

Most new high data rate/MIMO performance targets require geometry factors experienced by <10% of the user population.

Geometry factor distribution in urban cells
Example of interference-limited throughput*

HSDPA macrocell, single Rx + equalizer
15 code 64QAM, 20 Mbps peak
34 randomly distributed users

Quiz #2: What is the combined throughput and why?

- 680 Mbps
- 20 Mbps
- 13 Mbps
- 1.3 Mbps (0.26 b/s/Hz)

That is an average throughput of 40 kbps

* Source: 3GPP RAN WG4 R4-081344
Impact of femtocell deployment on throughput

Using the same macrocell add 96 femtocells
24 users migrate to femtocells
10 users remain on the macrocell

Quiz #3: What is the combined throughput and why?

- 270 Mbps [✓]
- 27 Mbps
- 2.7 Mbps
- 1.3 Mbps

That is an average throughput of 8 Mbps
A 200x improvement!

The remaining macrocell users go from 50 kbps to 170 kbps.
CCDF of throughput with and without femtocells

Detail showing 40 kbps median for macrocell

Full CCDF showing 8 Mbps median for macrocell plus 24 active femtocells

Projected spectrum and efficiency gains could push the blue trace to the right by 6x, this femtocell study moved it by 200x
Evidence of existing networks reaching capacity

Elliot Drucker: Hogs and Bandwidth

Netshare Officially Banned from the App Store
http://www.theiphoneblog.com/2008/09/14/netshare-officially-banned-from-the-app-store

Access to iTunes from 3G network limited unless on WiFi
http://techdirt.com/articles/20080729/0135151823.shtml
What is the outlook for capacity growth in the next 10 years?

The bulk of historical connections has been voice, more recently augmented by SMS.

To a first approximation Cooper’s law represents growth in wireless capacity.

But in the future it is all about data which will be limited by supply not demand.
What is the outlook for capacity growth in the next 10 years?

- Spectrum
- Efficiency
- Number of Cells
<table>
<thead>
<tr>
<th>Band</th>
<th>Uplink</th>
<th>Downlink</th>
<th>Duplex</th>
<th>Mode</th>
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<tr>
<td>1</td>
<td>1920</td>
<td>2110</td>
<td>130</td>
<td>FDD</td>
</tr>
<tr>
<td>2</td>
<td>1980</td>
<td>2170</td>
<td>20</td>
<td>FDD</td>
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<td>3</td>
<td>1930</td>
<td>1805</td>
<td>20</td>
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<td>FDD</td>
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<tr>
<td>6</td>
<td>840</td>
<td>885</td>
<td>35</td>
<td>FDD</td>
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<tr>
<td>7</td>
<td>2570</td>
<td>2690</td>
<td>50</td>
<td>FDD</td>
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<td>8</td>
<td>915</td>
<td>960</td>
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<tr>
<td>9</td>
<td>1844.9</td>
<td>1879.9</td>
<td>60</td>
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<td>1770</td>
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<td>340</td>
<td>FDD</td>
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<tr>
<td>11</td>
<td>1452.9</td>
<td>1500.9</td>
<td>23</td>
<td>FDD</td>
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<td>716</td>
<td>746</td>
<td>12</td>
<td>FDD</td>
</tr>
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<td>13</td>
<td>787</td>
<td>756</td>
<td>21</td>
<td>FDD</td>
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<tr>
<td>14</td>
<td>798</td>
<td>768</td>
<td>20</td>
<td>FDD</td>
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<td>FDD</td>
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<td>2600</td>
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<td>FDD</td>
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</tr>
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<td>0</td>
<td>TDD</td>
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<td>1880</td>
<td>1920</td>
<td>0</td>
<td>TDD</td>
</tr>
<tr>
<td>26</td>
<td>2300</td>
<td>2400</td>
<td>0</td>
<td>TDD</td>
</tr>
</tbody>
</table>

Lots of bands but overlapping and not all in the same geography
Spectrum upside for any one geography

Assume the European model of 340 MHz:

- 35+35 MHz of GSM @ 900 MHz
- 75 + 75 MHz of GSM @ 1800 MHz
- 60 + 60 MHz of UMTS FDD @ 2.1 GHz

Add 70 MHz from UHF band

Add max 200 MHz from 2.6 GHz band

Plus some 3.5GHz?

Spectrum upside could be 2x
What is the outlook for capacity growth in the next 10 years?

• Spectrum
• Efficiency
• Number of Cells
Average efficiency upside

Remaining gains in efficiency will come from:
• Wider channels enabling freq dependent scheduling
• MIMO & Beamforming
• Interference cancellation
• Advanced coding techniques

Historical average efficiency has been improving around 3x per decade.

A very rough figure for the next decade for affordable average efficiency gains is probably going to be similar to the historical trend at around 3x
• Consistent with LTE goals

Efficiency upside could be 3x
What is the outlook for capacity growth in the next 10 years?

• Spectrum
• Efficiency
• Number of Cells
Cell number upside

History shows that the bulk of growth in wireless capacity has come from increasing the number of cells. Today we are around one cell per 1000 users. This has huge potential to change.

It is not unreasonable to assume one cell per ten users which could be achieved with deployment of home base stations or femtocells into 30% of households.

From the operator’s perspective, growing capacity by having the end user pay for the CapEx and OpEx is very attractive!

Cell number upside could be 100x
Using current efficiency and spectrum projections, the increase of cell numbers remains the dominant means of growing capacity.
Projecting ahead shows the gap between average and peak rates in loaded cell will grow to 90x

![Graph showing data rates, efficiency, spectrum, and capacity over time with labels: Efficiency, spectrum, and capacity are normalized to single-band GSM in 1992. The average efficiency, spectrum, and capacity plots are normalized.]
And on a linear scale

The capacity crunch

Macrocell reality lies somewhere below this line
In a mature market, Value > price > cost

<table>
<thead>
<tr>
<th>Service</th>
<th>Price / volume</th>
<th>Price €</th>
<th>Cost / MByte</th>
<th>Price / MByte</th>
<th>Relative price</th>
</tr>
</thead>
<tbody>
<tr>
<td>SMS</td>
<td>160 Bytes</td>
<td>€0.15 / message</td>
<td>€ X</td>
<td>€1000</td>
<td>400,000</td>
</tr>
<tr>
<td>Voice</td>
<td>10 kbps</td>
<td>€0.05 to €0.5 / minute</td>
<td>€ Y</td>
<td>€ 0.7 - € 7</td>
<td>300 - 3000</td>
</tr>
<tr>
<td>Data service (capped at 3 Gbytes)</td>
<td>3 GBytes</td>
<td>€20 / month</td>
<td>€ Y/5</td>
<td>€ 0.007</td>
<td>3</td>
</tr>
<tr>
<td>Unicast Mobile TV (Capped at 50 hrs)</td>
<td>50 Hours @ 100 kbps</td>
<td>€5 / month</td>
<td>€ Y/5</td>
<td>€ 0.0023</td>
<td>1</td>
</tr>
</tbody>
</table>

The value of data is inversely proportional to the rate but the cost of delivery remains relatively constant.
Circuit-switched voice services and SMS are the profit backbone of the cellular industry. First and business class passengers!

Technology now allows users to route voice, video and message services over an "all-you-can-eat" or capped data service, paying perhaps €0.007 per seat in the hold!

There are only so many seats on the cellular plane. If profitable traffic shifts to low tariffs the cellular airline will go bust.

Users associate VoIP with low or no cost – this does not work for cellular. Cellular can’t afford users listening to internet radio or TV over low-price data services.
The macrocellular dilemma

For macrocellular to deliver mobile broadband these three attributes are all required:

1. High capacity & data rates
2. Ubiquitous coverage
3. Low or reasonable cost

Pick any two!

Conclusion: Macrocellular can’t do it alone. Small cells are essential.
Wireless traffic segmentation

Macro/micro Cellular
Ubiquitous mobile data / voice
Mobility and continuous coverage
Ability to control QoS
Limited capacity and data rates
High costs – OK for high value traffic
Often outdoors & moving
Requires ears & mouth

Hotspot/Femtocell
Opportunistic nomadic data
Hotspot coverage
Nomadic use
Distributed cost (not low cost)
Free or charged
Sitting down indoors
Requires eyes
Comparison of traditional cellular vs. hotspot for data delivery over next decade

<table>
<thead>
<tr>
<th></th>
<th>Macro/Micro</th>
<th>Hotspot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity</td>
<td>6X</td>
<td>100x ?</td>
</tr>
<tr>
<td>Coverage</td>
<td>Reducing (for higher rates)</td>
<td>Where it's needed</td>
</tr>
<tr>
<td>Complexity</td>
<td>Growing</td>
<td>Low, stable</td>
</tr>
<tr>
<td>Cost per bit</td>
<td>High and not falling fast enough</td>
<td>Very low</td>
</tr>
</tbody>
</table>

Improvements in macro network e.g. EDGE Evolution, HSPA+, LTE will continue but low-value high-volume traffic has to move to hotpots
Predicting the next winning technology
Often the “best” doesn’t win

• Ethernet vs. Token ring
• 802.11b vs. HiperLAN
• Windows 3.1 vs. Unix
• Iridium vs. GSM

“Perfection is the enemy of the good”
Gustave Flaubert
French Novelist 1821 - 1880
Which small cell technology will dominate? What about plain old Wi-Fi?

Love it or hate it, Wi-Fi is here to stay

Wi-Fi today is by far the biggest provider of home and nomadic wireless data services and so can’t be ignored.

By cellular standards it is a crude technology

- No power control
- No frequency awareness
- Limited mobility and handover capability
- Limited range

But Wi-Fi’s simplicity and low cost has led to mass deployment
The Wild West of municipal Wi-Fi

AP Antenna 7dBi
Site to site pathloss ~60 dB
WiFi ACLR1 ~30 dB
AP TX power 23 dBm
Uplink pathloss ~90 dB
Client power ~15 dBm
Client antenna -5 dBi
RX signal ~ -73 dBm
RX interference ~ -53 dBm

20 dB of interference!
Wireless anarchy even on adjacent channels!
Peak number of APs in one indoor location – 46!
(Bleeding Heart Tavern, Farringdon, London)

How can this ever work!!!

802.11 protocol is cognitive and tolerant of interference & bad planning
But it still worked! 742 kbps DL, 192 kbps UL (For a mere £6 per hour...)
Wi-Fi – Enabling 3GPP 200 laptops at a time

RAN WG1 & WG4 ad hoc
Prague August 2004
When teriyaki steak is unavailable or can’t be afforded...

Would you like some nybble and bytes with that Sir?

McDonald’s offers free Wi-Fi in U.K.

*Reuters:* McDonald’s has said it will offer free wireless Internet access at its 1,200 U.K. restaurants. The move makes the fast-food chain the country's biggest provider of free wireless broadband access.
So which hotspot technology will win?

The answer lies between the extremes of highly regulated femtocellular or the anarchy of Wild West WiFi:

Cellular control

Femtometer™

Today the needle can only move to the left. But how far will it swing?

WiFi enabled iPhone
Meet WeFi

Unleashing The Potential of unlicensed Spectrum
The growth of open WiFi

350M Wi-Fi access points already deployed*

• Homes & Offices
• Public places
• That is an AP for every 10 subscribers!

A growing number of these are businesses providing legitimate free Wi-Fi as a way of attracting customers

Some hotel chains
Non-chain small business
McDonalds (UK)
Starbucks (USA iPhone)
Some airports: San Jose, Phoenix, Portland…

* Source: Intel
But can WiFi deliver?

Networks are unplanned in “garbage” spectrum, but –

• Unlike cellular, 802.11 protocols were cognitive from the start,
• sensing the air interface rather than being centrally scheduled
• Robust against poor channel selection and no planning
• By no means perfect but good enough in most cases
• 802.11n managed MAC will be better

All dense networks are expensive regardless of the technology

Despite perceptions, mass WiFi is NOT a cheap alternative!

• Leverage community to distribute the cost!

How about terminals?

• WiFi is becoming standard in high-end phones

But WiFi is so hard to use…
It could be as Easy as 3G!

Start...

Select...

Enjoy!

Automatically connects you to Wi-Fi and your favorite content in one click.
Managing WiFi using cellular

The ubiquitous cellular network is used for control

- WiFi Network management via users’ terminals
- Maintain cellular connection with WiFi users
- Security, authentication if WiFi
- Time critical traffic

Wi-Fi carries the non-critical traffic

- Music and video downloads
- Streaming video, Pictures, Web

Requires no direct interface with infrastructure
Framework for hotspots scalable aggregation
Think of it this way:

Just enough cellular control

Loads of WiFi Traffic!

A small carrier effort could deliver huge gains!
Resource aggregation through Community participation

WiFi discovery and ranking

Enticing business owners to share WiFi

“Flowers & Bees”
Exponential growth of discovery

WeFi Access Points

Feb-08 Mar-08 Apr-08 May-08 Jun-08 Jul-08 Aug-08 Oct-08 YE08

0 2,000,000 4,000,000 6,000,000 8,000,000 10,000,000 12,000,000 14,000,000 16,000,000

9M 13.8M

Cambridge Wireless
Technology vs. Topology
Moray Rumney 29th Jan 2009
Over 9 Million access points worldwide (October ‘08)

Over 60,000 new APs acquired daily by WeFi user devices
What Could Wi-Fi Bring to Operators?

We know WiFi is far from perfect but…

Maybe today it’s the right vehicle to reduce cost!
Which small cell technology will dominate? Can femtocells outperform and replace Wi-Fi?

The potential for cellular femtocells to deliver the future growth of wireless is very real but:

• The industry remains largely focussed on improving macrocellular efficiency which is driving up cost and complexity
• Many of the engineering and business model challenges of femtocells remain to be solved
Femtocell key challenges

• It’s all about interference mitigation!
• No RRM spec yet for femtocells!
• A hackers paradise – build your own cellular network…
• Business models - Open vs. closed access
• No obvious solution yet for cross network Femtocell
  • Multiple femtocells per household or force family onto one operator?
• Net neutrality – who owns the backhaul?
  • Could blow femtocell competition off the planet – will vary by country
• Could it hurt my cat?
  • Possible public backlash over radiation concerns?
Keeping the mobile broadband wagon rolling

Increasingly urgent need to shift low-value high volume traffic away from high-cost macro-cellular networks

Provision of alternative delivery mechanisms

- Localized, nomadic
- Low cost – no cost – distributed cost
- Picocells – Femtocells – WiFi

Need for robust interworking/control from macro to local

So which technology will deliver - some criteria to ponder:

- Money is becoming very tight
- Good enough is good enough
- Existing solutions have an advantage
So which hotspot technology will win?

The answer perhaps now lies between the lesser extremes of not so highly regulated femtocellular and a more tamed Wi-Fi:

Taming Wi-Fi and developing Femtocells offer substantial and affordable benefits for mobile broadband
Thank you for listening!