Challenge 2020:

1000 times more capacity at todays cost & energy

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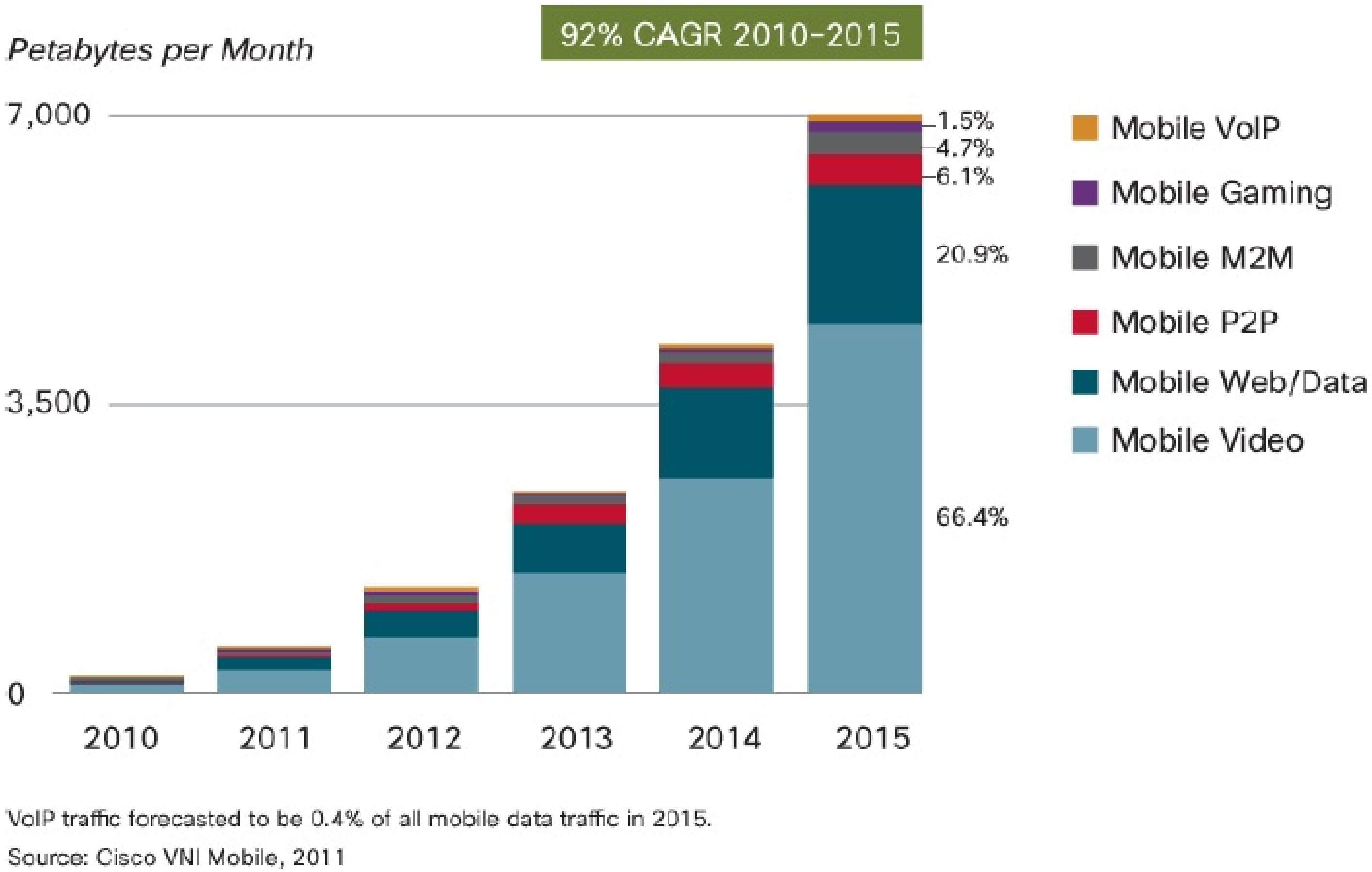
Mobile Data avalanche



Cisco forecast: 2015 – 26x

Extrapolation: 2020 - 1000x

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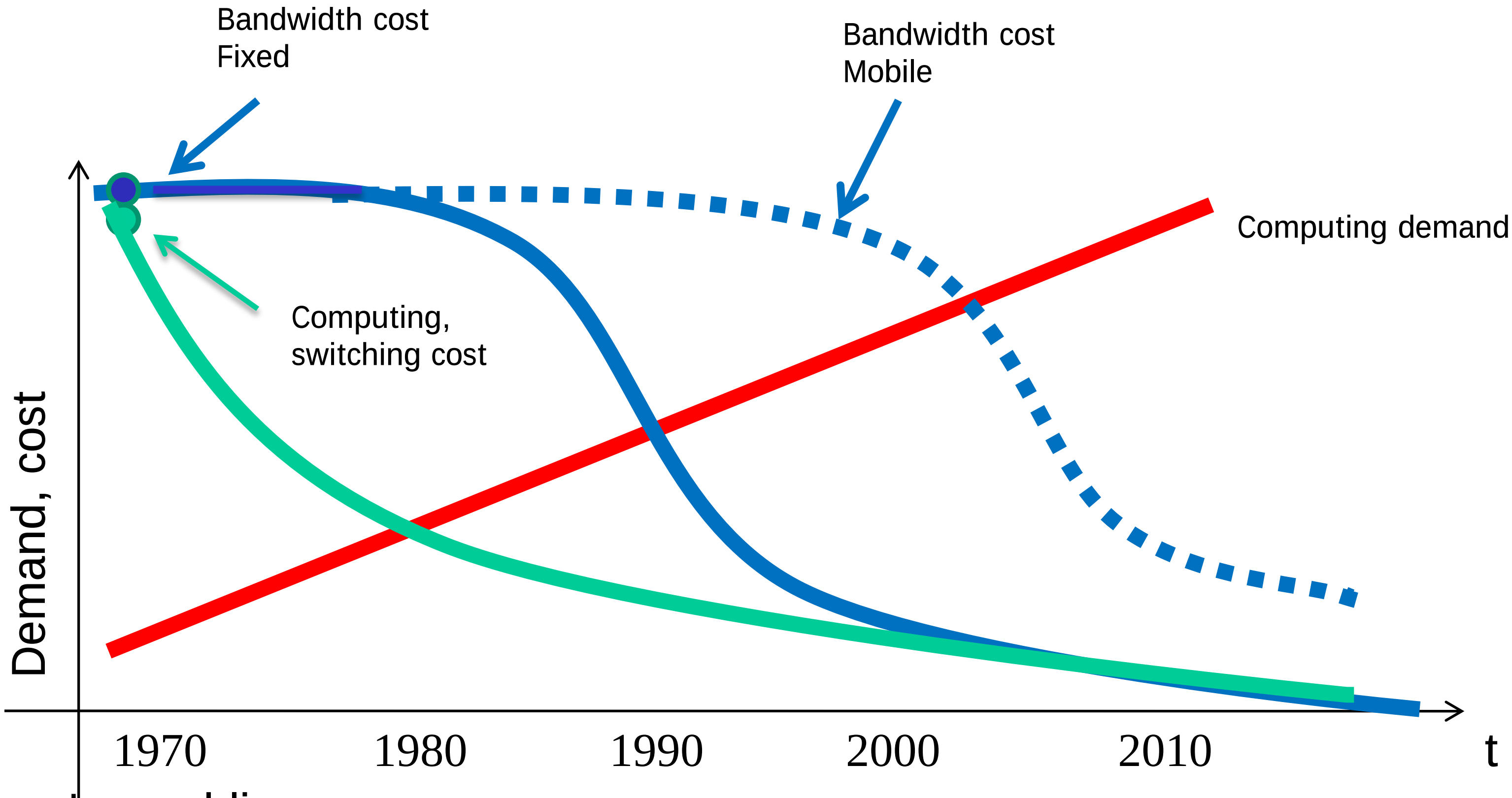
Computation & Communication Paradigms



Leased lines
Computer centers

Packet switching
PC, server-client

Cloud computing

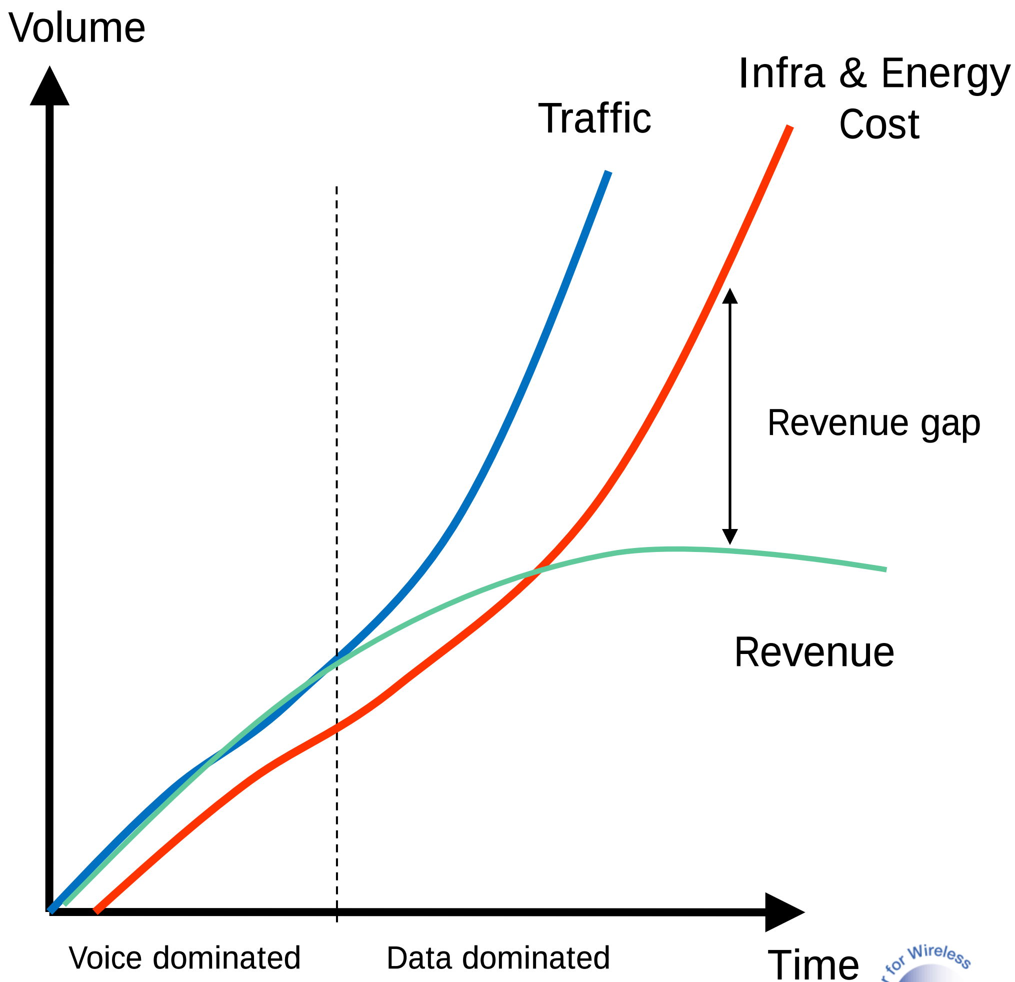
Mobile Services everywhere

World wide proliferation of Mobile Data

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

More for less money

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



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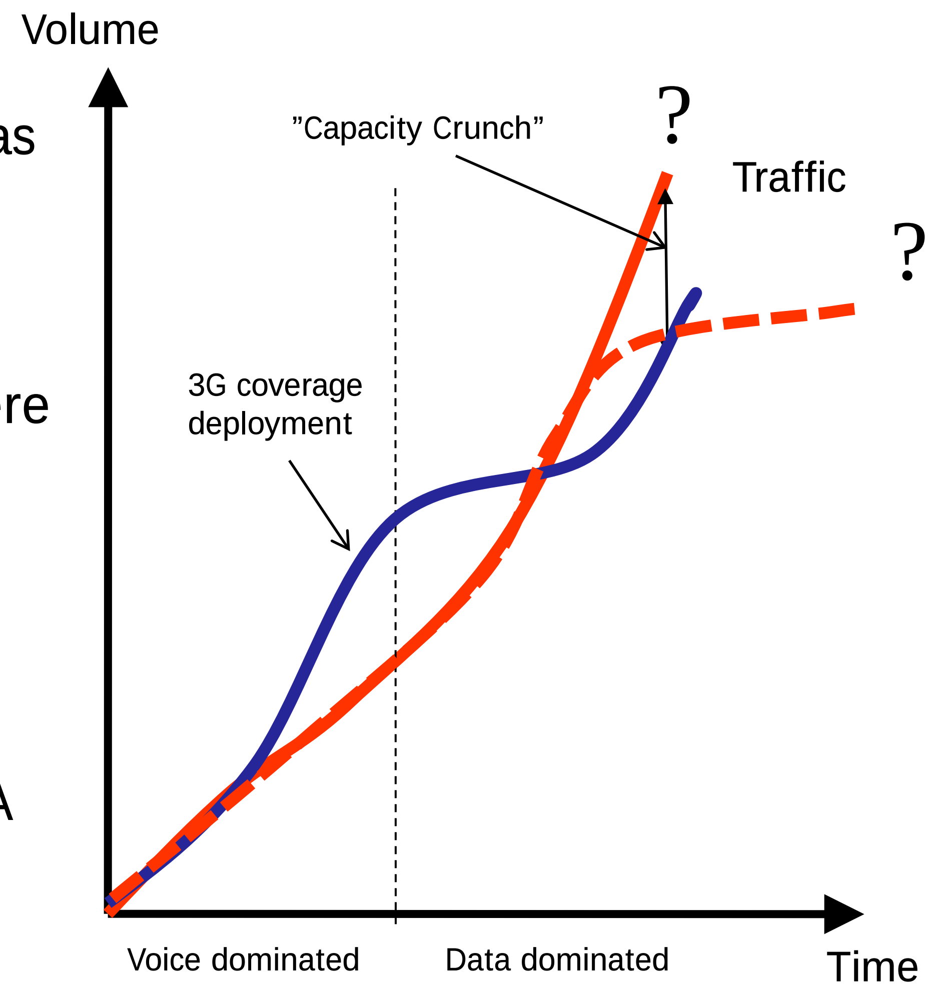
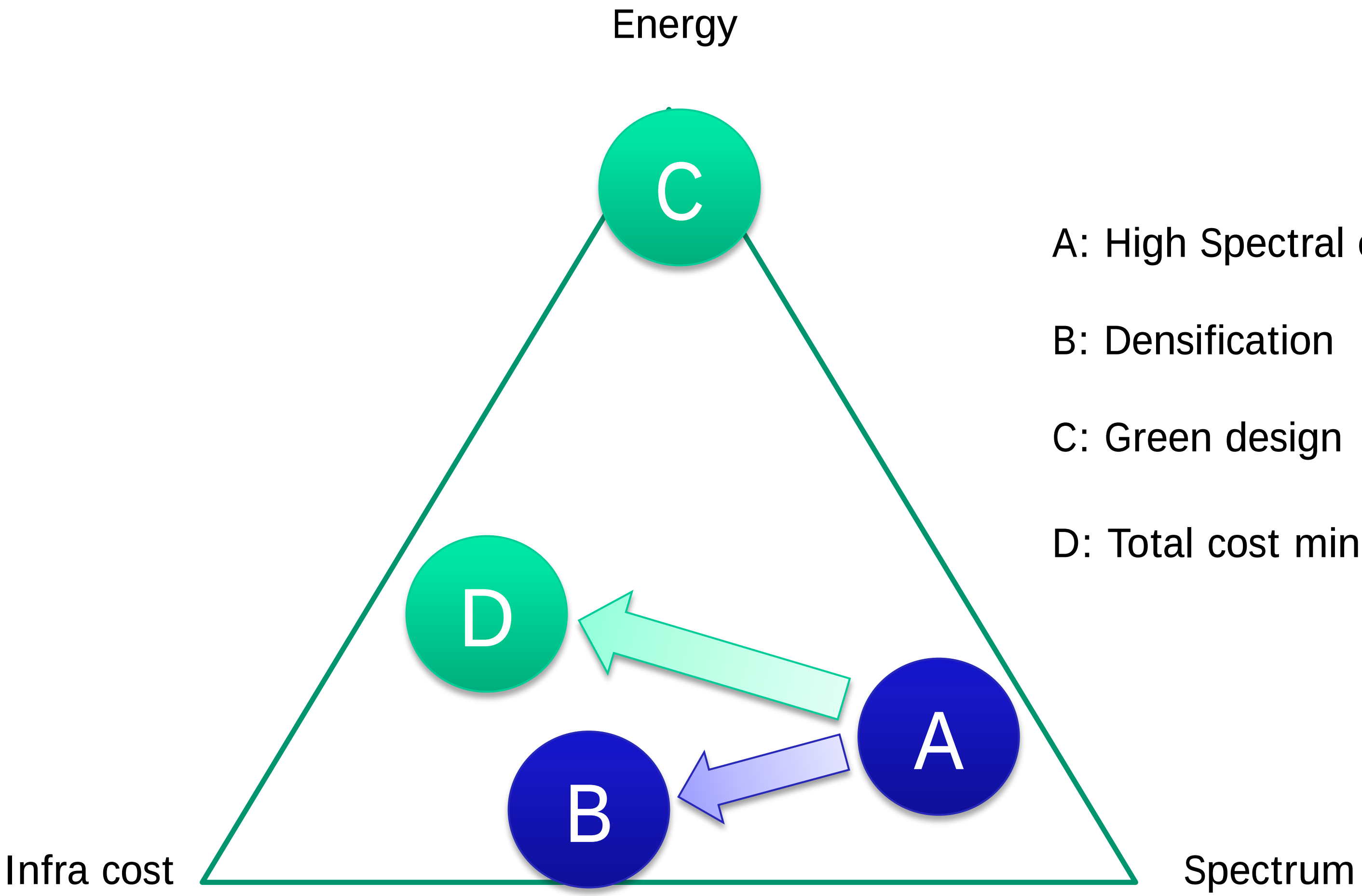
- but will operators keep up ?

- 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



A: High Spectral efficiency

B: Densification

C: Green design

D: Total cost minimization

$$C_{tot} = C_{spectrum} + C_{infra} + C_{energy}$$

S. Tombaz, A. Västberg, J. Zander, Energy- and Cost-Efficient Ultra-High-Capacity Wireless Access , 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 ?

Company	Spectrum	Spectral efficiency	Densification	Total capacity increase
Nokia Siemens	10x	10x	10x	1000x
Huawei	3x	3.3x	10x	100x
NTT Docomo	2.8x	24x	15x	1000x

What does capacity mean ?

$$R_{tot} = N_{user} R_{user}$$

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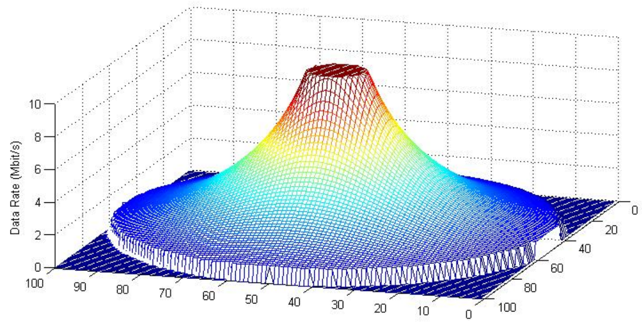
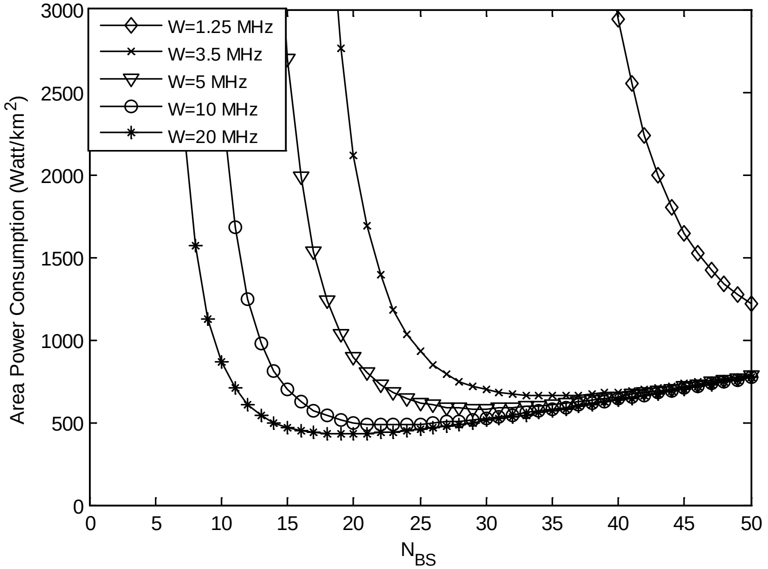
Spectral efficiency & PHY Layer improvements





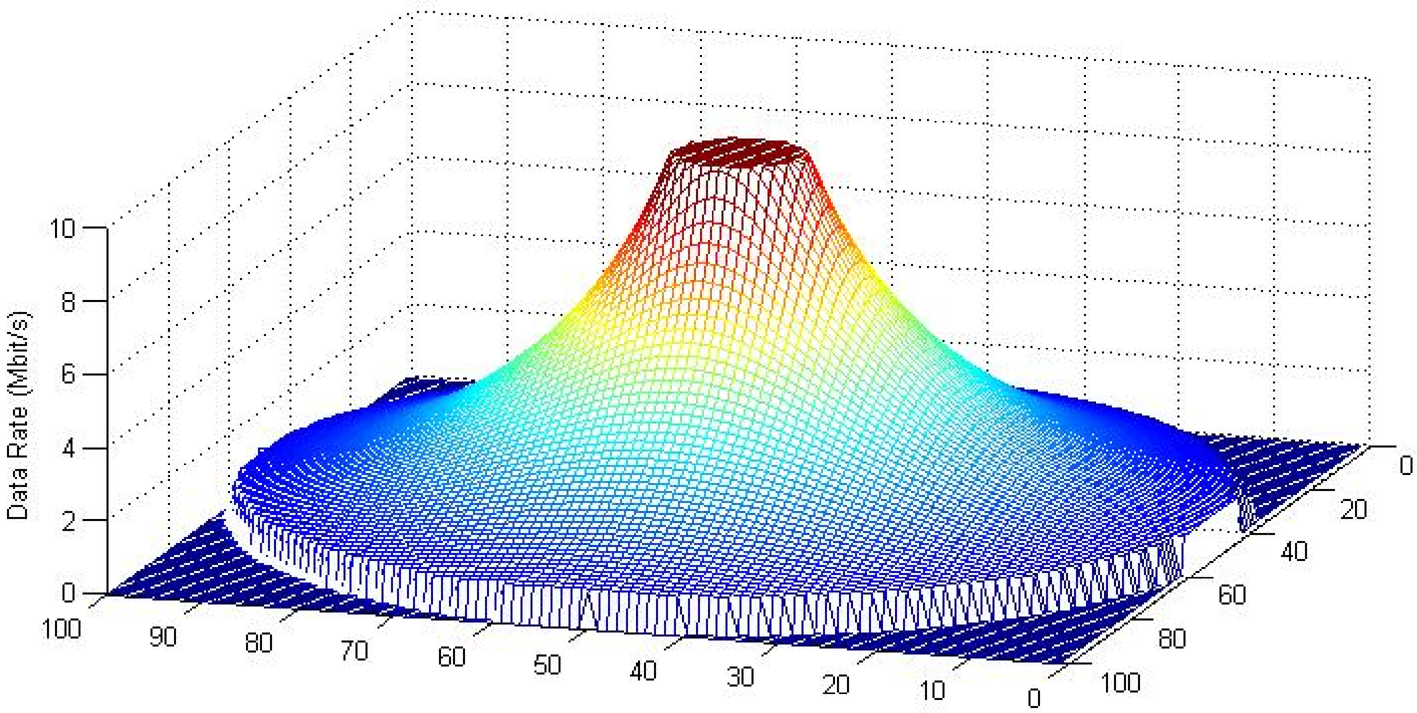
- Operation today almost at Shannon limit

$$R = nW \log\left(1 + \frac{P}{I_0 W}\right)$$

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

S. Tombaz, A. Västberg, J. Zander, Energy- and Cost-Efficient Ultra-High-Capacity Wireless Access , IEEE Wireless Communications, October 2011.

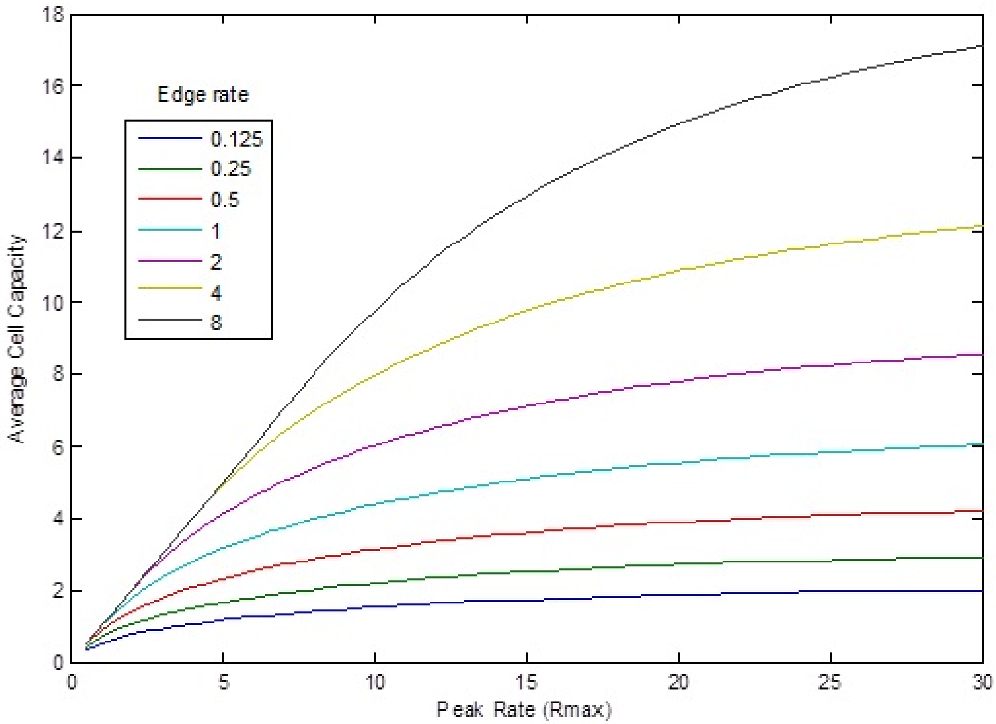
Capacity and Peak Rate are not simply related



Capacity ≠ Peak Rate

Moore's law not applicable to concrete and steel

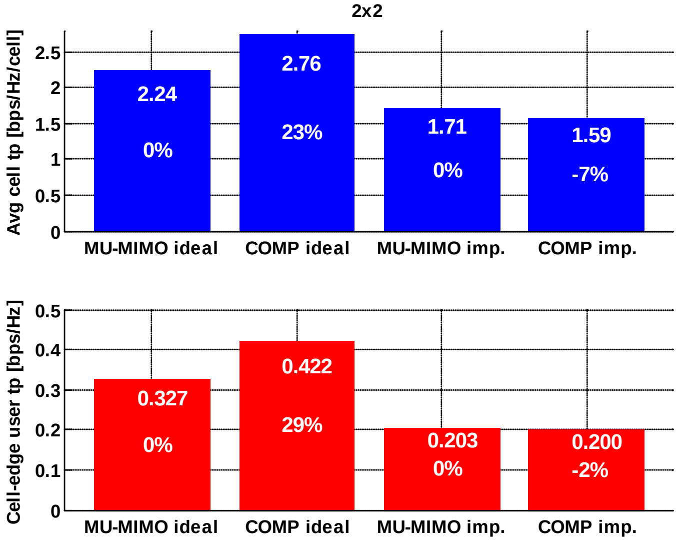
Peak vs Edge Rates



- 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/quatization
  - CSI feedback capacity & processing



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

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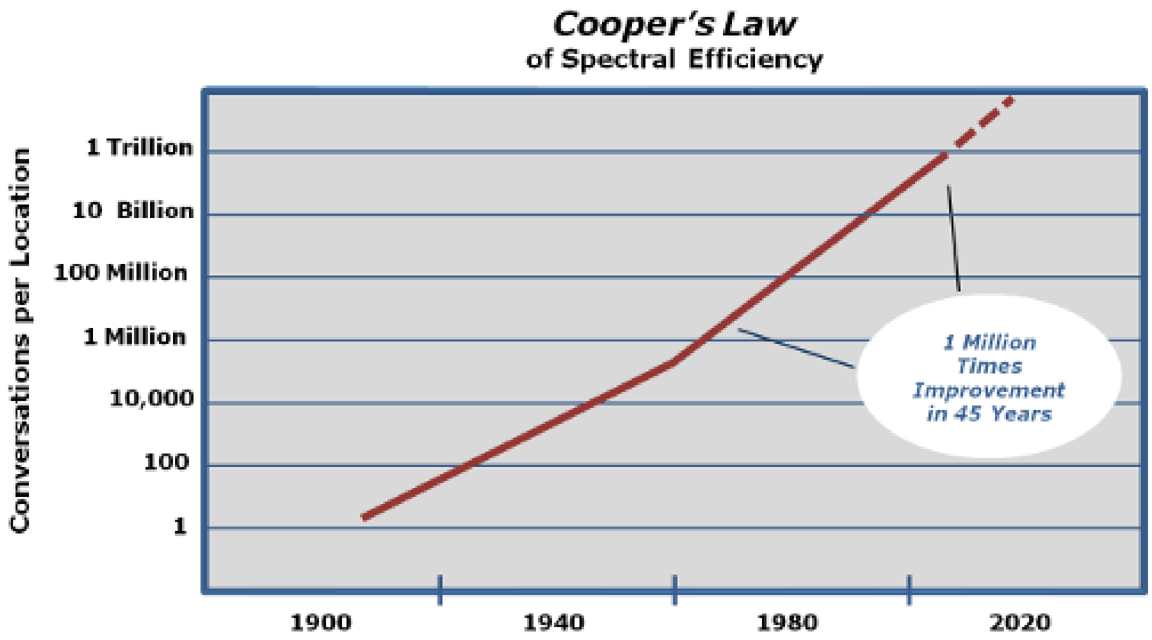
Cooper's law



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

- 1.000.000 times more capacity over last 45 year
  - 25x more spectrum
  - 25x better modulation/signal processing
  - 1600x densification (more base stations)

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Cost for densification

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

"Zander's Law"

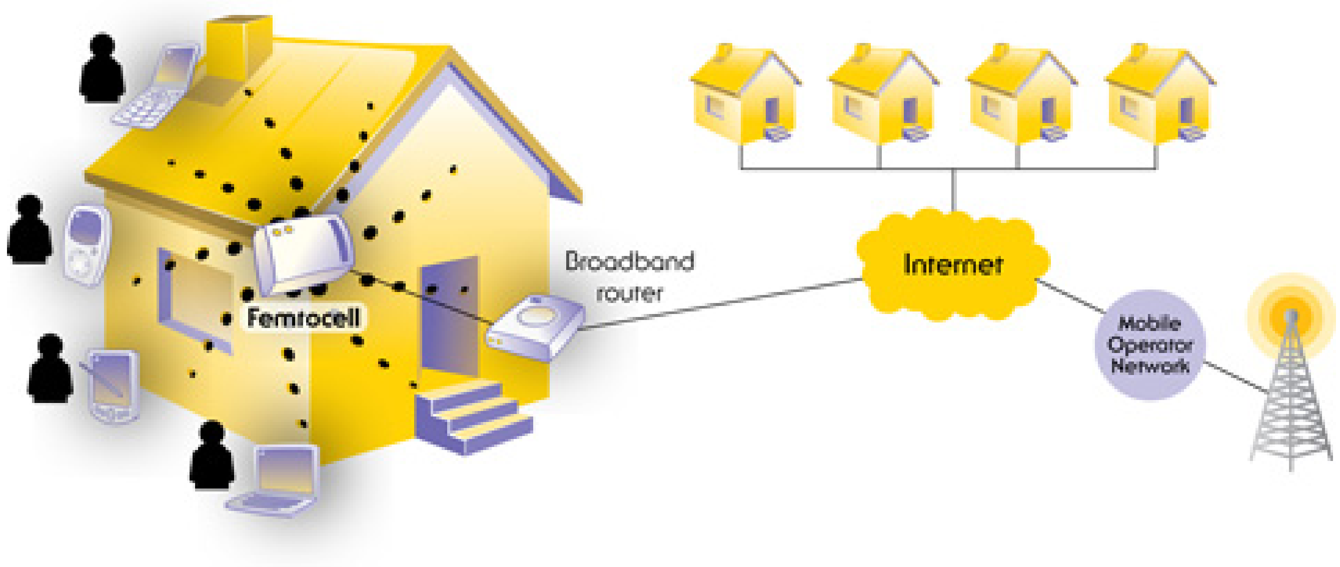
$$C_{BS} = C_{site} + C_{backhaul} + C_{Equipment}$$

Densification: Technology shift

- Industry grade eq
- High power
- 24-7 availabilty
- 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



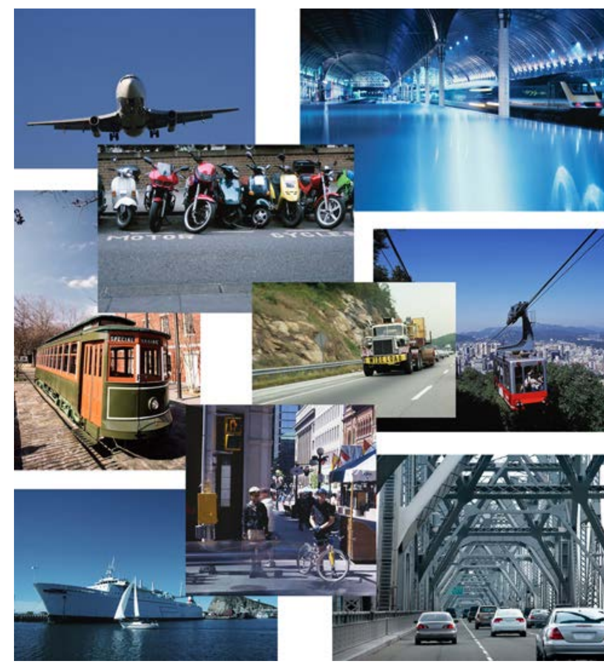
- Technology: Not an issue !
- Business model: Cooperation !

”HET NETs”

Infrastructure sharing

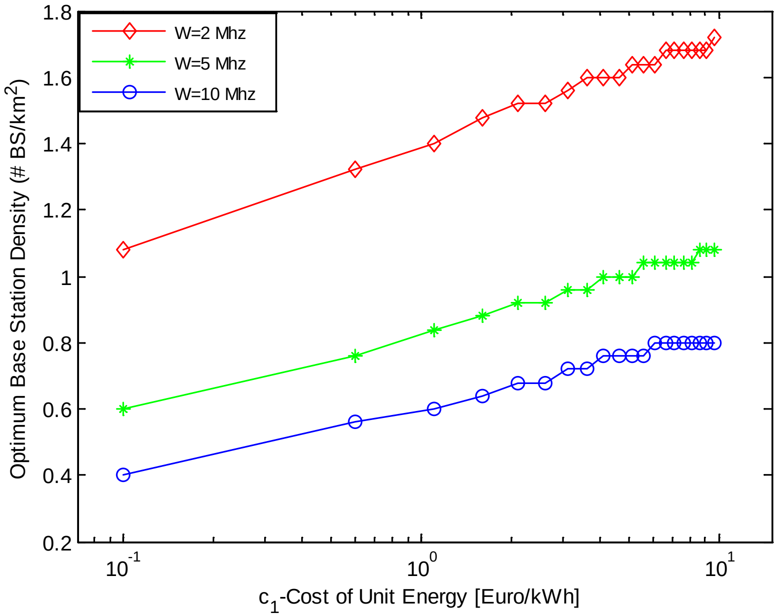
- Multiple competing parallel infrastructures

- 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)

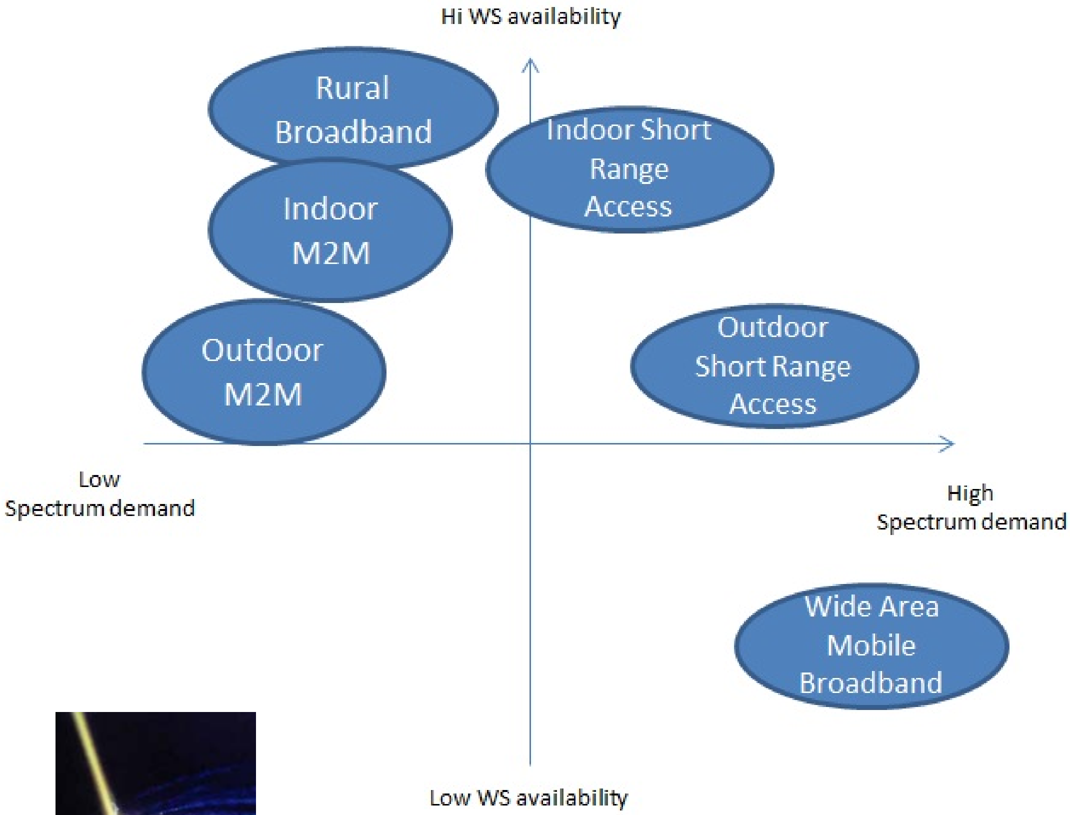


S. Tombaz, A. Västberg, J. Zander, Energy- and Cost-Efficient Ultra-High-Capacity Wireless Access , IEEE Wireless Communications, October 2011.

Spectrum options ?

	Exclusive <6 GHz	Shared < 6 GHz	Secondary <6 GHz	Exclusive > 10 GHz
Availability	Very Low	Low (100 MHz)	Good (>1 GHz) for indoor use	Very good
Advantages	• Guaranteed QoS • Long-term investments	• Spectrum available • Low cost equipment/deployment	• Spectrum available • Low cost equipment/deployment	Very high capacity Low interference
Disadvantages	High deployment cost	• No QoS guarantees • Low availability	• Limited QoS guarantees • Regulatory uncertainty	LOS propagation, antennas Dedicated Deployment

Commercial Feasability 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

QUASAR

SEVENTH FRAMEWORK PROGRAMME

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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 <u>low-band</u> spectrum → lower cost, lower energy consumption
- Several new spectrum options available

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Read more & Interact !

wireless.kth.se

theunwiredpeople.com

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Additional slides

Cellular Design for Power/Total Cost minimization

Energy consumption modelling

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

- Power consumption

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

Proportional to #base stations

Independent of #base stations

Energy consumption modelling (2)

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

$$P_{rx}(d) = \frac{c' G P_{tx}}{d^{\alpha}} \qquad P_{tx} = \left[2^{\frac{\bar{R}}{W}} - 1 \right] \frac{N_0 W}{cG} R_{cell}{}^{\alpha}$$

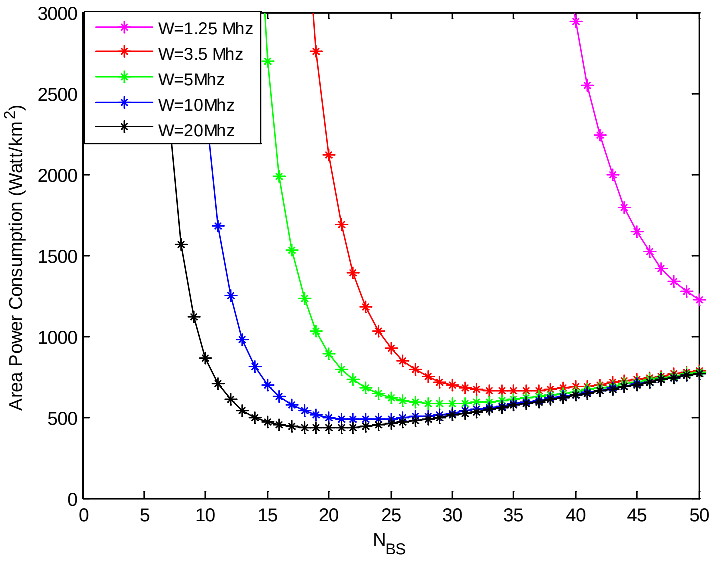
- Average spectral efficiency $S = \frac{\bar{R}}{W}$

$$\mathrm{P}_c = \left(N_{BS} \left[a \left\{ \frac{N_o W}{cG} \left(2^{\frac{\bar{R}_{t\,tot}}{N_{BS} W}} - 1 \right) \left(\frac{\mathrm{A}}{\pi N_{BS}} \right)^{\alpha/2} \right\} + b_{radio} + b_{backhaul} + y \frac{\bar{R}_{tot}}{N_{BS}} \right] + d \right) / A$$

"Green" Architecture

- If power/energy is the dominant constraint;

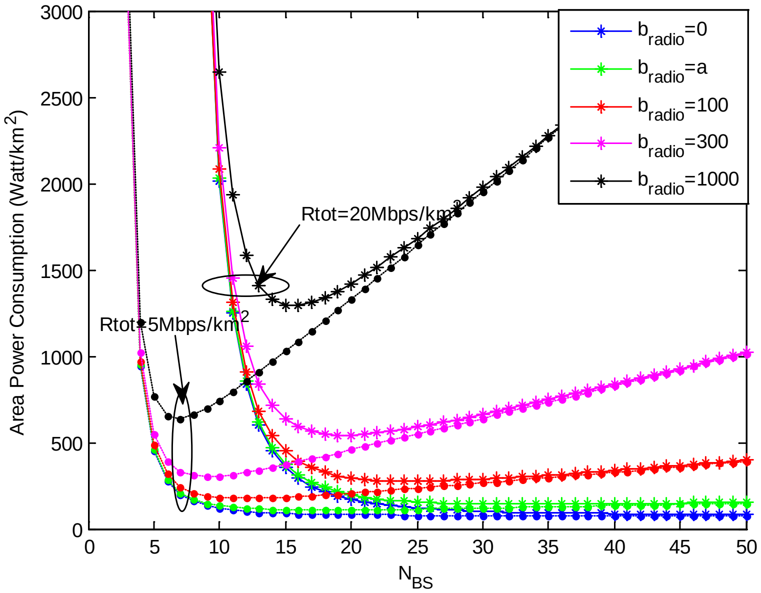
$$\lim_{N_{BS\to\infty}} P_c(N_{BS}) \to \infty \qquad \alpha > 2$$



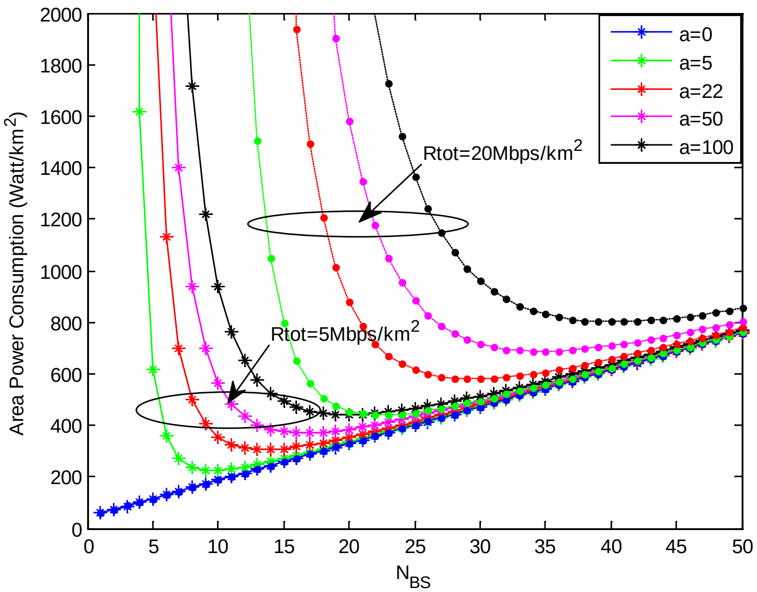
There is always a non-null and finite that minimizes the areapower consumption.

Green Architecture

- Idle power



PA - efficiency



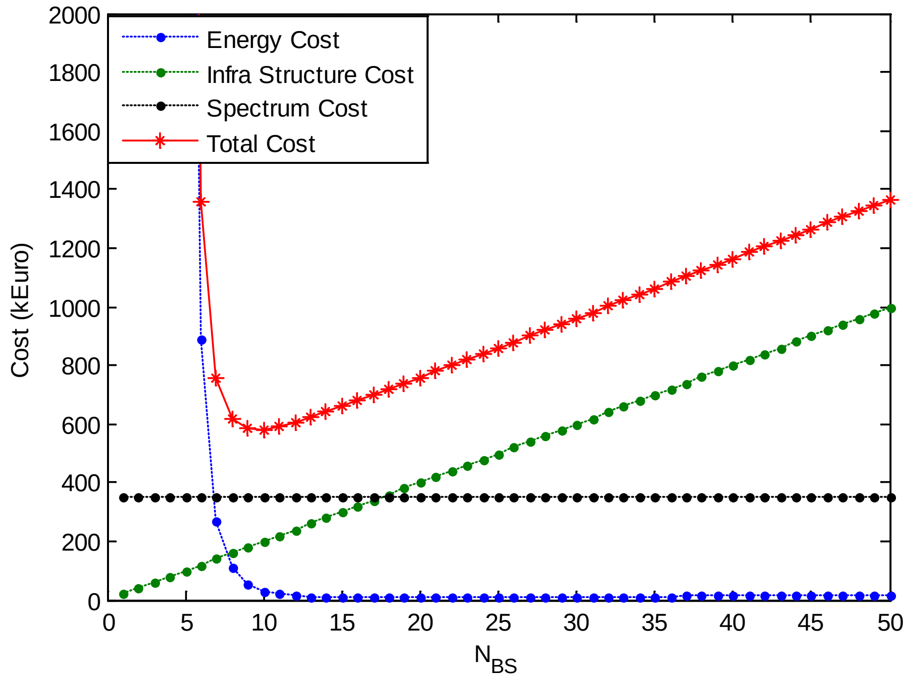
Deployment of Minimal Total Cost

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

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

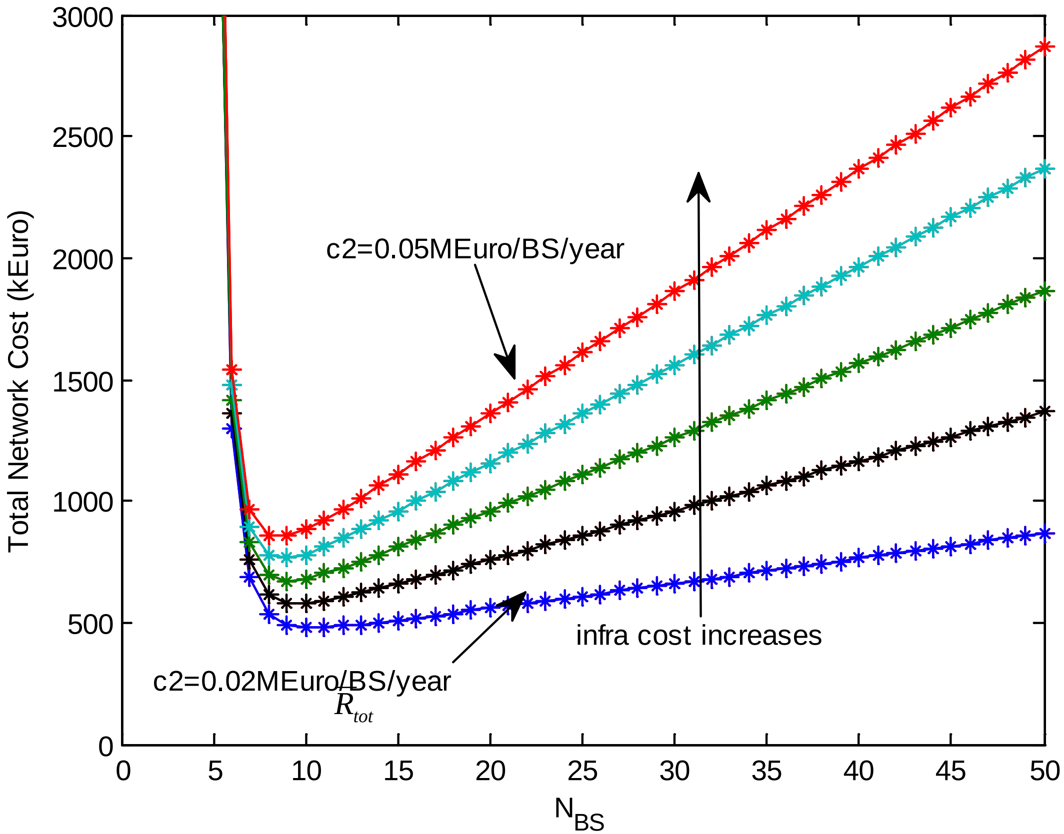
  - C0[€/BS]: Annual cost per base station
  - C1 [€/Energy Unit]: Annual energy cost
  - C2 [€/Mhz]: Annualized spectrum cost

Deployment of Minimal Total Cost



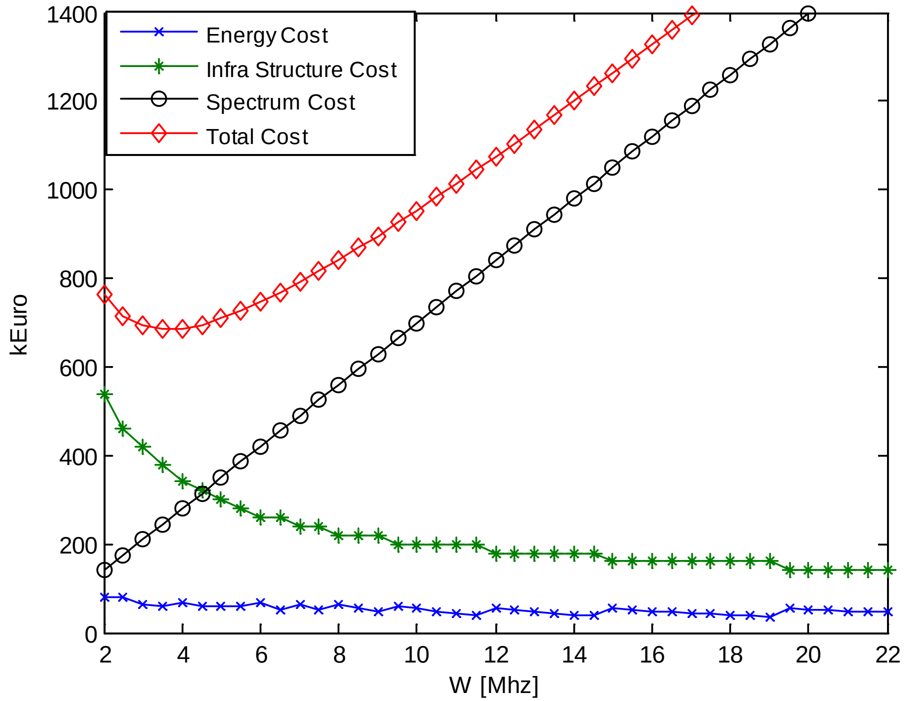
- Minimum total cost now occurs at a much lower number of base stations than in the energy-only minimization.
- Spectrum cost constant – provides only a level shift of the total cost;

Increasing infrastructure cost



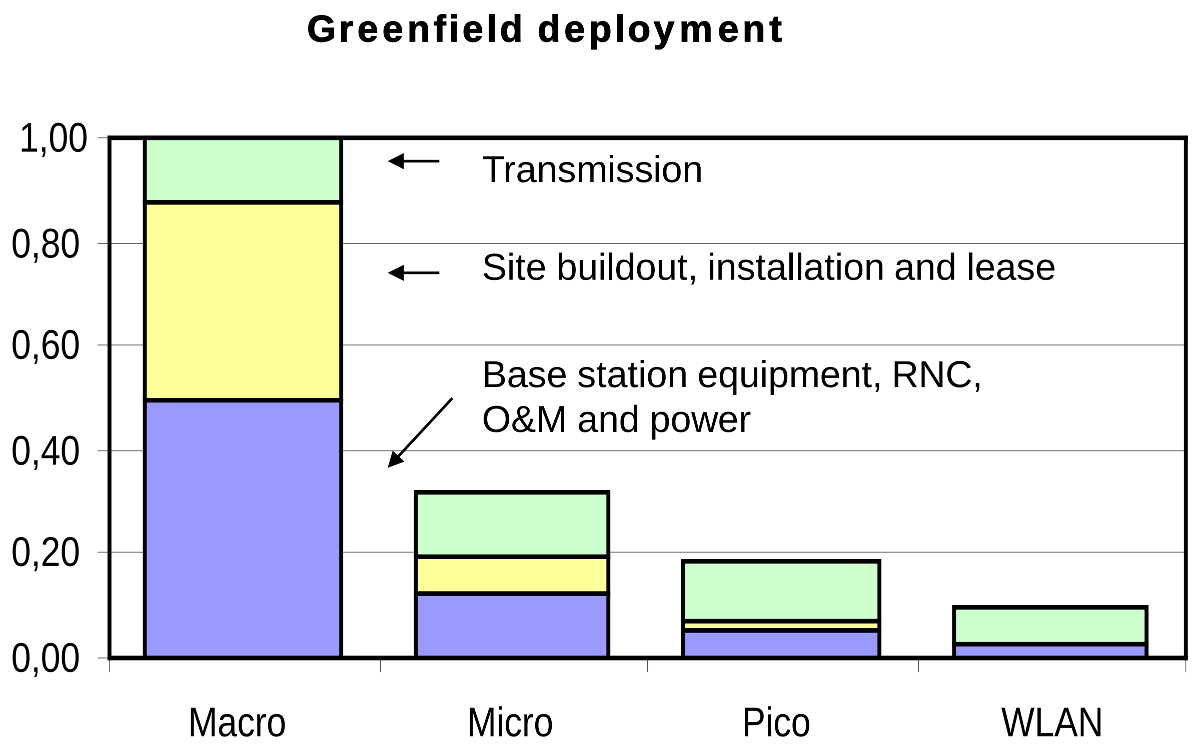
- Total cost increases
- Optimal number of base station is not that much affected.

Spectrum cost impact



- As the spectrum cost increases, optimum spectrum expenditure moves closer to the “energy asymptote”

Cost drivers



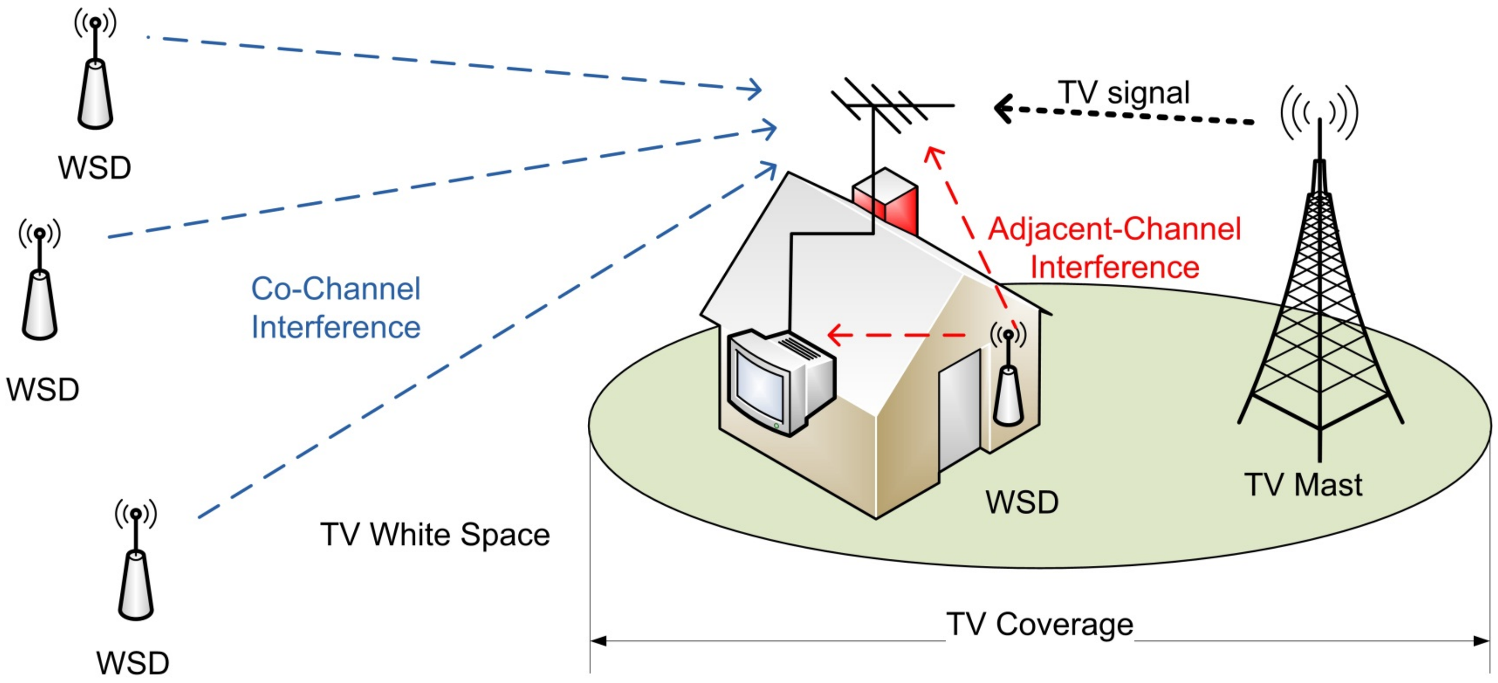
(Klas Johansson, ”Cost Effective Deployment Strategies for Heterogeneous Wireless Networks”, Doctoral Thesis, KTH 2007)

QUASAR Technical findings

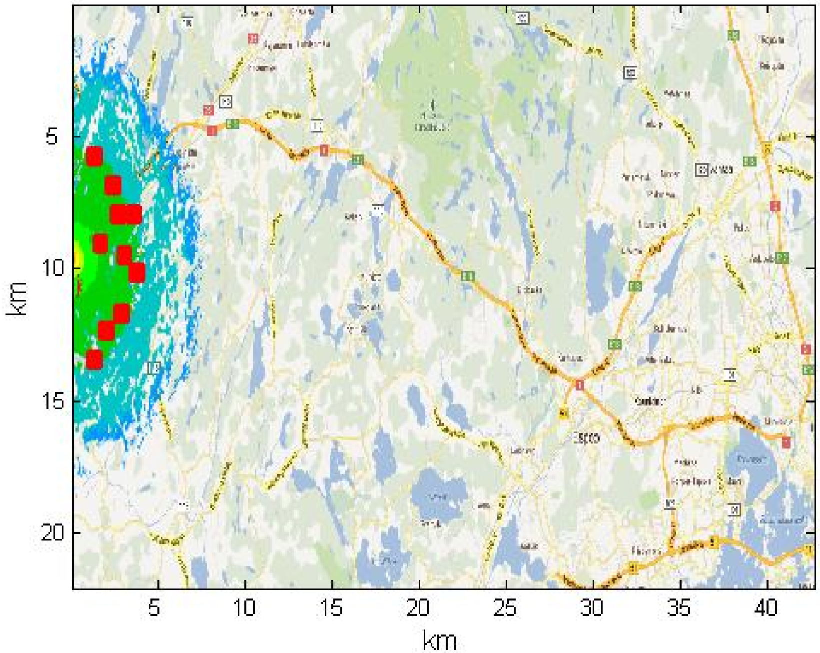
QUASAR Key technical findings

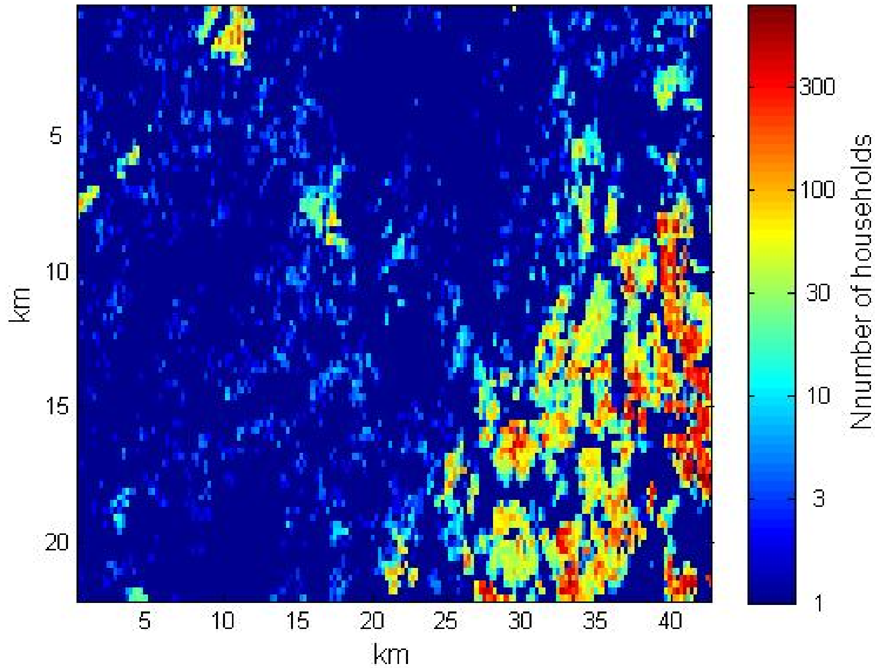
- Plenty of spectrum available – but very scenario & location specific - commercial success is where we can live with this
- Aggregate interference critical for the scalability – massive use of secondary spectrum
  - Both co-channel & and adjacent channel interference has to be considered
- ”Cognitive” 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



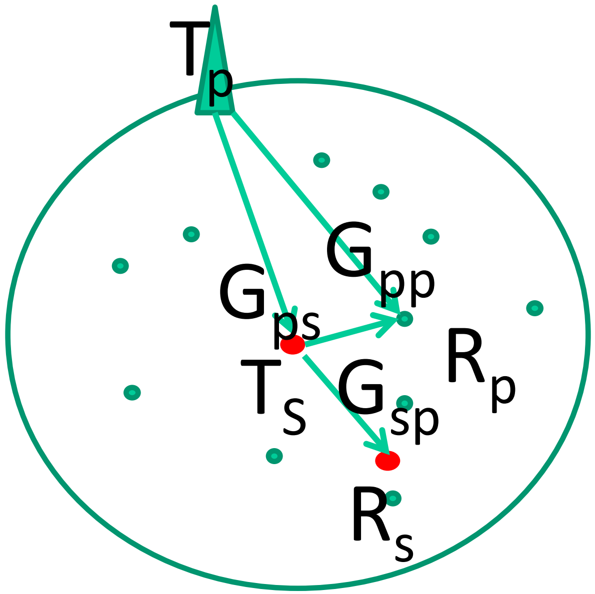


TV coverage area, TV test points
and secondary deployment area

Density of the households
Each household → 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



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