Beyond 4G: What lies ahead for cellular system design?

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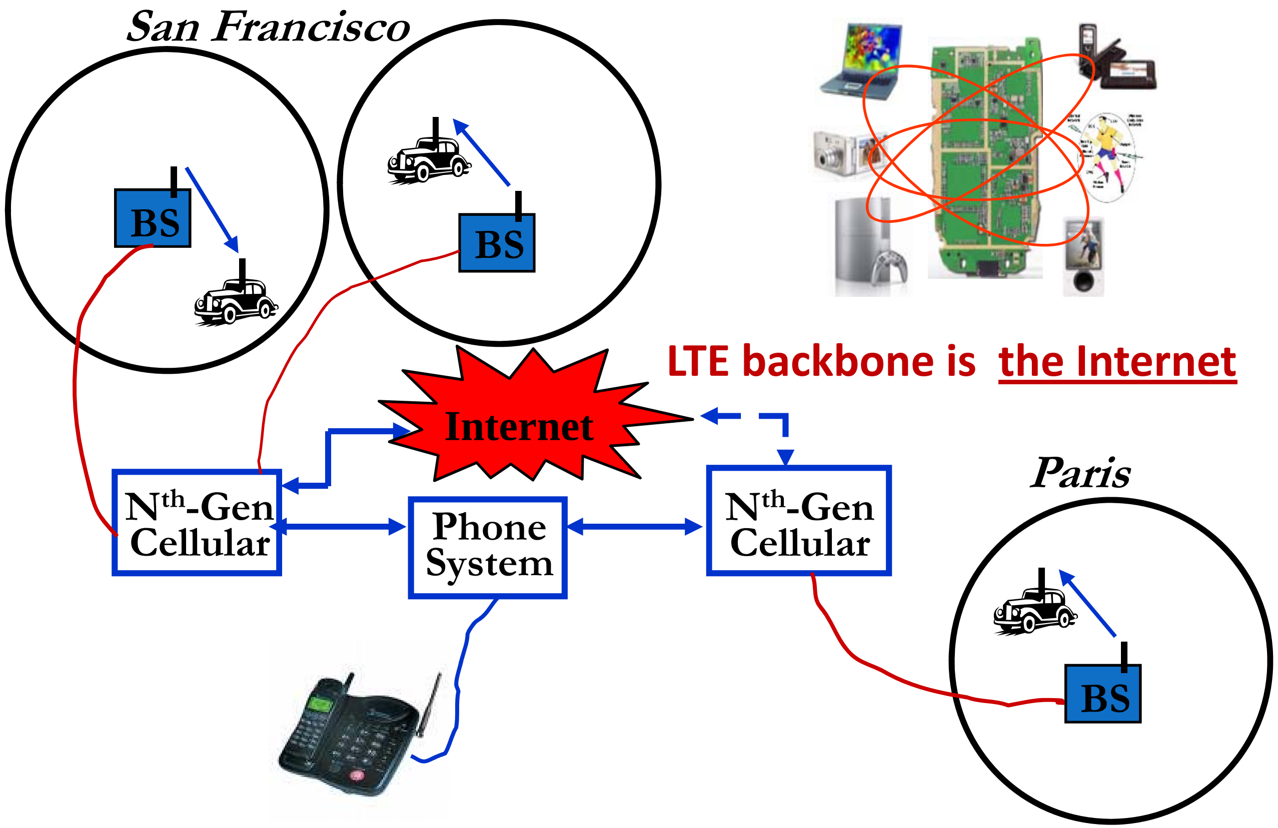
Future Cell Phones

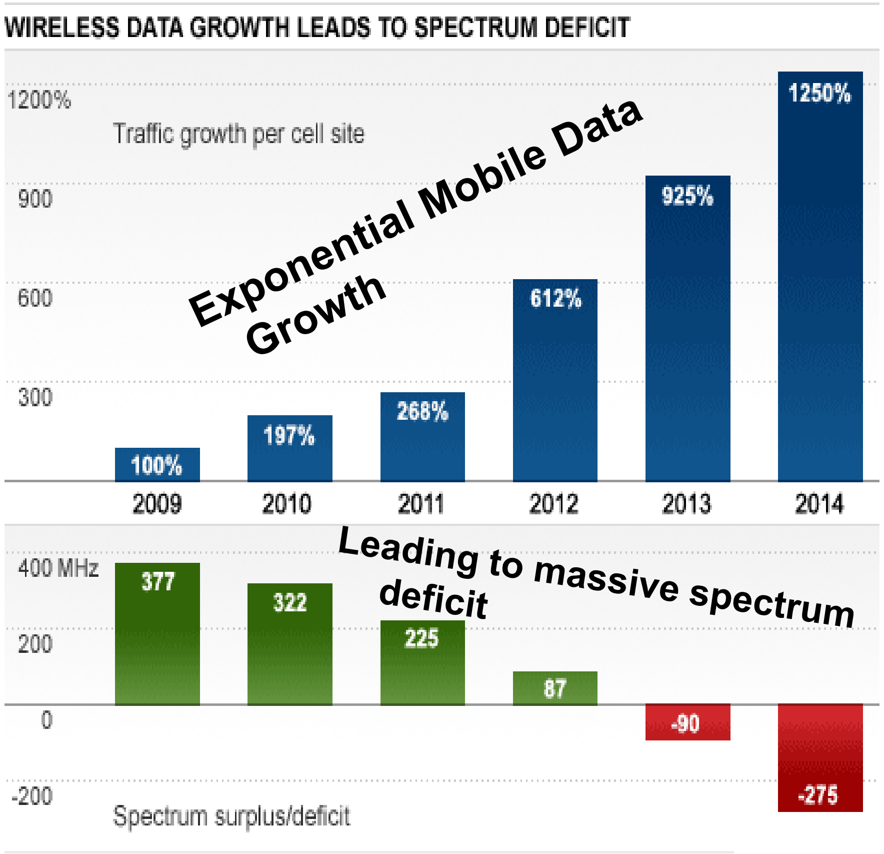
Burden for this performance is on the backbone network



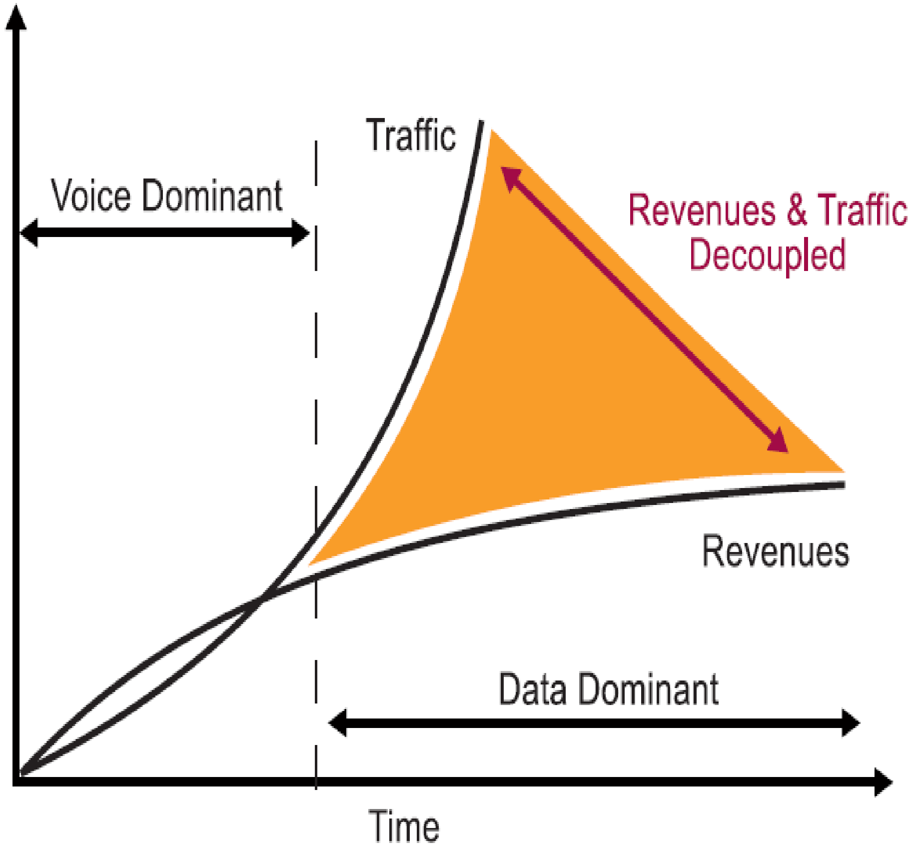
Much better performance and reliability than today

- Gbps rates, low latency, 99% coverage indoors and out

Careful what you wish for…



Source: FCC



Source: Unstrung Pyramid Research 2010

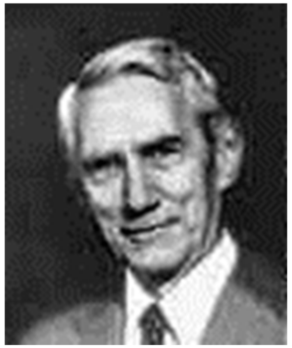
Growth in mobile data, massive spectrum deficit and stagnant revenues require technical and political breakthroughs for ongoing success of cellular

Can we increase cellular system capacity to compensate for a 300MHz spectrum deficit?

Without increasing cost?

or power consumption?

What would Shannon say?

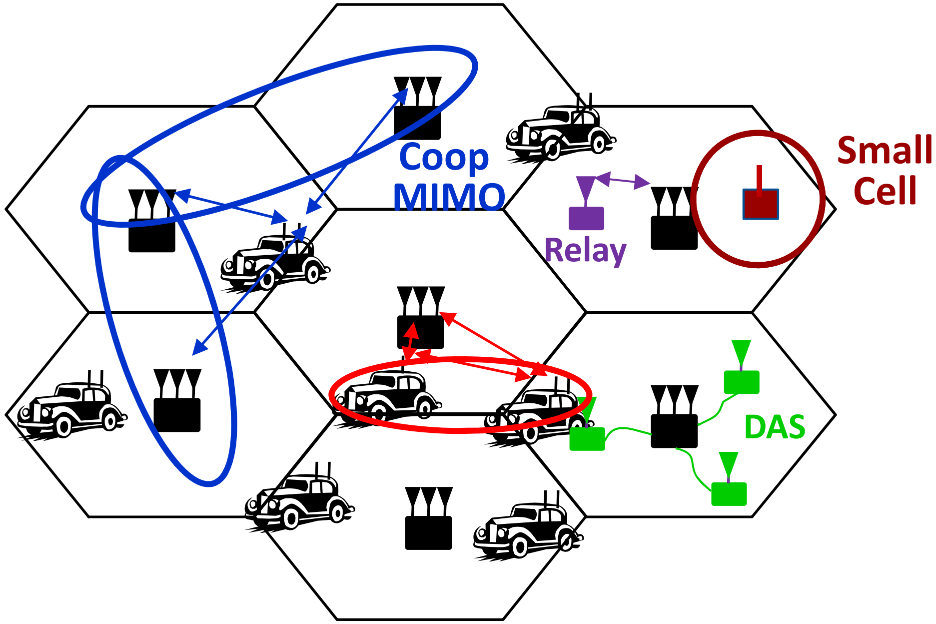


Are we at the Shannon limit of the Physical Layer?

We don't know the Shannon capacity of most wireless channels

- Time-varying channels with memory/feedback.
- Channels with interference or relays.
- Uplink and downlink channels with frequency reuse, i.e. cellular systems.
- Channels with delay/energy/$$$ constraints.

Rethinking "Cells" in Cellular



How should cellular systems be designed?

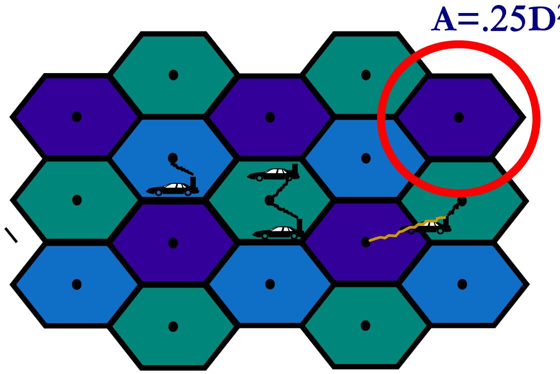
Will gains in practice be big or incremental; in capacity or coverage?

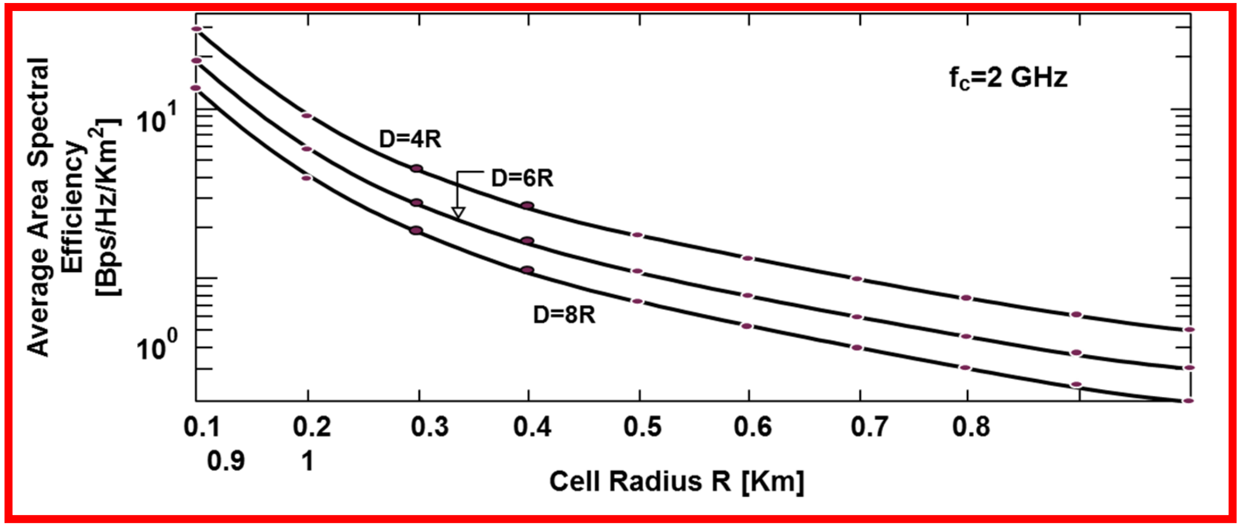
- Traditional cellular design "interference-limited"
  - MIMO/multiuser detection can remove interference
  - Cooperating BSs form a MIMO array: what is a cell?
  - Relays change cell shape and boundaries
  - Distributed antennas move BS towards cell boundary
  - Small cells create a cell within a cell
  - Mobile cooperation via relaying, virtual MIMO, analog network coding.

Are small cells the solution to increase cellular system capacity?

Yes, with reuse one and adaptive techniques (Alouini/Goldsmith 1999)

Area Spectral Efficiency

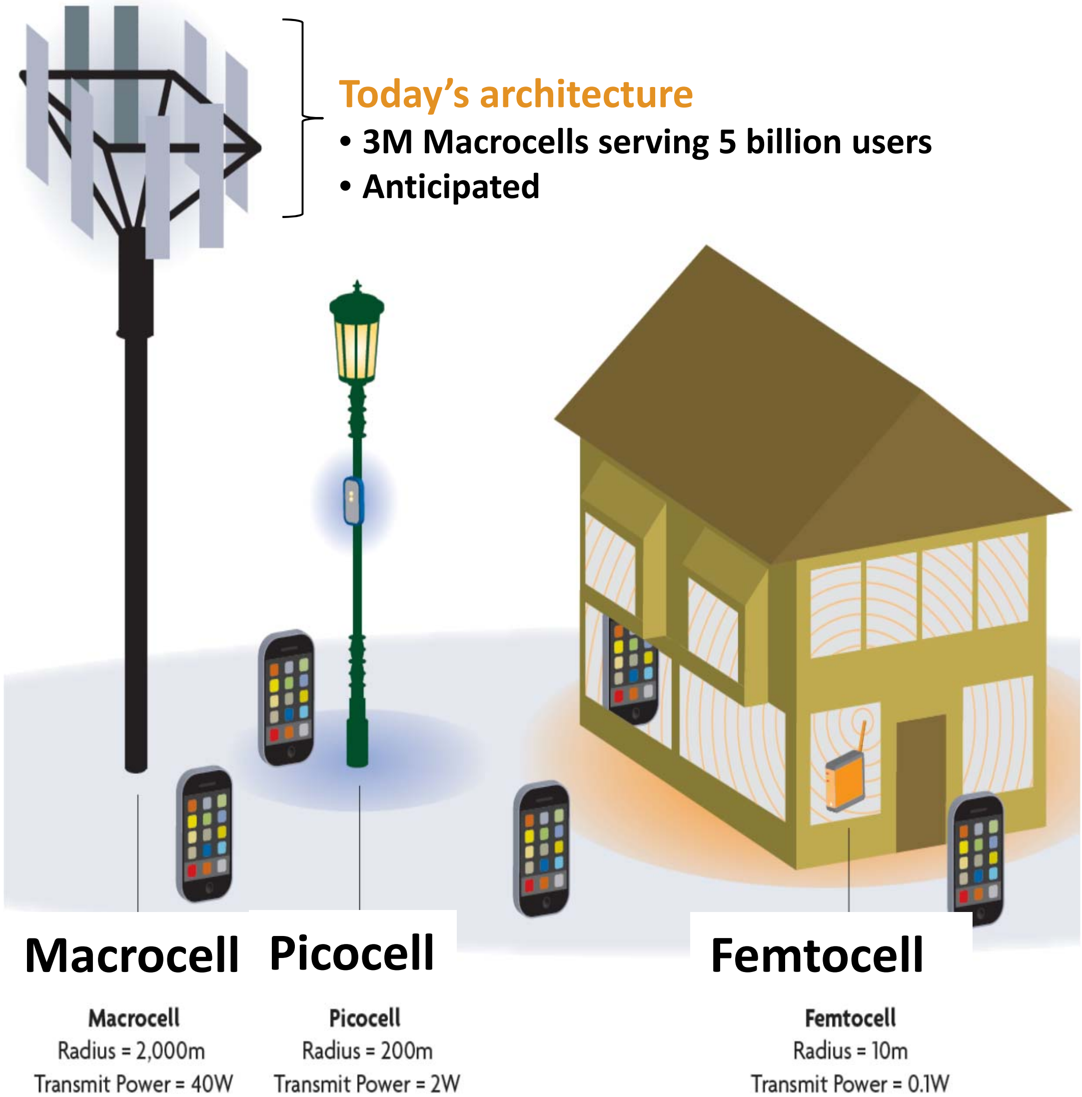




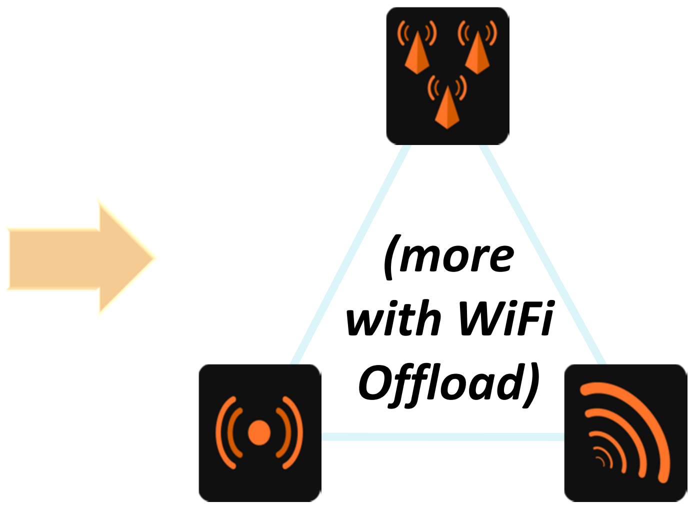
- S/I increases with reuse distance (increases link capacity).
- Tradeoff between reuse distance and link spectral efficiency (bps/Hz).
- Area Spectral Efficiency: $A_e = \Sigma R_i / (.25 D^2 \pi)$ bps/Hz/Km^2.

The Future Cellular Network: Hierarchical

Today's architecture
- 3M Macrocells serving 5 billion users
- Anticipated



10x Lower COST/Mbps



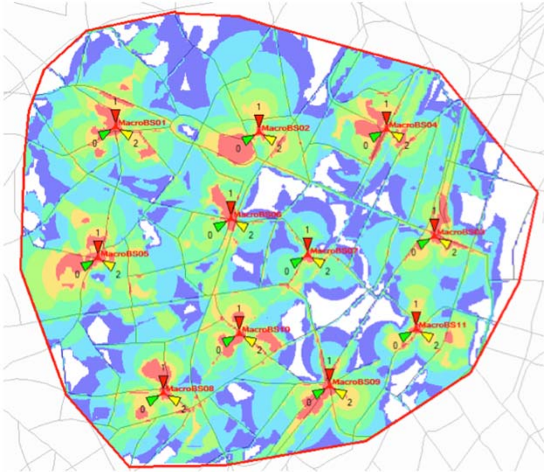
10x CAPACITY Improvement

Near 100% COVERAGE

Future systems require Self-Organization (SON) and WiFi Offload

Traditional Macro *vs.* SON Enabled H-RAN

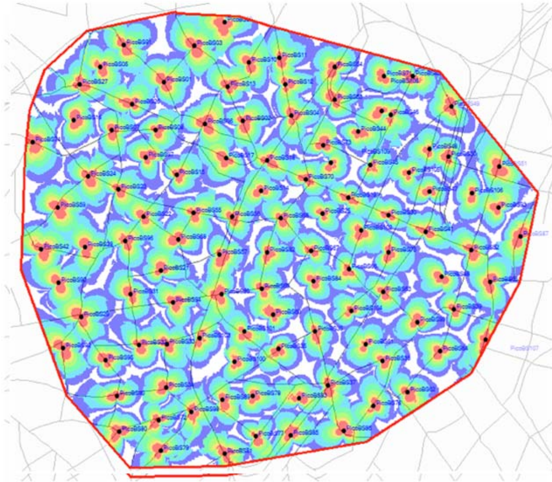
Macro BS Only



Chicago Downtown Modeling Assumptions:

1. Chicago Downtown model (Calculation area: 64.5 km^2)
2. 38 Macro BS sites (3 sectors)
3. 340 Pico BS (3 sectors)
4. ~66000 users were simulated with Monte Carlo method

H-RAN: Macro + Pico BS



H-RAN advantage

- 10x CAPACITY
- 10x lower $/Mbps
- ~100% COVERAGE

	Macro BS	Macro + Pico optimized
Users trying to connect	66680	66680
Connected users	**31023**	**50902**
Effective MAC Aggregate Throughput (DL)	**1020 Mbps**	**12 060 Mbps**
Effective MAC Aggregate Throughput (UL)	**389 Mbps**	**4 204 Mbps**

Macro BS - Cost Per Mbps	**$1,341/Mbps**
Pico BS - Cost Per Mbps (no backhaul/site acq)	**$111/Mbps**
CapEx Reduction Factor	**12x**

Why SoN? Deployment Challenges

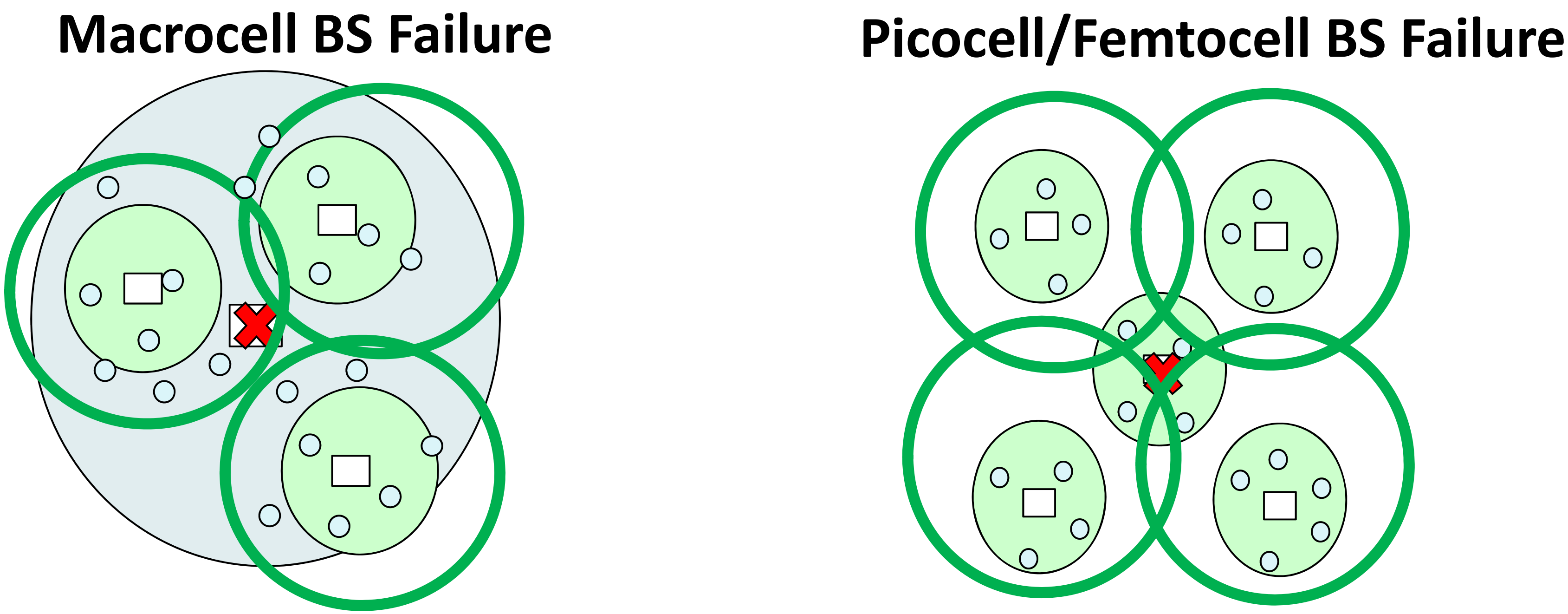
Deploying One Macrocell	Effort (MD – Man Day)
New site verification	**1**
On site visit: site details verification	0.5
On site visit: RF survey	0.5
New site RF plan	**2**
Neighbors, frequency, preamble/scrambling code plan	0.5
Interference analyses on surrounding sites	0.5
Capacity analyses	0.5
Handover analyses	0.5
Implementation on new node(s)	**0.5**
Field measurements and verification	**2**
Optimization	**2**
Total activities	**7.5 man days**

5M Pico base stations in 2015[1]:
- 37.5M Man Days = 103k Man Years
- Exorbitant costs
- Where to find so many engineers?

Why SoN?
- **Automated configuration**
- **Interference Management**
- **Throughput/Coverage Optimization**
- **Mobility Management**
- **Cellular Offload**

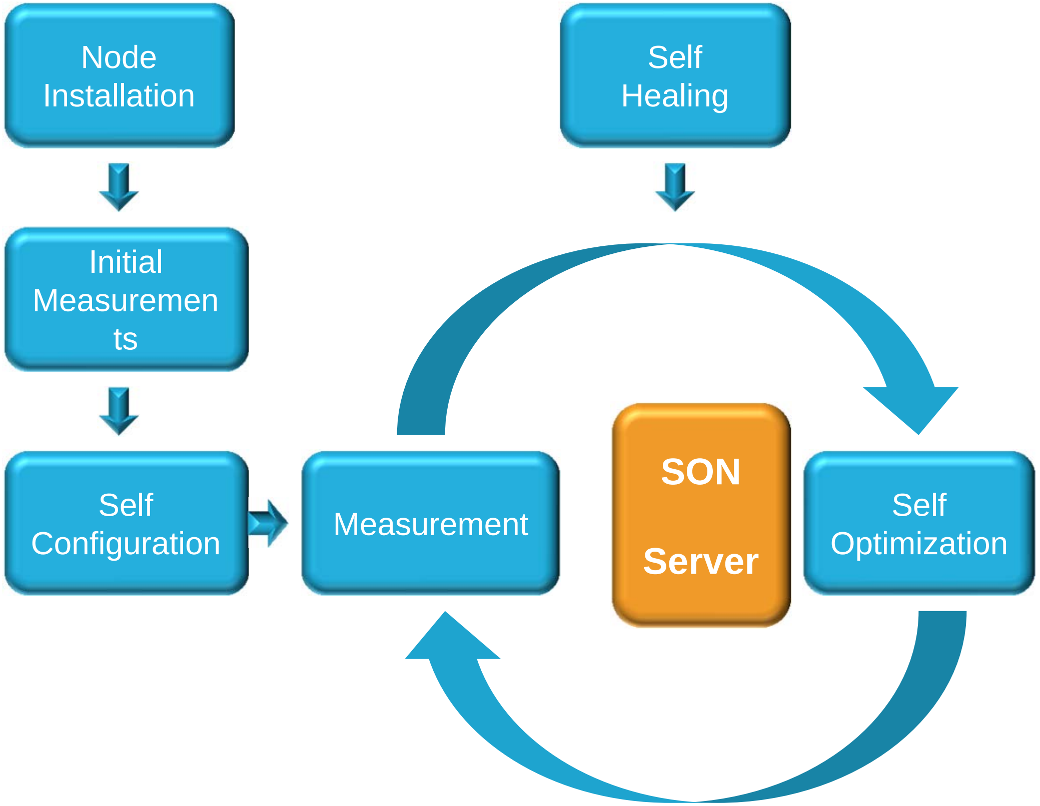
[1]*Source*: ABI Research

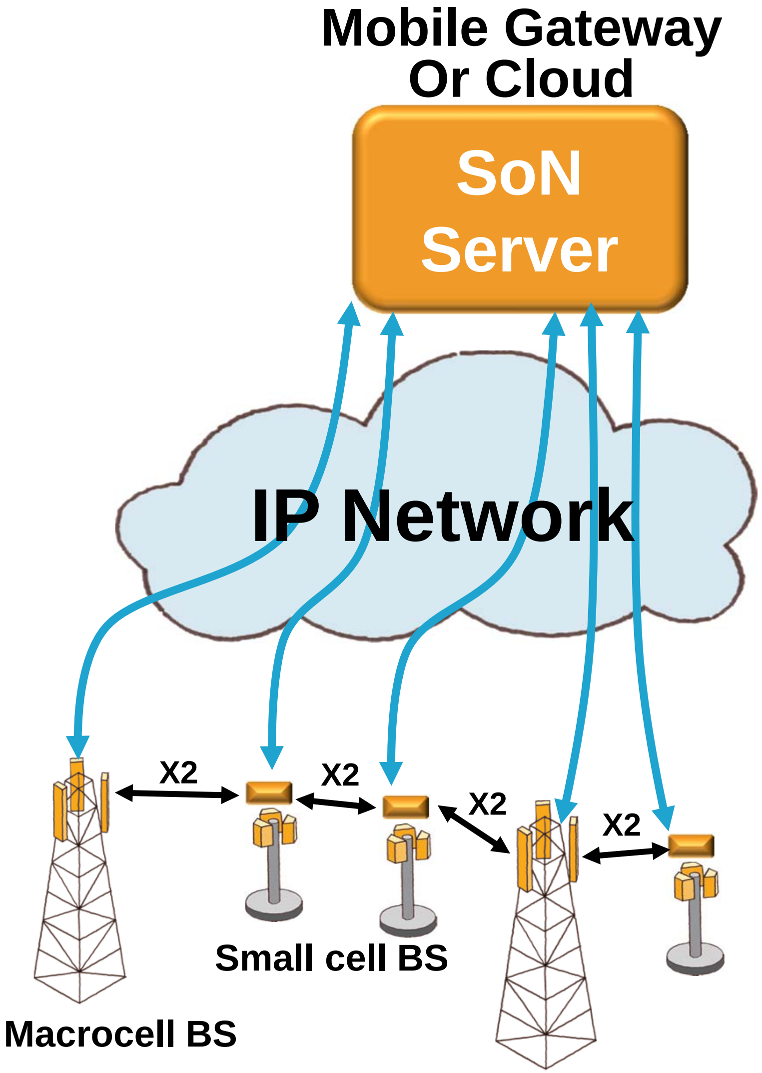
Self-Healing Capabilities of SON



- SON algorithm detects failures in macro/pico/femto BSs
- Dynamically adjusts TX power and antenna tilt of to cover “orphaned” mobiles
- Similar algorithm used to shut down BSs to save energy

SON Premise and Architecture



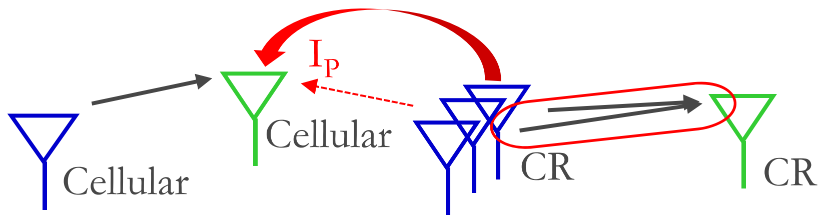


Algorithmic Challenge: Complexity

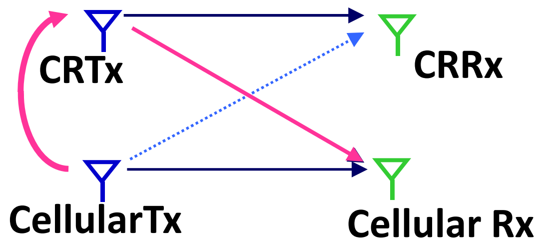
- Optimal channel allocation was NP hard in 2nd-generation (voice) IS-54 systems
- Now we have MIMO, multiple frequency bands, hierarchical networks, …
- But convex optimization has advanced a lot in the last 20 years

Innovation needed to tame the complexity

Cognitive Radios



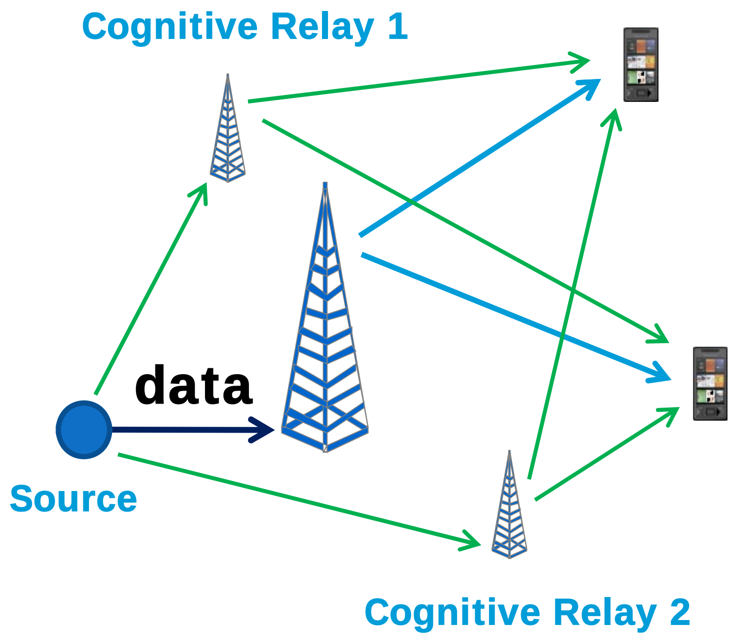
MIMO Cognitive Underlay



Cognitive Overlay

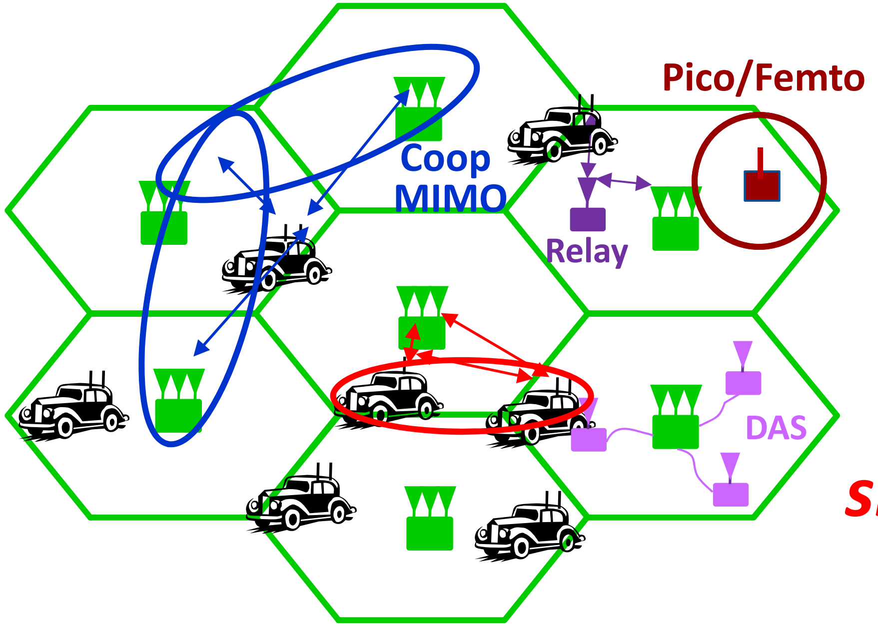
- Cognitive radios support new wireless users in existing crowded spectrum <u>without degrading licensed users</u>
  - Utilize advanced communication and DSP techniques
  - Coupled with novel spectrum allocation policies
- Technology could
  - Revolutionize the way spectrum is allocated worldwide
  - Provide more bandwidth for new applications/services
- Multiple paradigms
  - Underlay (exploiting unused spatial dimensions) and Overlay (exploiting relaying and interference cancellation) promising

Cellular Systems with Cognitive Relays



- Enhance robustness and capacity via cognitive relays
  - Cognitive relays overhear the source messages
  - Cognitive relays then cooperate with the transmitter in the transmission of the source messages
  - Can relay the message even if transmitter fails due to congestion, etc.

Green" Cellular Networks



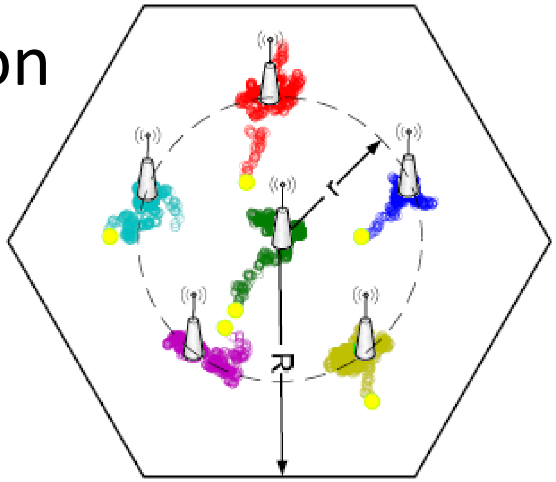
How should cellular systems be redesigned for minimum energy?

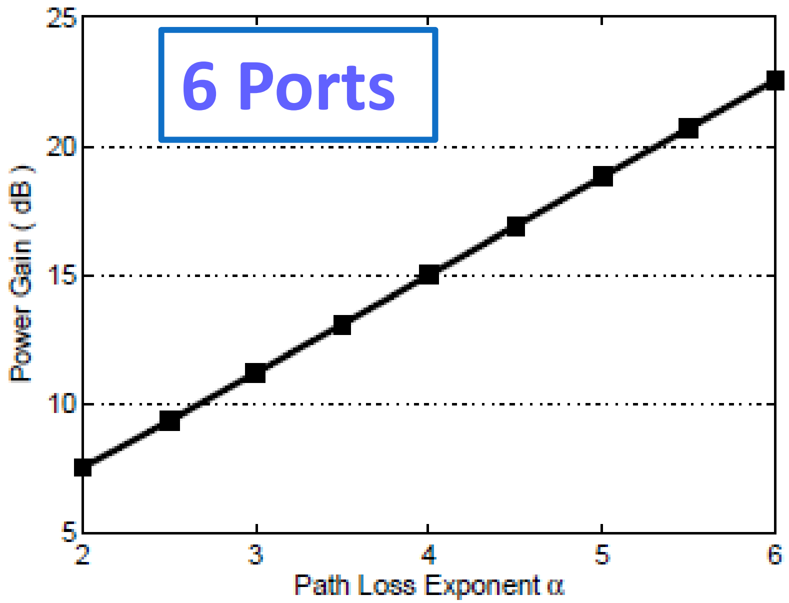
Research indicates that significant savings is possible

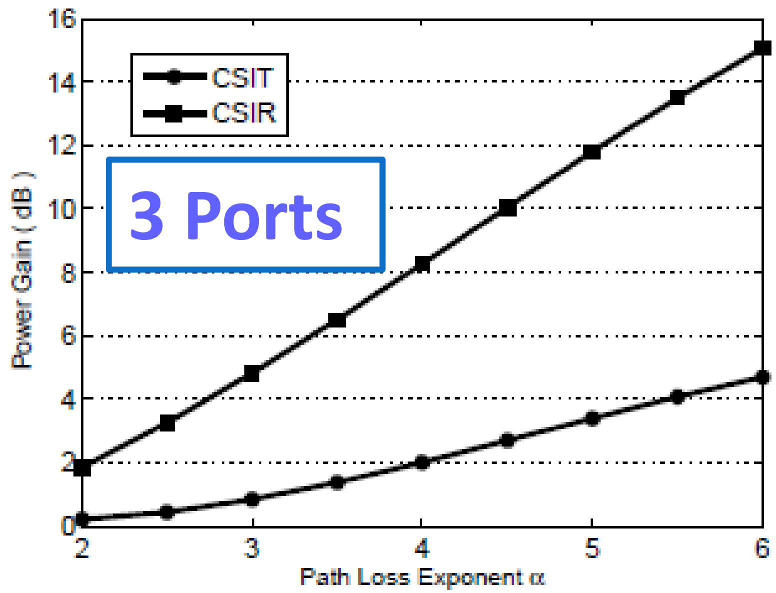
- Minimize energy at both the mobile *and* base station via
  - New Infrastructures: cell size, BS placement, DAS, Picos, relays
  - New Protocols: Cell Zooming, Coop MIMO, RRM, Scheduling, Sleeping, Relaying
  - Low-Power (Green) Radios: Radio Architectures, Modulation, coding, MIMO

Antenna Placement in DAS

- Optimize distributed BS antenna location
- Primal/dual optimization framework
- Convex; standard solutions apply
- For 4+ ports, one moves to the center
- **Up to 23 dB power gain in downlink**
  - **Gain higher when CSIT not available**

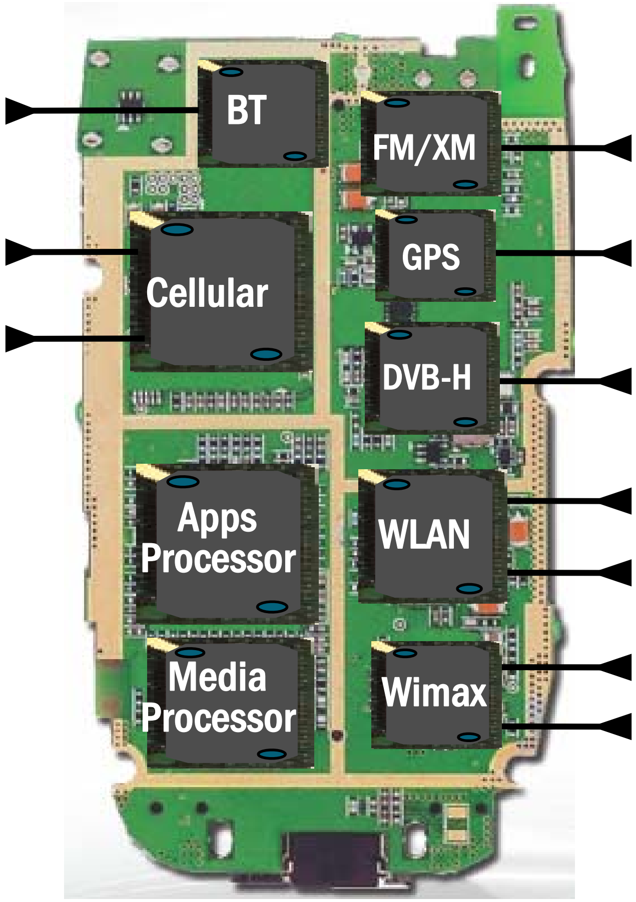






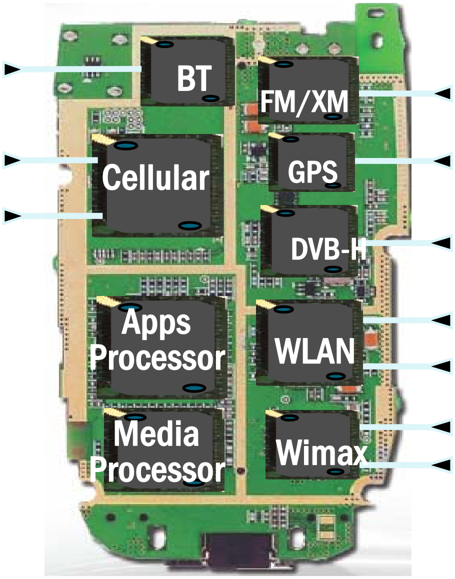
Device Challenges

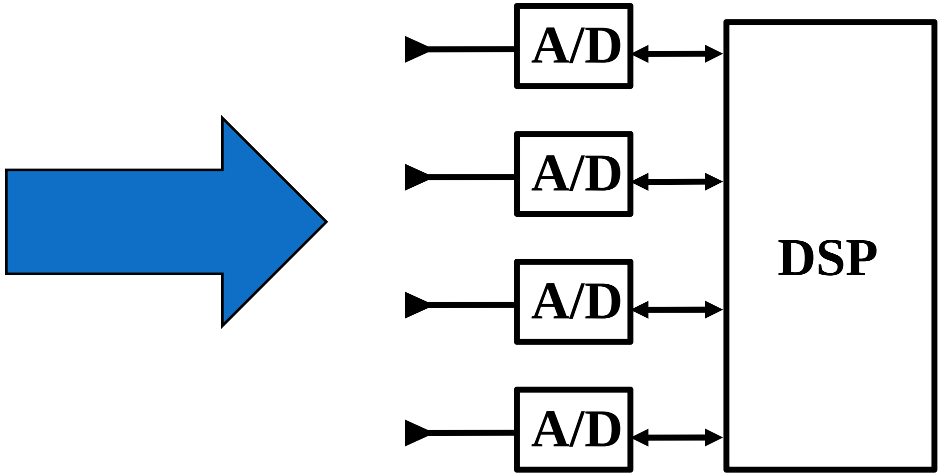
- Size and Cost
- Power and Heat
- Multiband Antennas
- Multiradio Coexistance
- Integration



Software-Defined (SD) Radio:

Is this the solution to the device challenges?





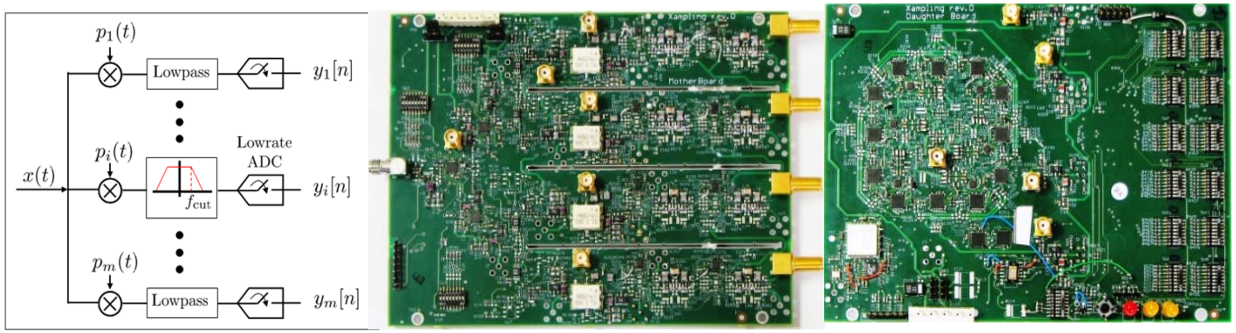
- Wideband antennas and A/Ds span BW of desired signals
- DSP programmed to process desired signal: no specialized HW

Today, this is not cost, size, or power efficient

Compressed sensing may be a solution for sparse signals

Compressed Sensing

- Basic premise is that signals with some sparse structure can be sampled below their Nyquist rate

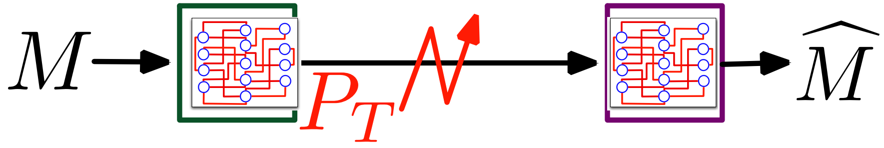


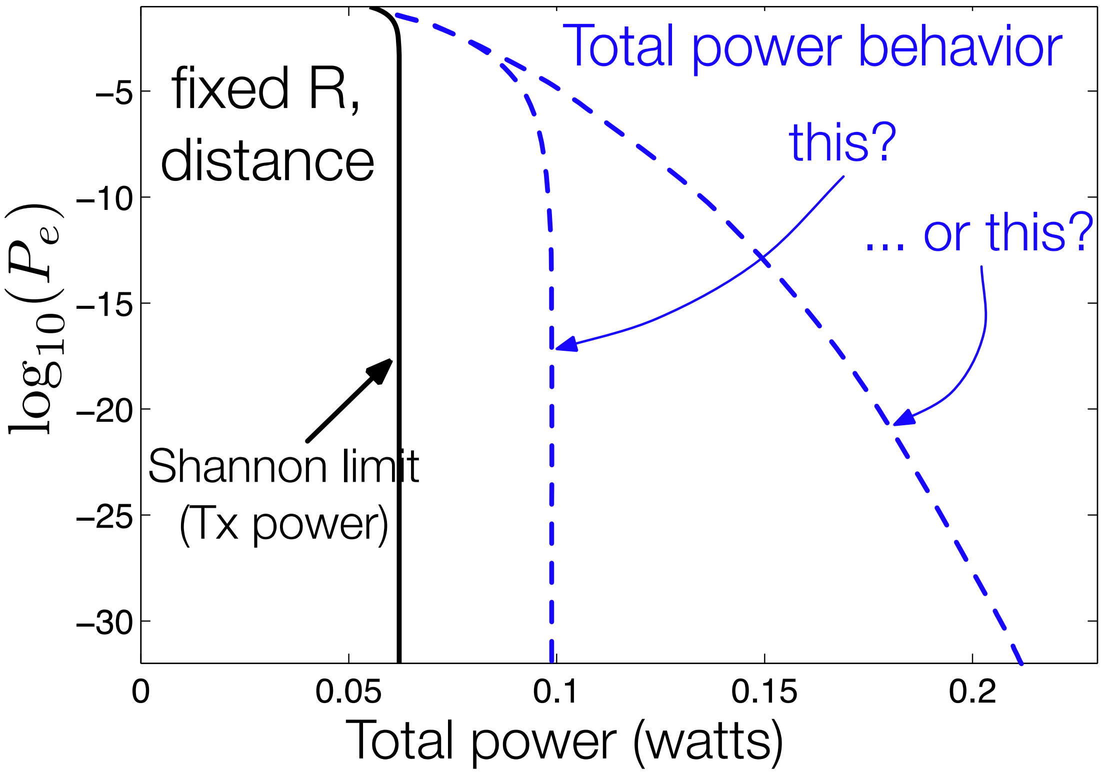
- Signal can be perfectly reconstructed from these samples by exploiting signal sparsity

- This significantly reduces the burden on the front-end A/D converter, as well as the DSP and storage

- Key enabler for SD, low-energy, and white-space radios?
  - Only for incoming signals “sparse” in time, freq., space, etc.

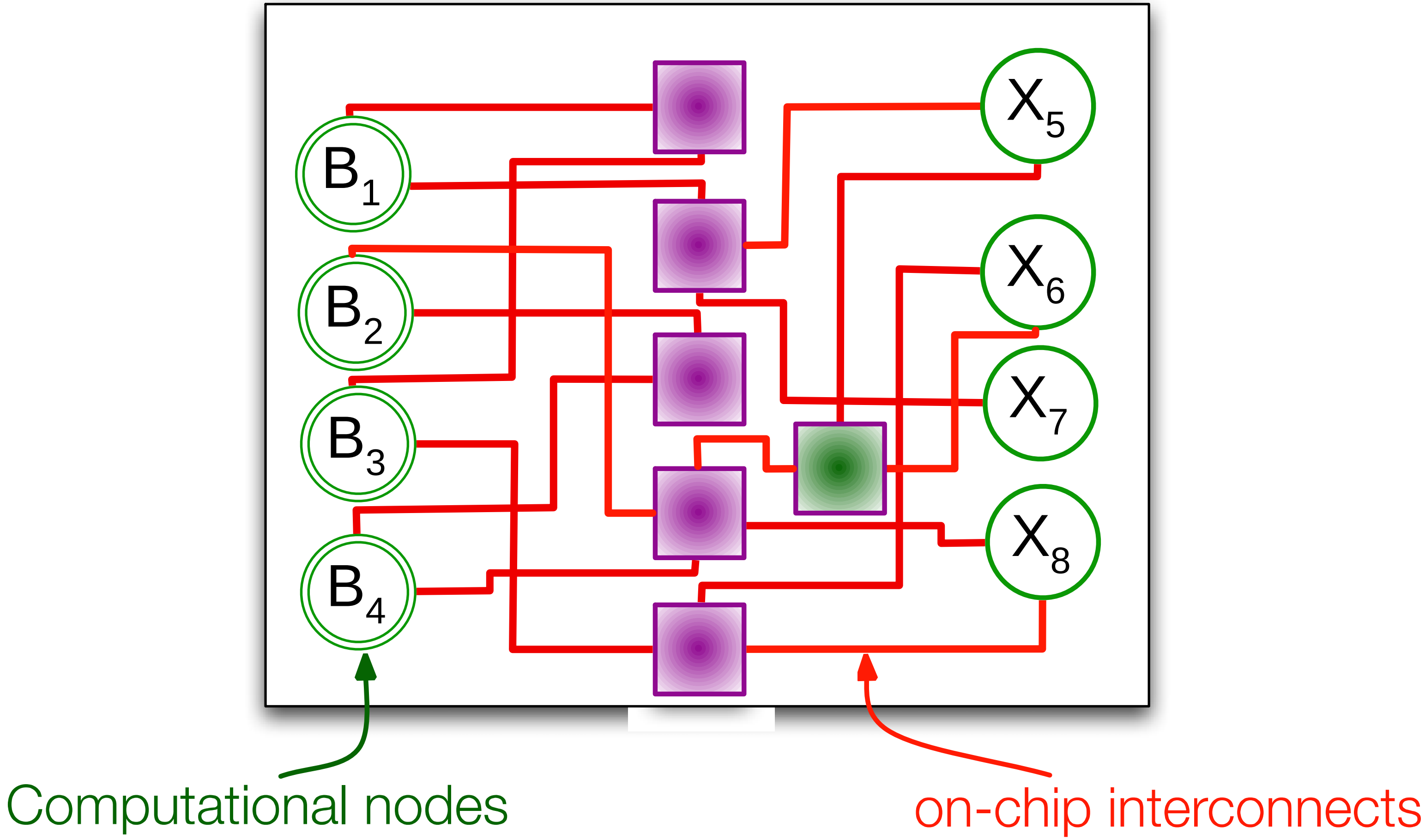
Codes for minimal total energy consumption





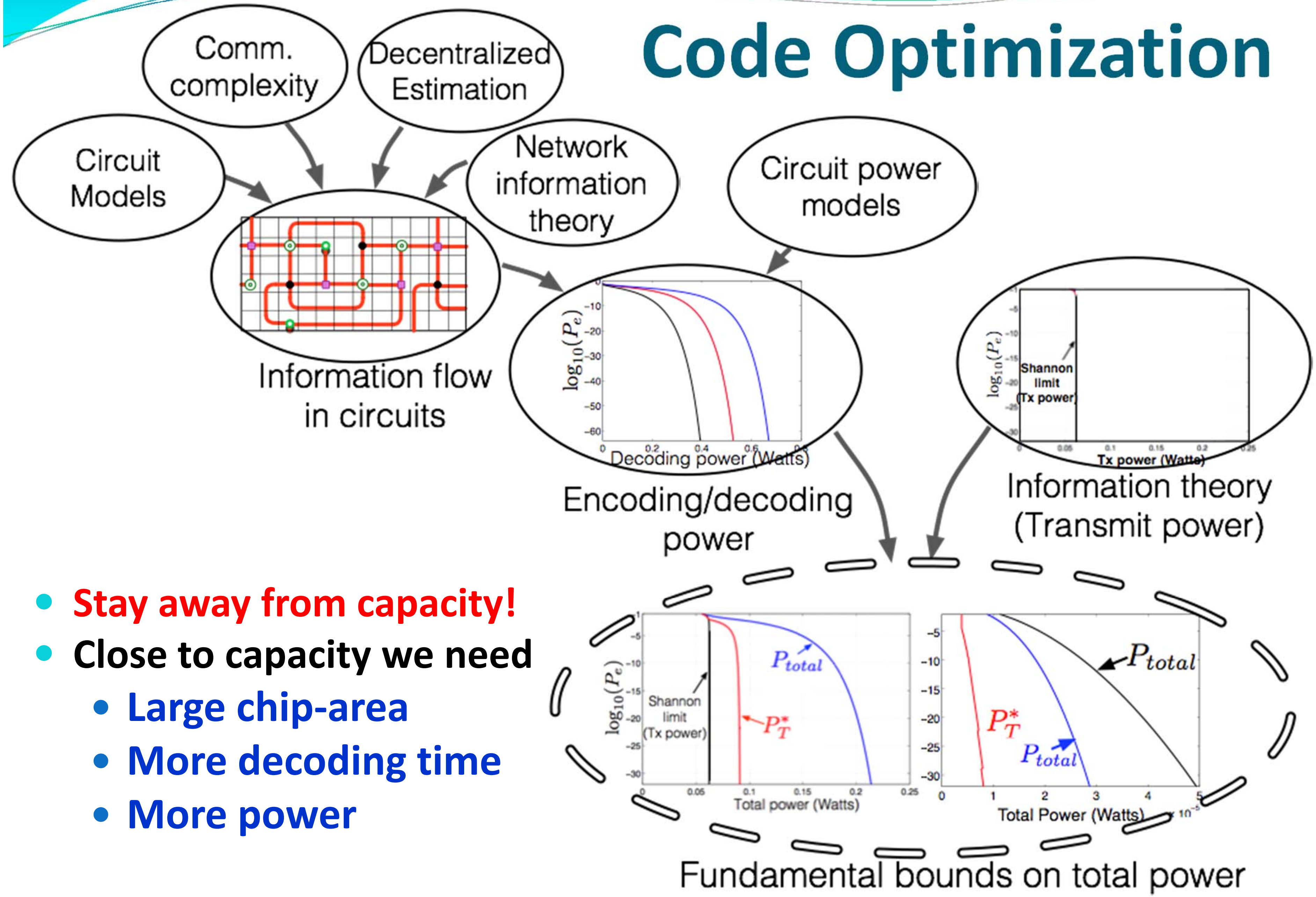
Is Shannon-capacity still a good metric for system design?

Power consumption via a network graph
power consumed in nodes and wires



Extends early work of El Gamal et. al.'84 and Thompson'80

Code Optimization



- **Stay away from capacity!**
- **Close to capacity we need**
  - **Large chip-area**
  - **More decoding time**
  - **More power**

Summary

- Much work to be done on future cellular system design
- We are not at the Shannon limit of the PHY, and don't even know what it is.
- The "optimal" way to design cellular networks is wide open for innovation.
- True breakthroughs in hardware needed
- The challenges to make future cellular systems successful are not only technical.