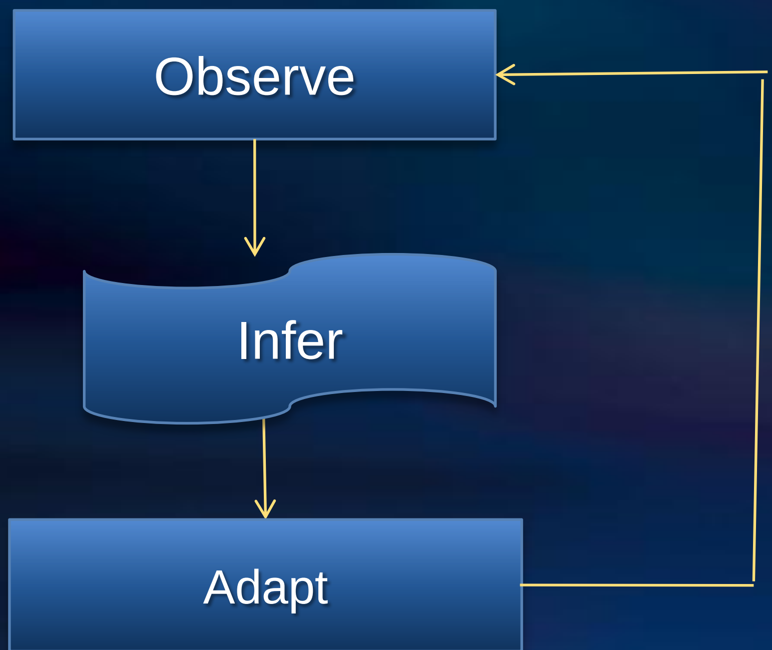
Revisiting Wireless Networking in the Cognitive Radios Era

Victor Bahl
Microsoft Research

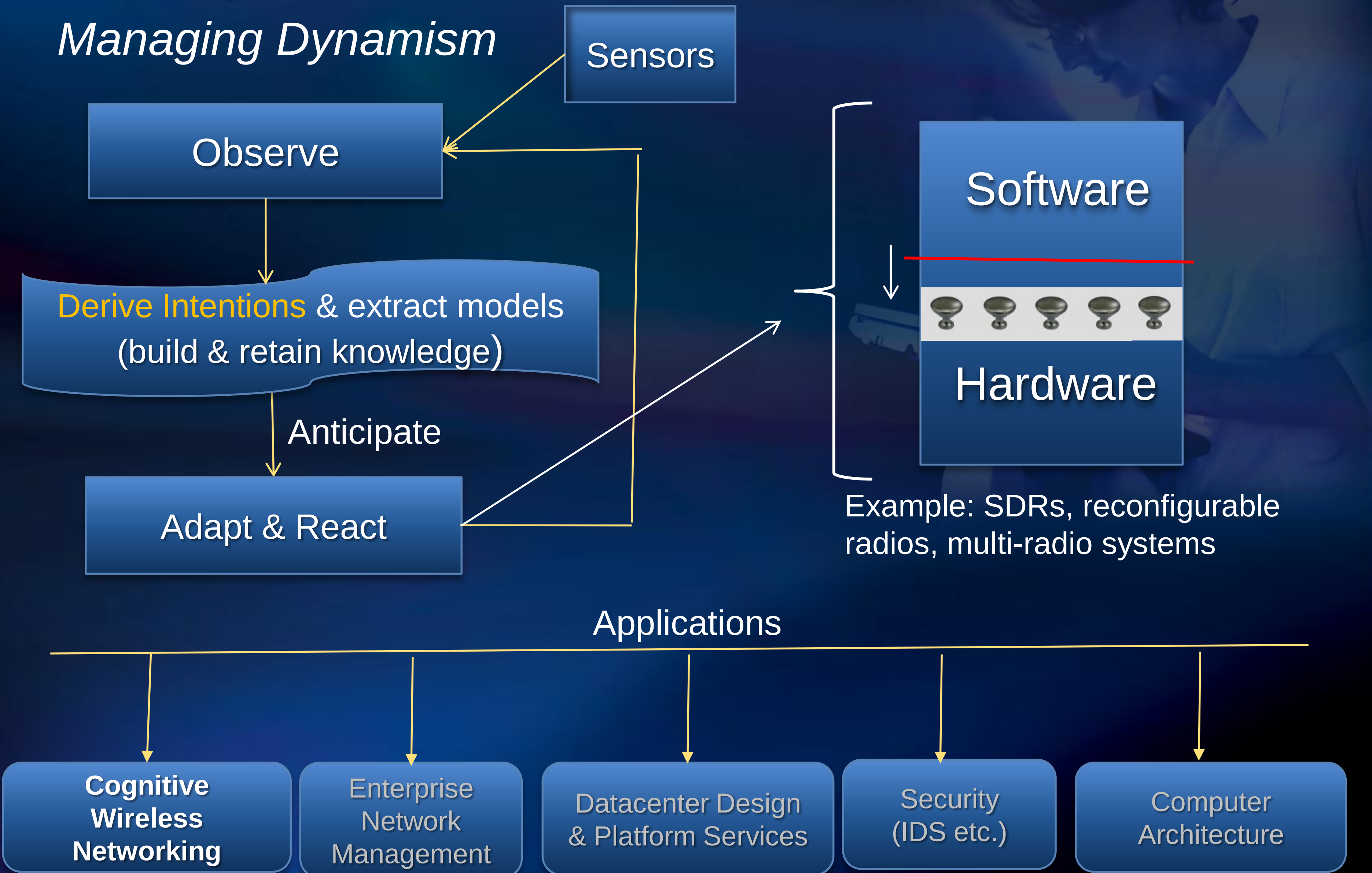


Examples: TCP, CSMA/CA,
Autorate, AD, ….

Intention Aware Networking

Understanding End-to-End Goals

Managing Dynamism



Definitions

- Cognitive Radio

  a radio that is aware of and can sense its environment, learn from its environment, and adjust its operation according to some objective function

- Cognitive Network

  a network that has a cognitive process that perceives current network conditions, and then plans, decides, and acts on those conditions. The network can learn from these adaptations and uses them to make future decisions, all while taking into account end-to-end goals.

Cognitive Wireless Networking

Research Program

Wireless Meshes, Ubiquitous Personal Networks, Wireless Office, Wireless LANs, Vehicular networks

Licensed Spectrum

- White Space Networking
  - KNOWS
- Management & Policy
  - SPARK

Unlicensed Spectrum

- Redesigning ISM Networks
  - CogWiFi
- Management & Policy
  - Etiquettes

Enabling Technologies: SDR, Frequency agile radios, multi-radio systems…..

Scenario Driven Approach

Enable new scenarios

- Ubiquitous Personal Networks (UPN)
- …

Revisit existing scenarios

- Mesh Networking
- …

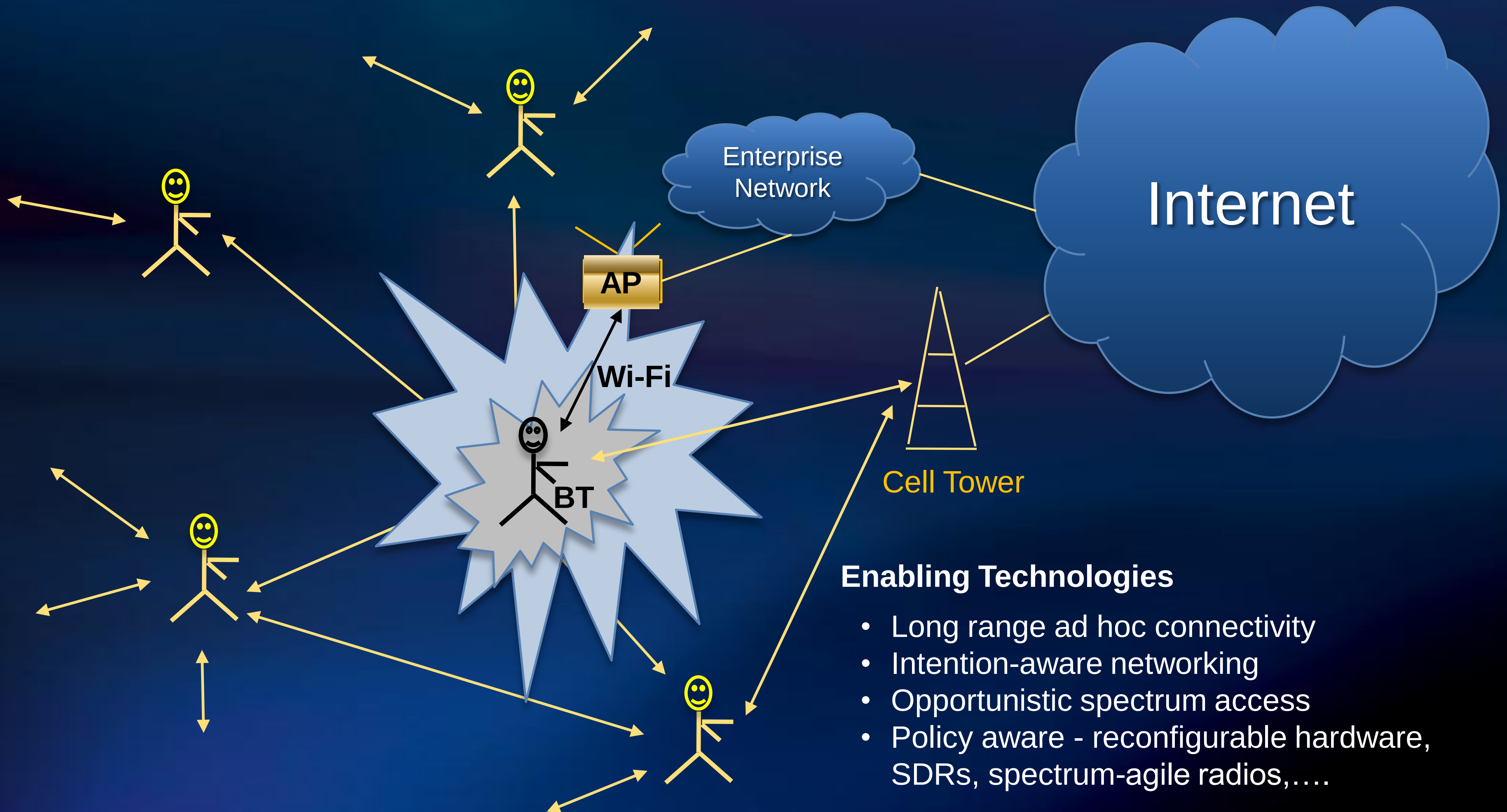
Microsoft Research

UPN

Ubiquitous Personal Network

Description

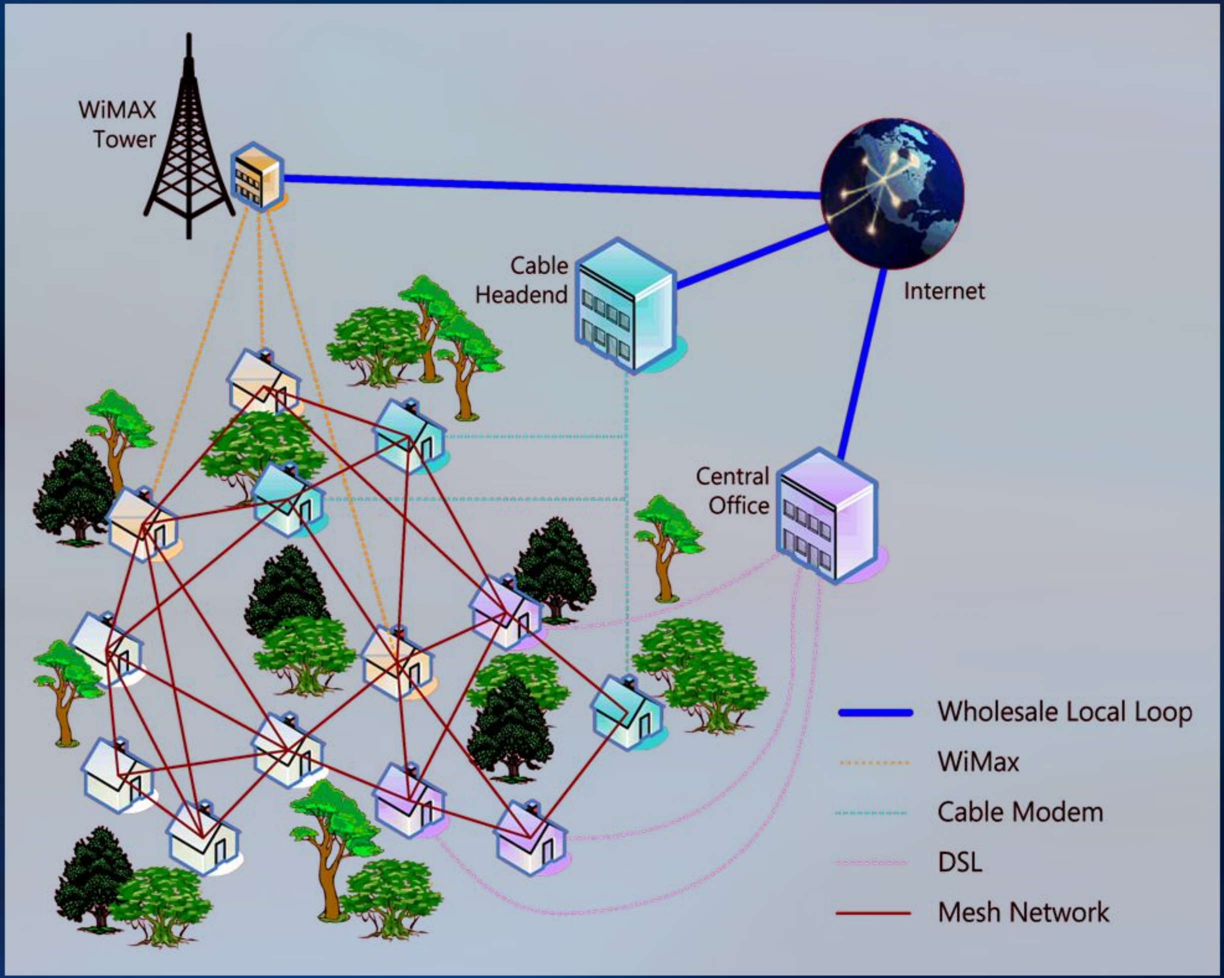
- Your own personal private network - anytime, everywhere.
- No infrastructure required
  …but interacts seamlessly with available network(s)
- Provides **free** high-bandwidth connectivity to devices & people
  …a natural for location-aware mobile social networking



Enabling Technologies

- Long range ad hoc connectivity
- Intention-aware networking
- Opportunistic spectrum access
- Policy aware - reconfigurable hardware, SDRs, spectrum-agile radios,….

Mesh Networking



Wireless mesh networks have the potential to bridge the Broadband divide

Microsoft Research

Why Meshes?

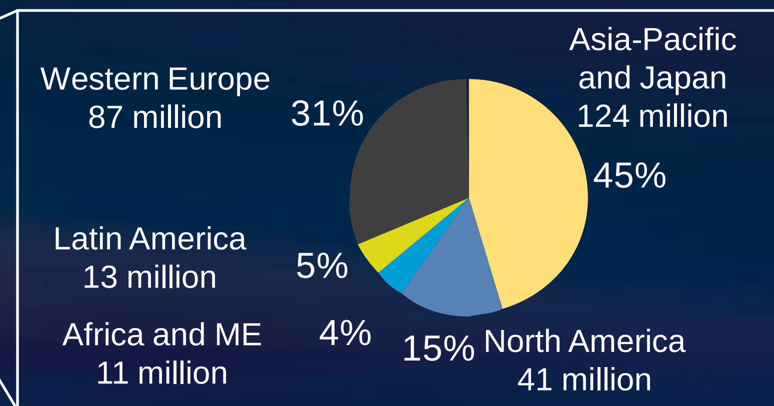
Worldwide Internet Penetration < 20%

Worldwide, Internet and broadband use are concentrated in Asia-Pacific, Europe, and North America

1 Billion Internet Users Worldwide

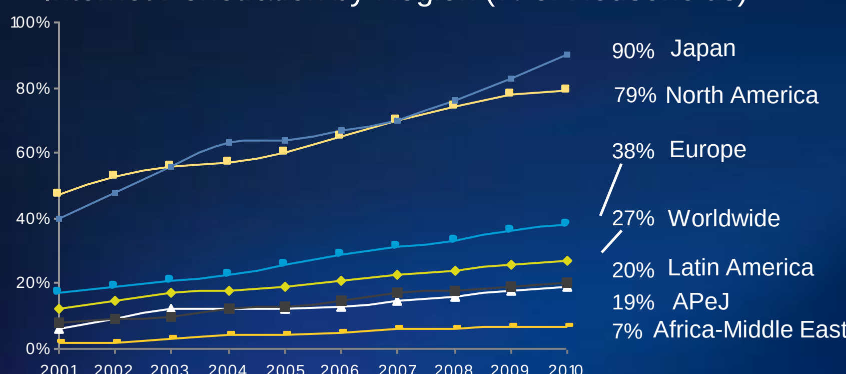
Worldwide Broadband versus Narrowband Penetration (% Internet accounts)

Broadband Users Worldwide (Millions)



Worldwide Internet Penetration Is Growing (any device)

Internet Penetration by Region (% of Households)



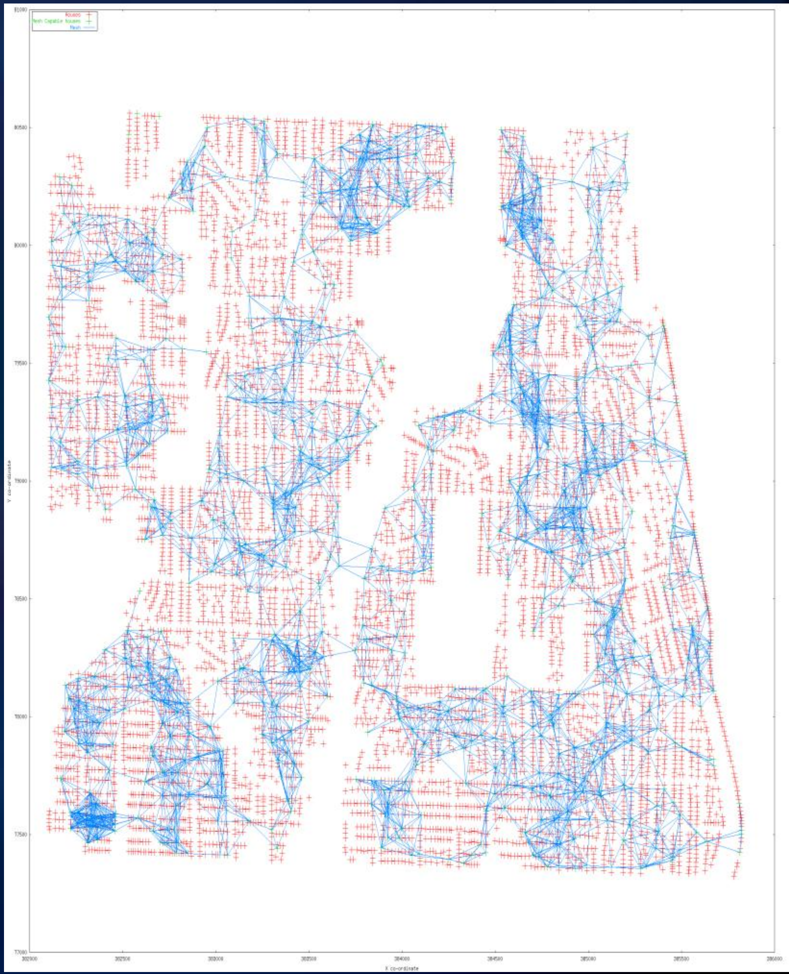
Broadband penetration is the prime lever of Internet activity growth

Source: Pyramid Research, April 2006. Internet use may include access via devices other than PCs.

Microsoft Research

Viability Studies

- 5-10% subscription rate needed for suburban topologies with current wireless ranges (> 100 m)
- Once a mesh forms, it is usually well-connected
  - i.e. number of outliers are few (most nodes have > 2 neighbors)
- Need to investigate other joining models
- Business model considerations are important



Range is key for good mesh connectivity

Microsoft Research

But…

5 GHz:

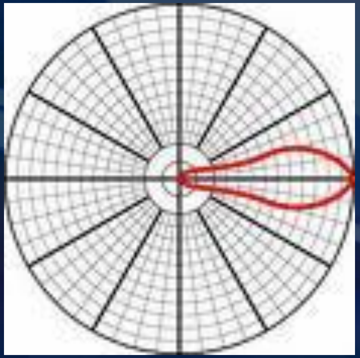
- Bandwidth is good,
- Published 802.11a ranges (Yellow circles) decent
- Measured range (red circle) poor
- Range is not sufficient to bootstrap mesh until installed % is quite high

Microsoft Research

The Bloody Range Problem

Directional antennas?

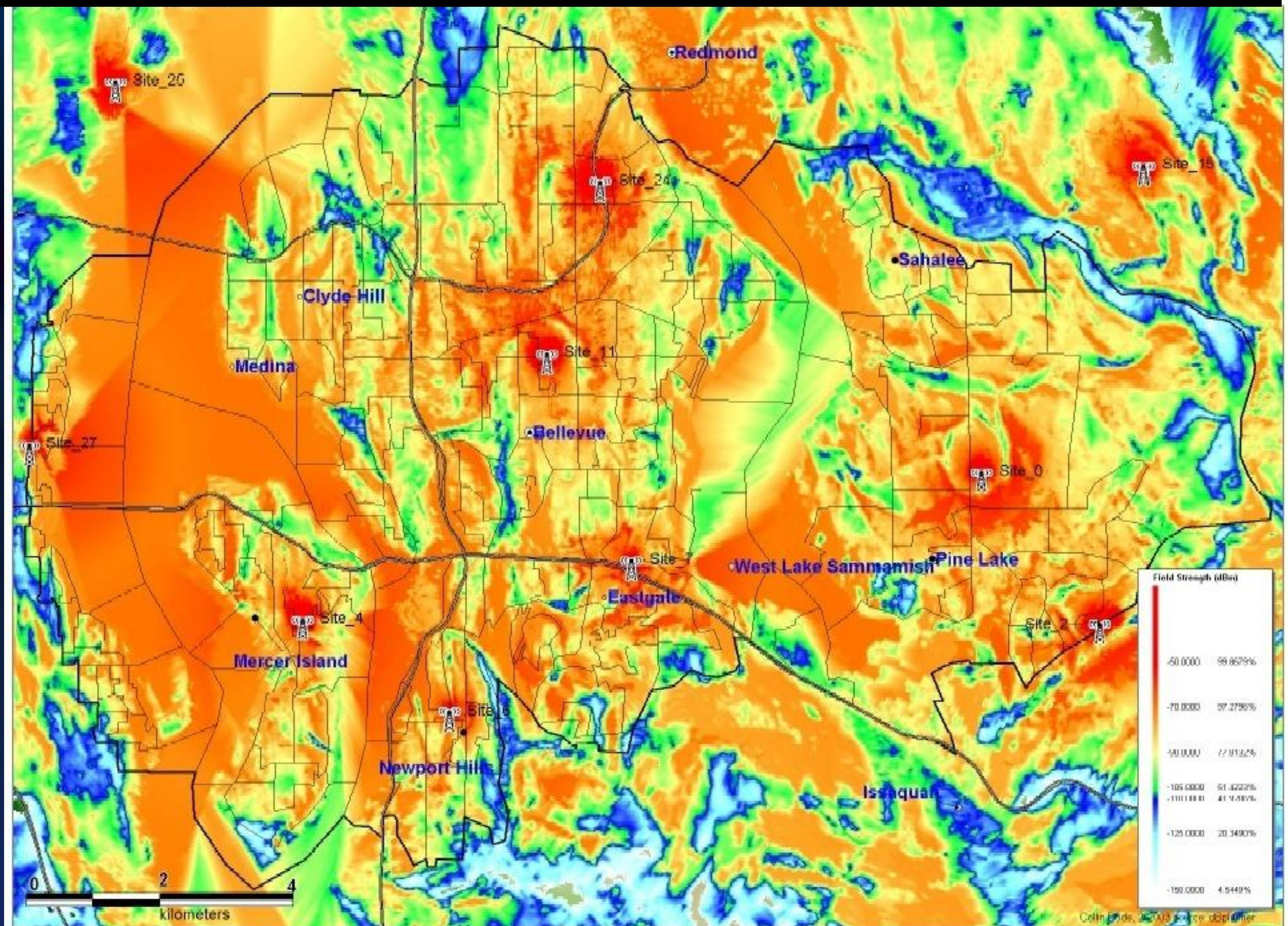
- Placement issues
  - Zoning laws
  - Truck roll
  - Insurance cost
- Maintenance



What about lower frequencies?....

Propagation at 2600 MHz: 10 Sites

Seattle Eastside: Bellevue and Sammamish



~ 250 km^2

Good Coverage

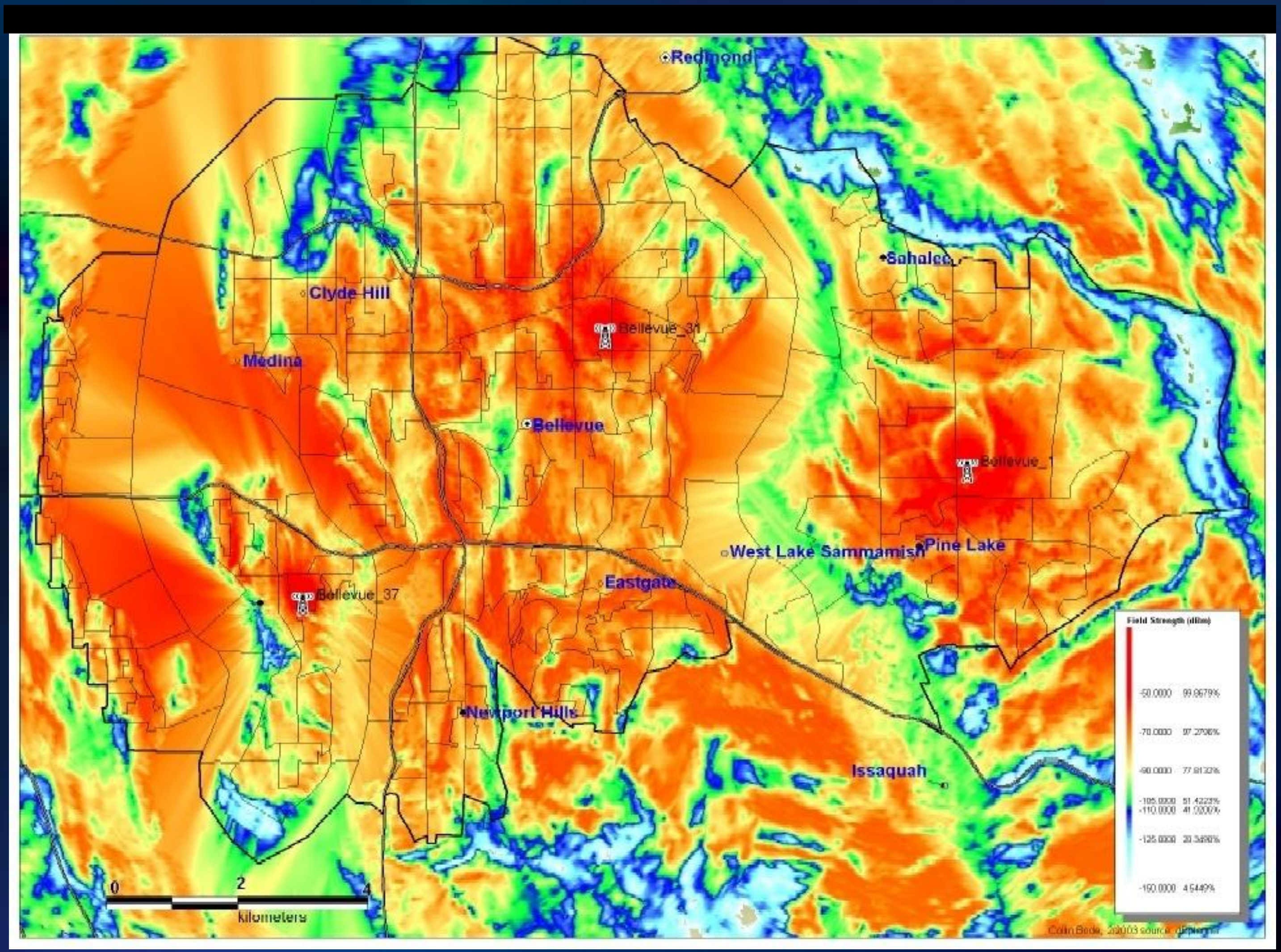
Bad Coverage

Limits of Indoor

Map courtesy Chris Knudsen, Vulcan Capital

Propagation at 700 MHz: 3 Sites

Seattle Eastside: Bellevue and Sammamish



~ 250 km²

Good Coverage

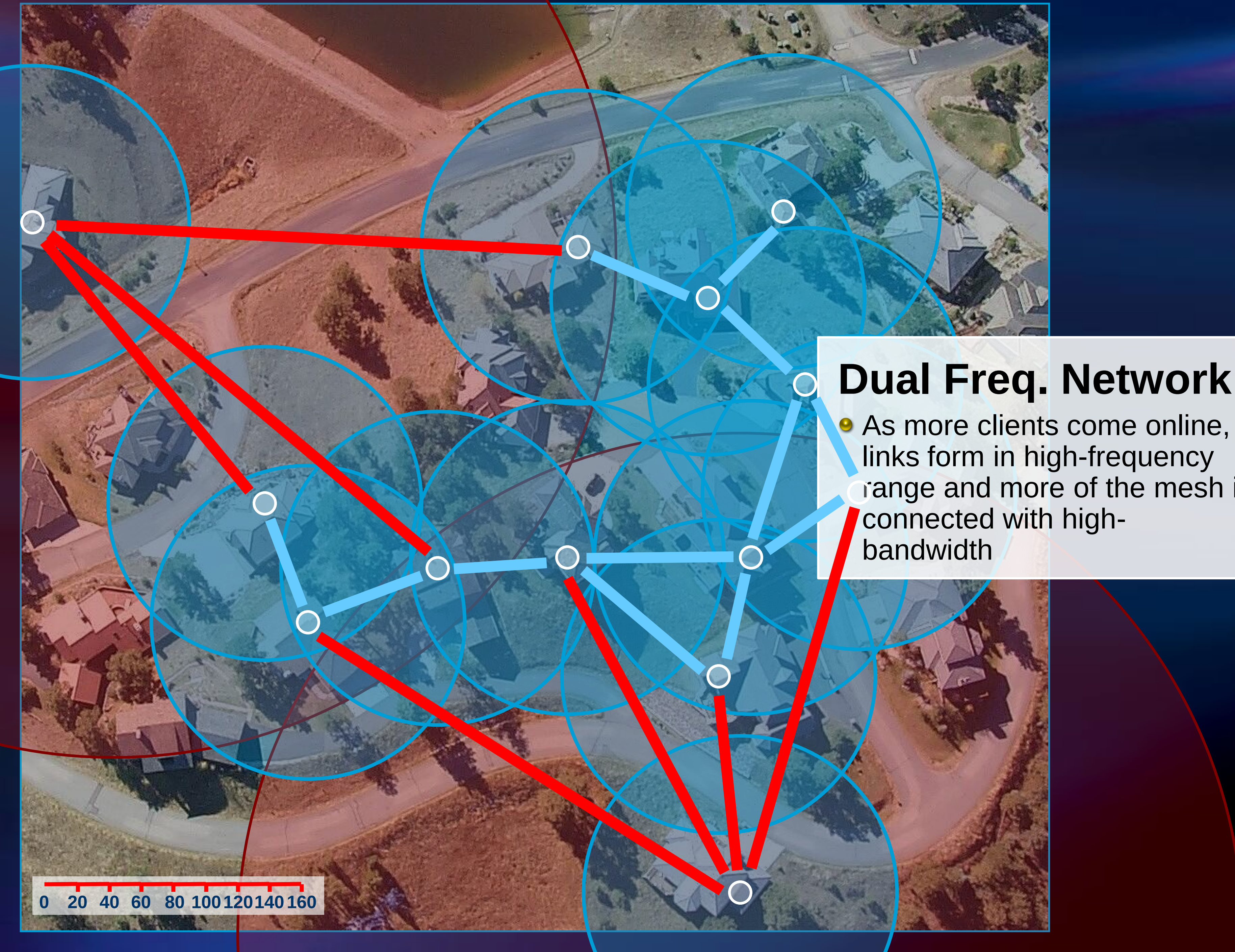
Bad Coverage

Limits of Indoor

Map courtesy Chris Knudsen, Vulcan Capital

600-700 MHz:

- Much better range: about 7 times further than 5 GHz at equal power settings
- Three 2 MHz channels can bootstrap a neighbourhood with ~3-5 Mbps

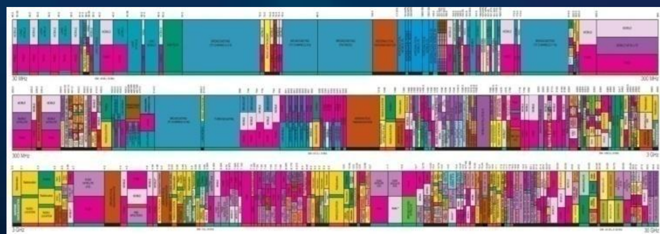


Dual Freq. Network

- As more clients come online, links form in high-frequency range and more of the mesh is connected with high-bandwidth

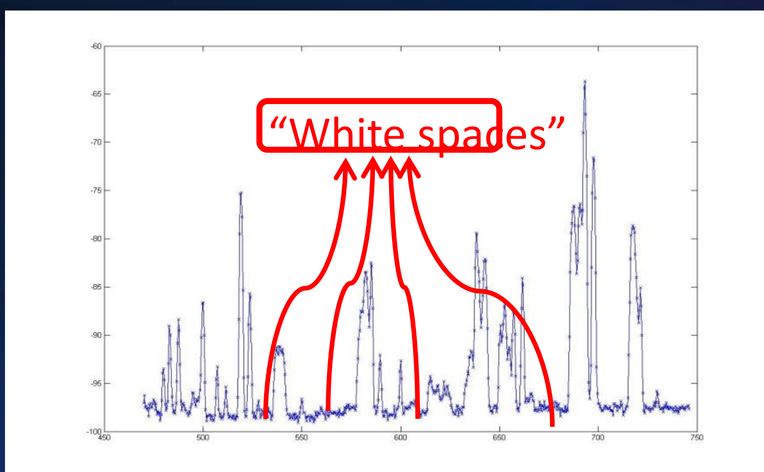
Sprectrum Aware Networking

Is it all being used?

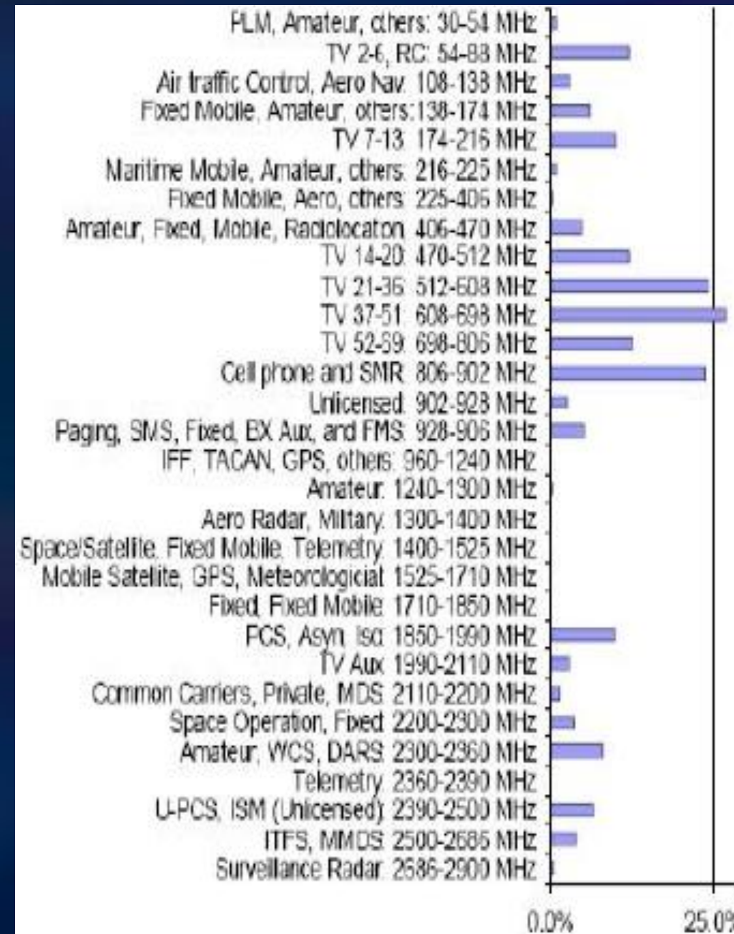


[30 MHz – 30 GHz]

5.2% in use!



470 MHz Frequency 750 MHz



Source:
Shared Spectrum Company

Microsoft Research

Can we buy more?

Yes (On-going 2008 spectrum auction)

But:

- Should the govt. sell a “national resource”?
  - Success stories: GSM, CDMA, 3G, WiMax(?)…
  - Cons: Underutilization e.g. 15% utilization in TV Bands

- Should it be unlicensed (but regulated)?
  - Success stories: WiFi, Bluetooth, Zigbee, …
  - Cons: Overcrowding: "junk bands"

Classic debate “Properties versus Commons”

Microsoft Research

The Broadband Debate

…two sides to the coin

Proponents

- Local and state government should provide Wi-Fi access free everywhere (**Significant macroeconomics benefit**)
- Propel the nation to the forefront of the broadband era
  - Lower cost, faster deployment (specially in rural areas)
  - Stimulate competition by raising service standards

Detractors

- Unfair to ask private sector to compete with local government who have tax dollars
- Not a utility, highly competitive enterprise
- Continuously changing due to innovation

Can we improve utilization?

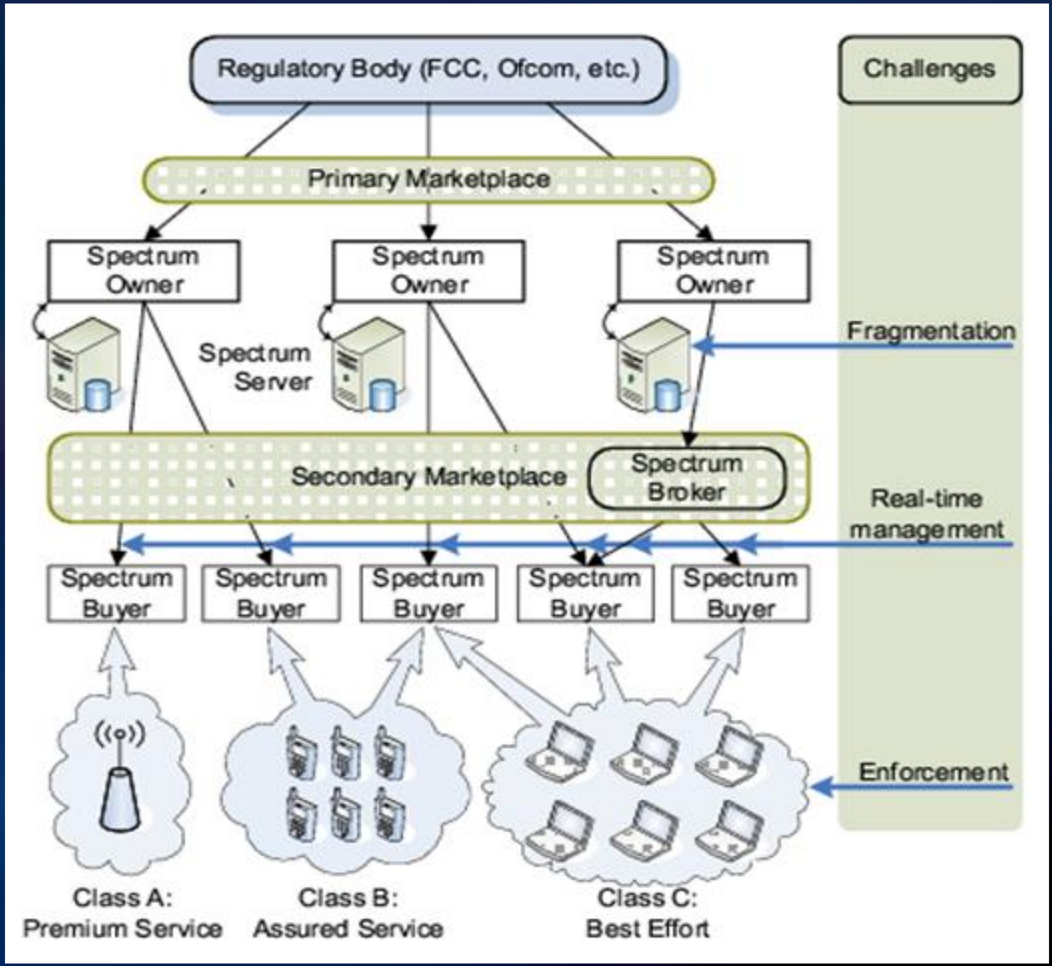
Options:

- Sub-lease the spectrum
- Opportunistically use the spectrum

Spectrum Subleasing
System Architecture

HotMobile 2006

- Regulatory bodies
  - FCC, Ofcom
- Primary user
  - Owns the spectrum (through a long-term lease)
- Secondary user
  - Need limited, opportunistic, access to spectrum
- Spectrum brokers
  - Aggregates unused spectrum and makes it available to secondary users



Microsoft Research

Time Bounded Spectrum Leases

Good Idea?

- Generate revenue for spectrum owners
- Allow end users to communicate legally
- Future-Proof: Allow innovations in communication technologies
  - Adapts to RF hardware capabilities and standards

Microsoft Research

Implications

Properties:

- **High utilization**
  - Under-utilized spectrum in licensed bands must be efficiently used by Secondaries
- **Flexible usage**
  - No restriction on what PHY/MAC techniques Secondaries should use
- **Fair usage**
  - Primaries should be confident that Scondaries do not overstay their privileges

Challenges:

- **Real-time spectrum allocations and revocation**
  - DSCP: DHCP-equivalent protocol for spectrum
- **Efficient algorithms for spectrum utilization**
  - Need to mitigate spectrum fragmentation
- **In-band enforcement of secondary spectrum use**
  - Hardware-based implementation for FCC certification

Spectrum Allocation

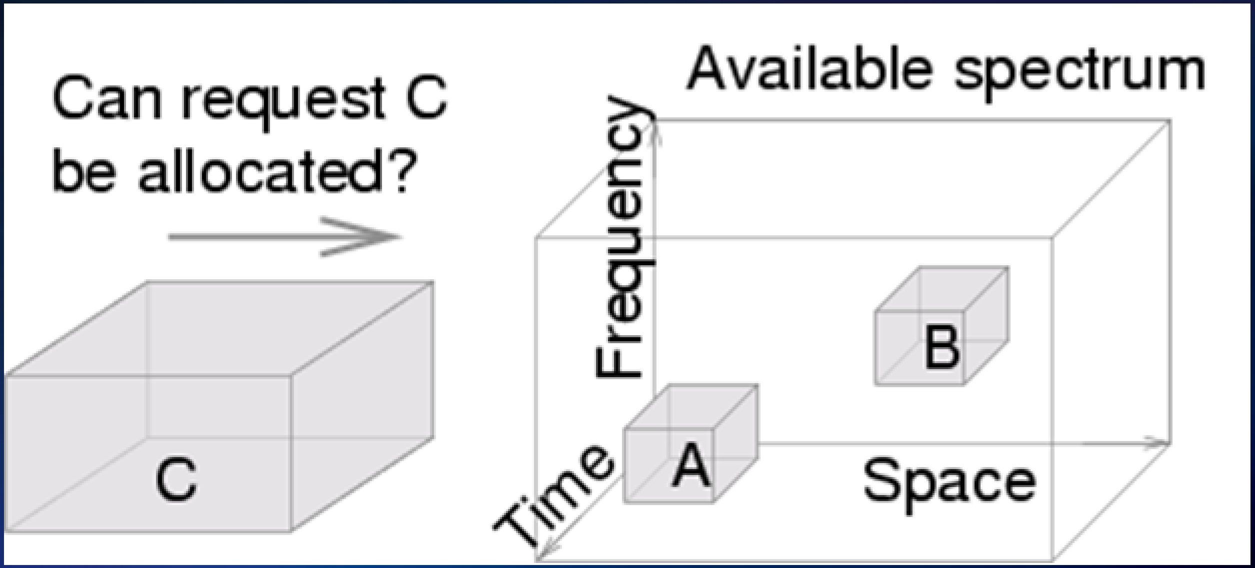
HotMobile 2006

What are the optimization objectives?

for spectrum owner (airline pricing model)
for lease owner (choosing the best price-performance point)

How to avoid fragmentation?

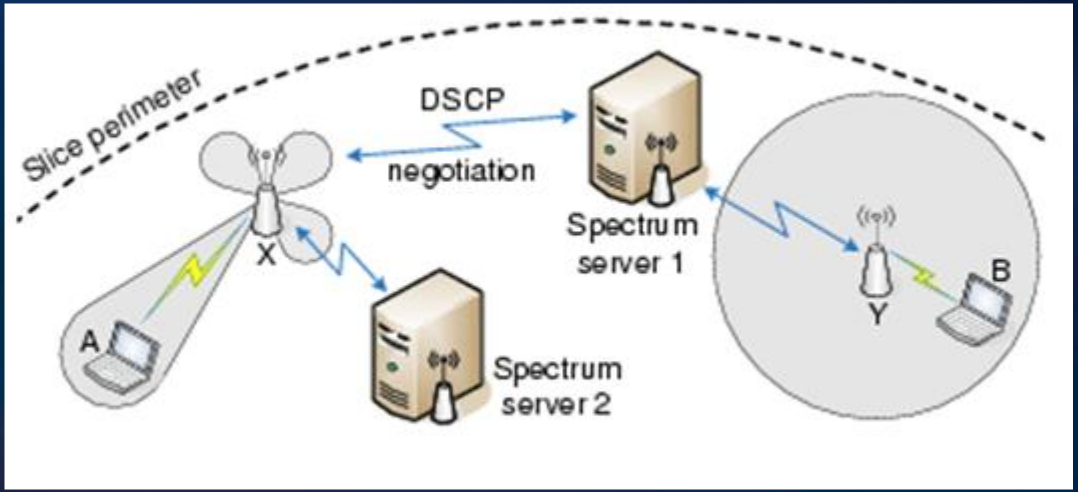
- Extend memory and disk fragmentation mitigation algorithms
- Differential pricing - Penalize requests that fragment more

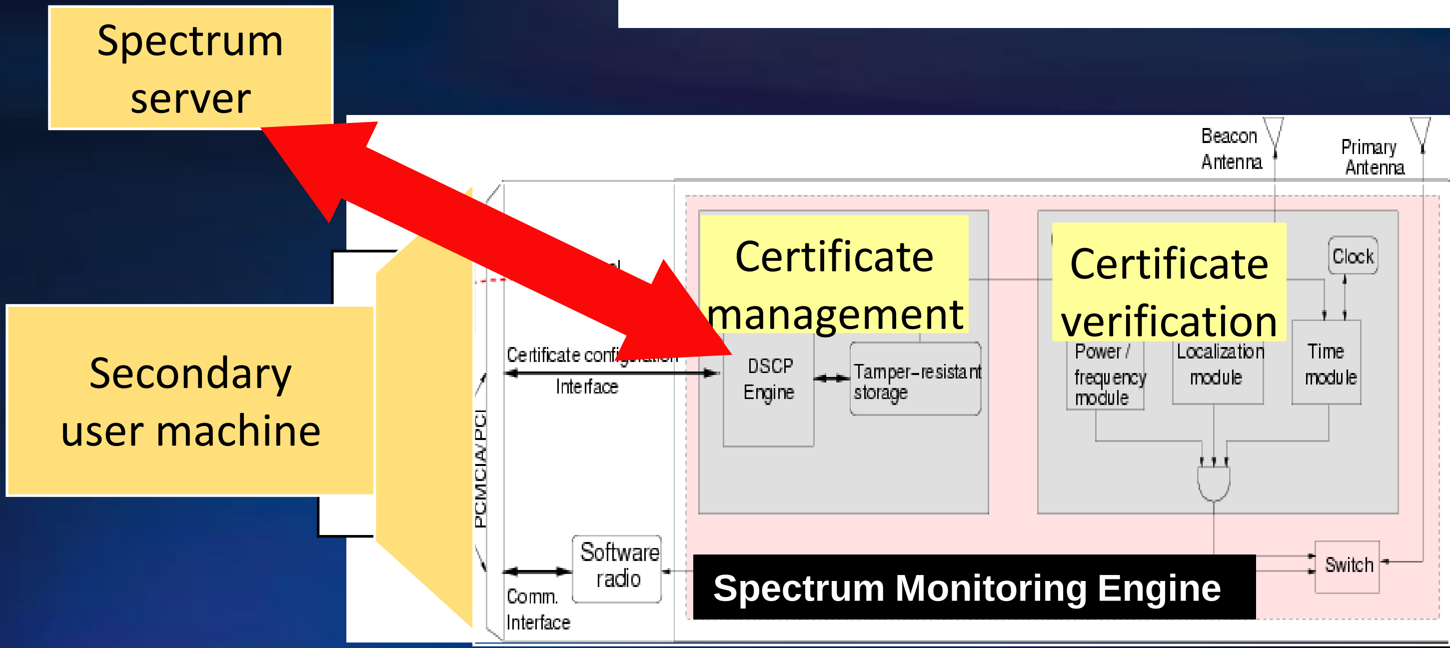


Microsoft Research

Monitoring & Enforcement

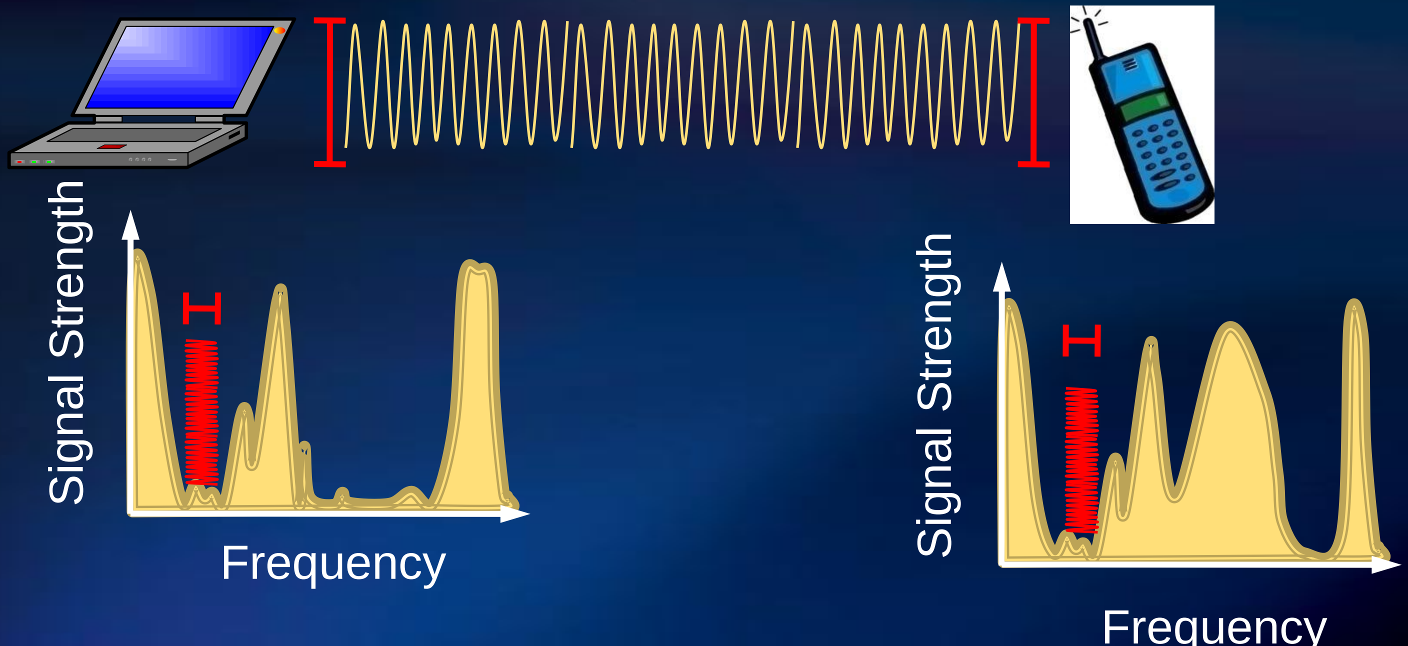
Power Fence





Opportunistic Use

- Dynamically identify currently unused portions of the spectrum
- Configure radio to operate in free spectrum band
  - Take smart (cognitive?) decisions how to share the spectrum



Microsoft Research

Spectrum Management

DySpan 2007

Opportunity for Clean-Slate Design

New Hardware Capabilities

White Space

New Protocols and Algorithms

Clean Slate Design

- Reconfigurable transceivers
- Multiple-radios
- Fast scanners

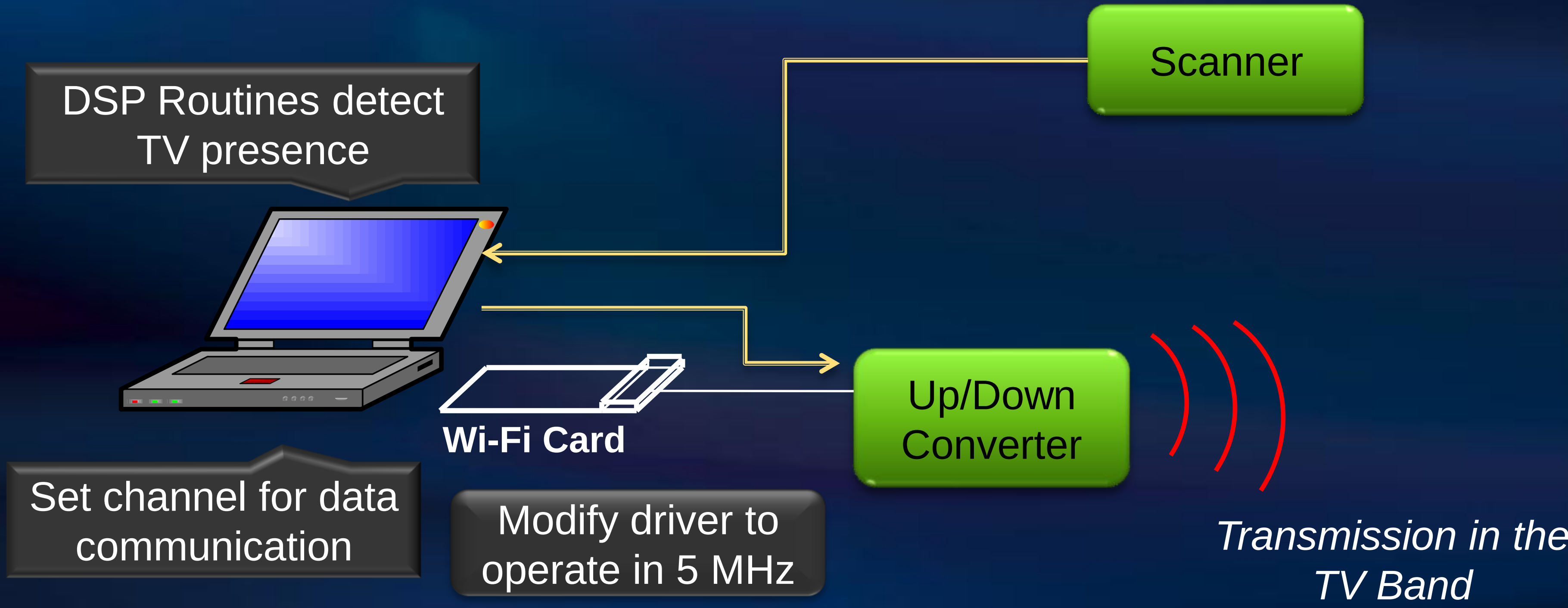
- Time-Spectrum Block Allocation
- Adjusting channel-widths
- Dynamic, adaptive, local,…

Innovation

Microsoft Research

Hardware

LANMAN 2007



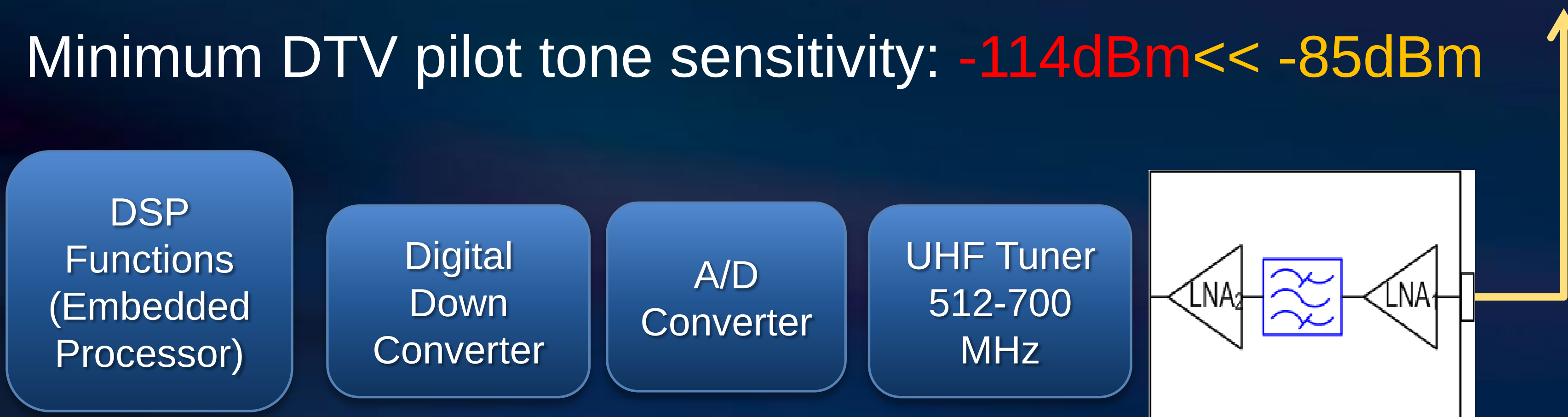
Primary Components

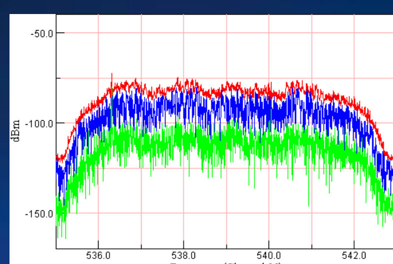
- Wideband spectrum scanner
- Tunable UHF half-duplex transceiver
- Network processor

Microsoft Research

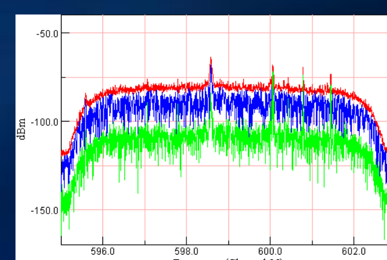
Wideband Spectrum Scanner

- Discover vacant TV channels in 512-698 MHz
- Scan Frame Bandwidth: 8 MHz
- Scan Frame FFT size: 2048 MHz
- Minimum DTV pilot tone sensitivity: -114dBm<< -85dBm





DTV



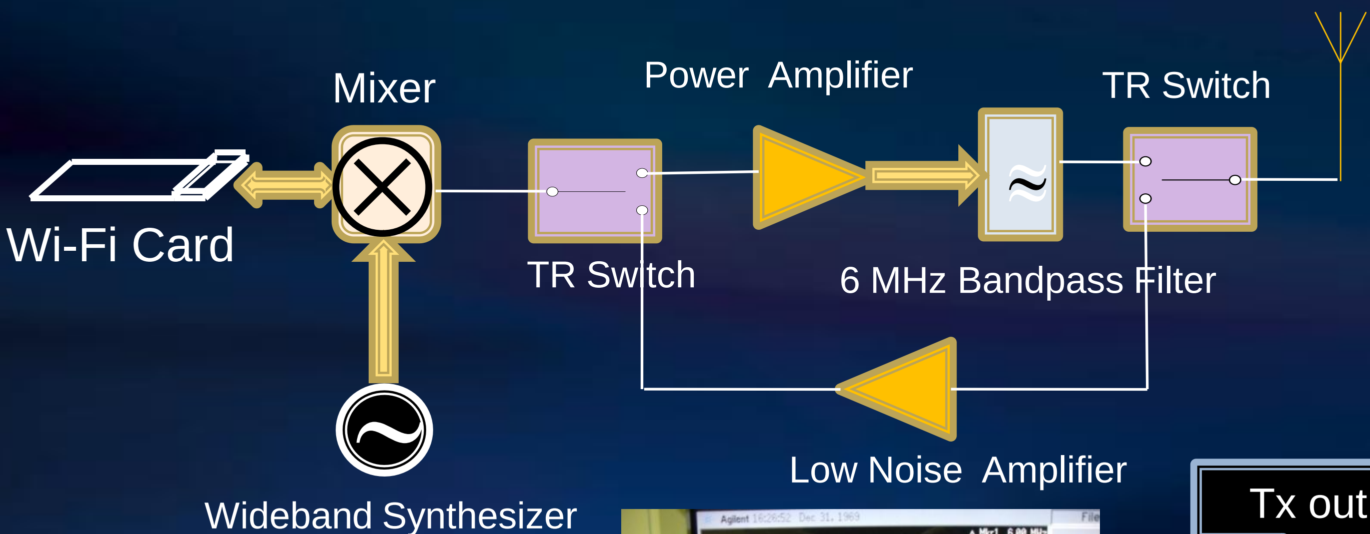
NTS
C

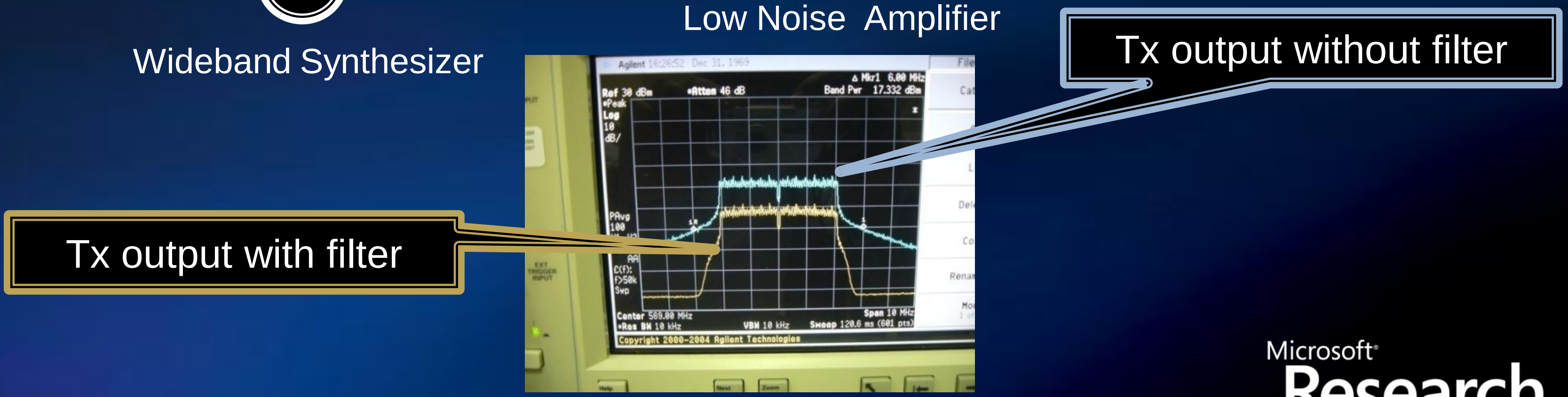
Performance: TV Signal Detection

Microsoft Research

UHF Translator

- Uses 2.4 GHz 802.11g for primary signal generation
- Shapes OFDM signal to fit in 6 MHz TV Band
- 100 mw of Tx power with 30 dB TPC





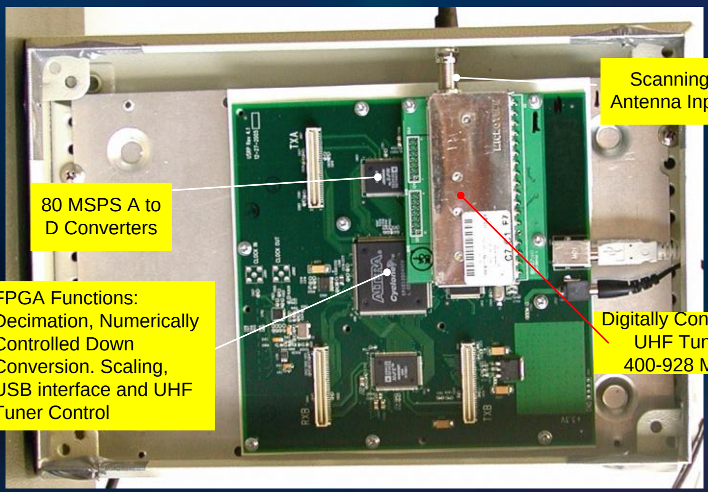
Performance: UHF Translator Output

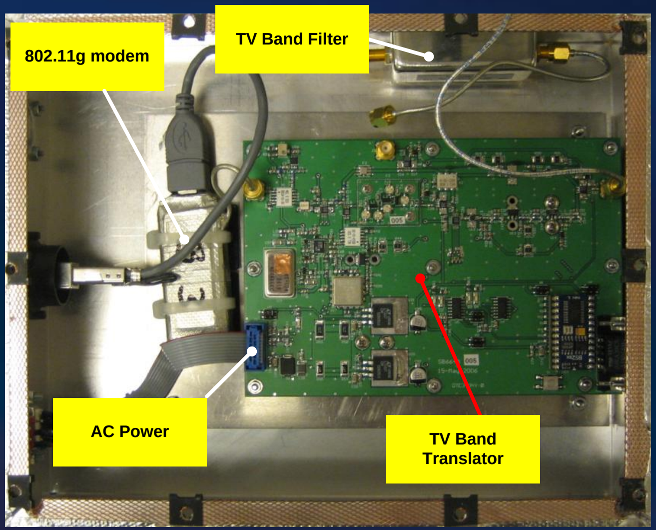
Network Processor

- Integrates scanner with UHF translator
  - Determines white spaces by processing scanner output
  - Sets appropriate parameters at the UHF translator
- Processes samples from scanner
  - Applies 2048 FFT on scanner samples
  - Matches feature templates for digital TV, analog NTSC signals, etc.
- Controls parameters of the UHF translator
  - Channel frequency, Tx power

Note: When not scanning, receive on the 900 ISM band. Tunable transceiver for 400—928MHz

Prototype

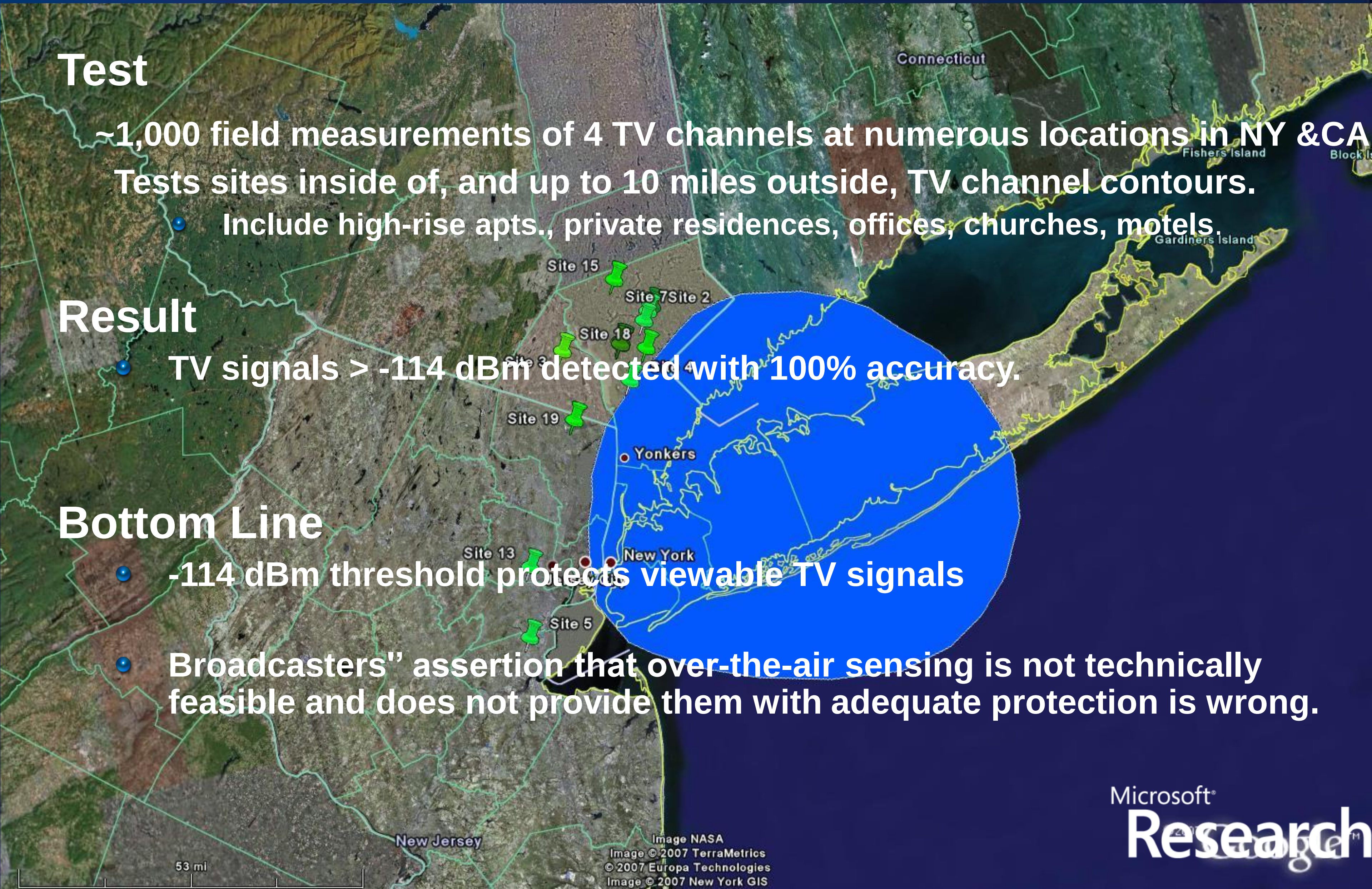




Microsoft's White Space device

Microsoft Research

Microsoft - Phillips Field Study Summary



Test

~1,000 field measurements of 4 TV channels at numerous locations in NY &CA

Tests sites inside of, and up to 10 miles outside, TV channel contours.

- Include high-rise apts., private residences, offices, churches, motels.

Result

- TV signals > -114 dBm detected with 100% accuracy.

Bottom Line

- -114 dBm threshold protects viewable TV signals
- Broadcasters" assertion that over-the-air sensing is not technically feasible and does not provide them with adequate protection is wrong.

Microsoft Research

Networking Challenges

MobiHoc 2007

The KNOWS Project

How should nodes connect?

Which spectrum-band should two cognitive radios use for transmission?

1. Channel-width…?
2. Frequency…?
3. Duration…?

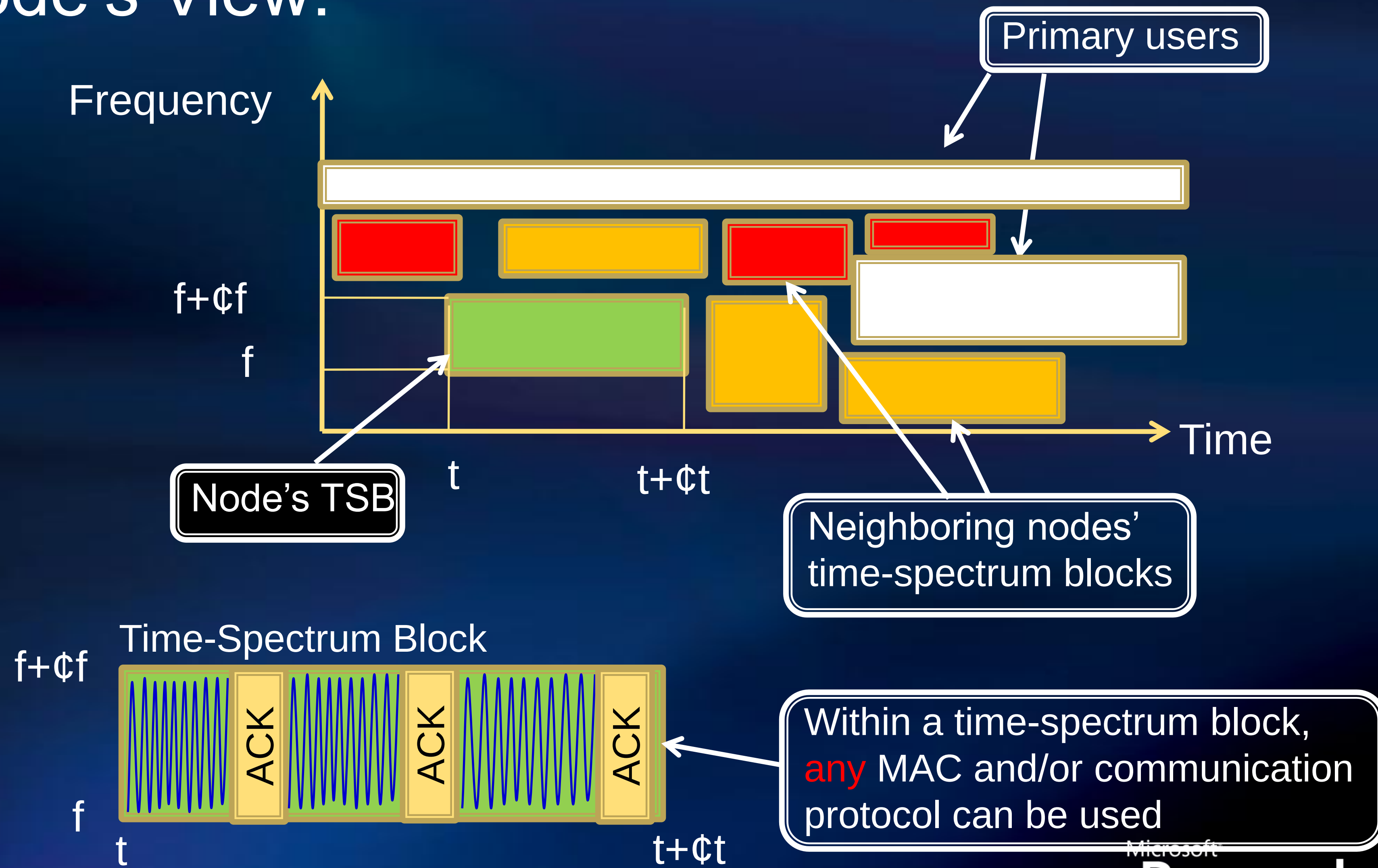
Need analysis tools to reason about throughput & overall spectrum utilization

What protocol should we use for efficiently allocating Time-spectrum blocks in the space?

Microsoft Research

Time Spectrum Block (TSB)

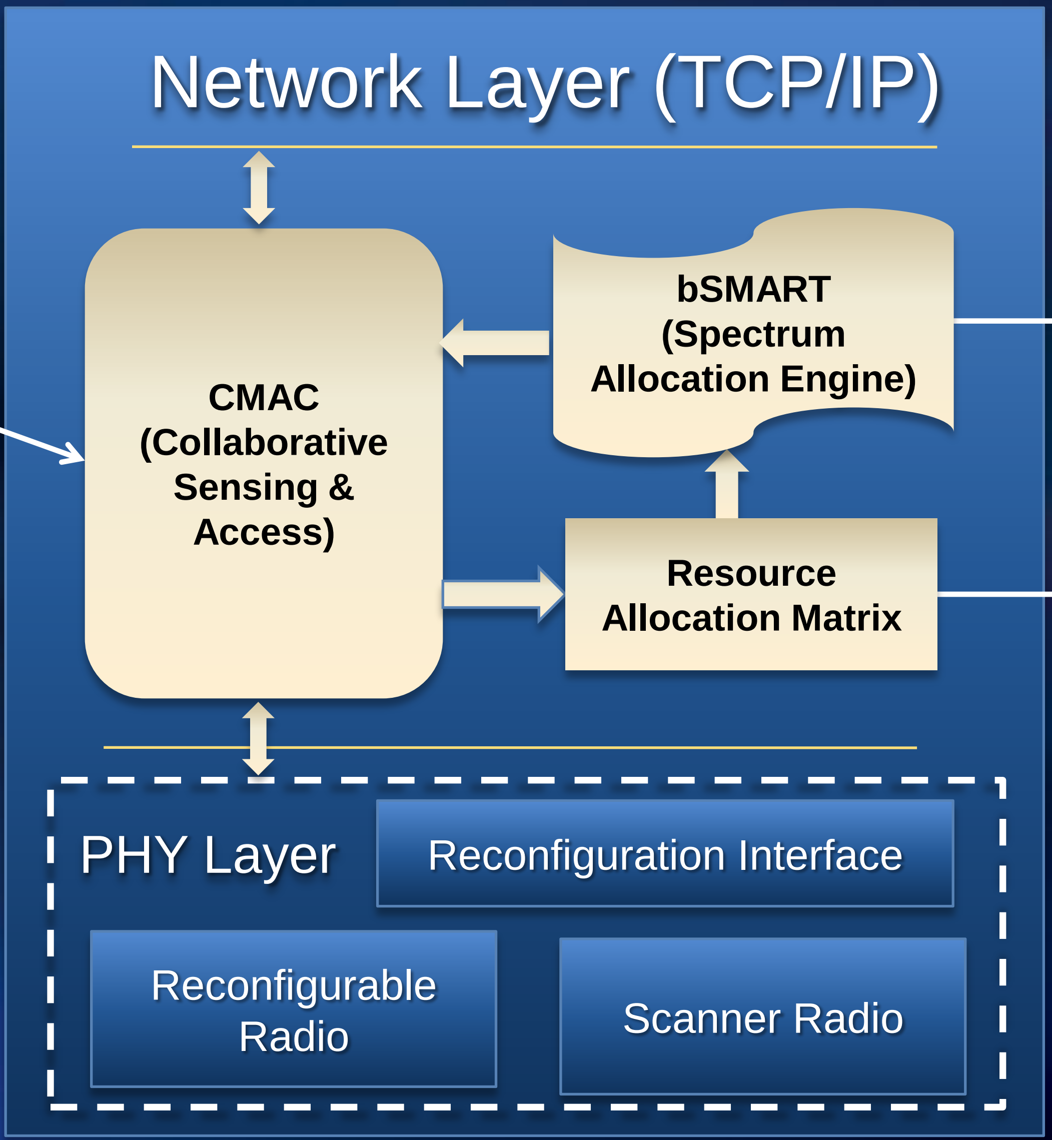
Node's View:



The KNOWS Stack

DySpan 2007

Negotiates location of TSB using RTS-CTS-DTS mechanism



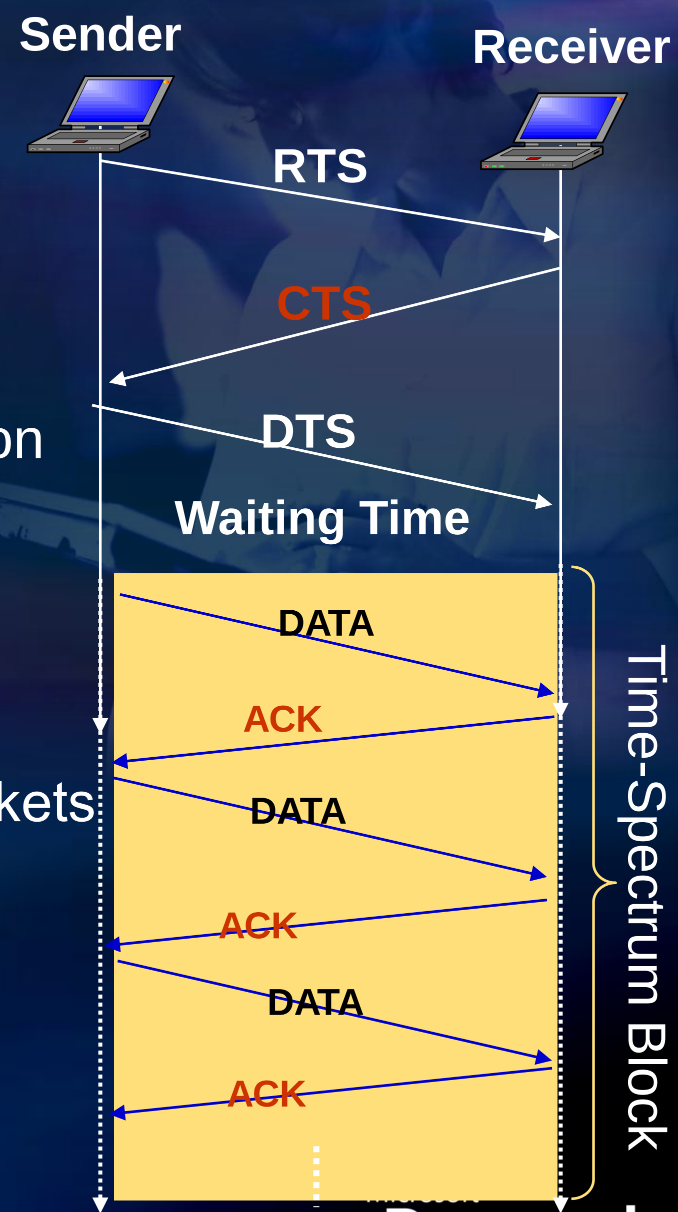
Determines size of TSB to map app. req. to available spectrum

Keeps track of neighbors TSB

Microsoft Research

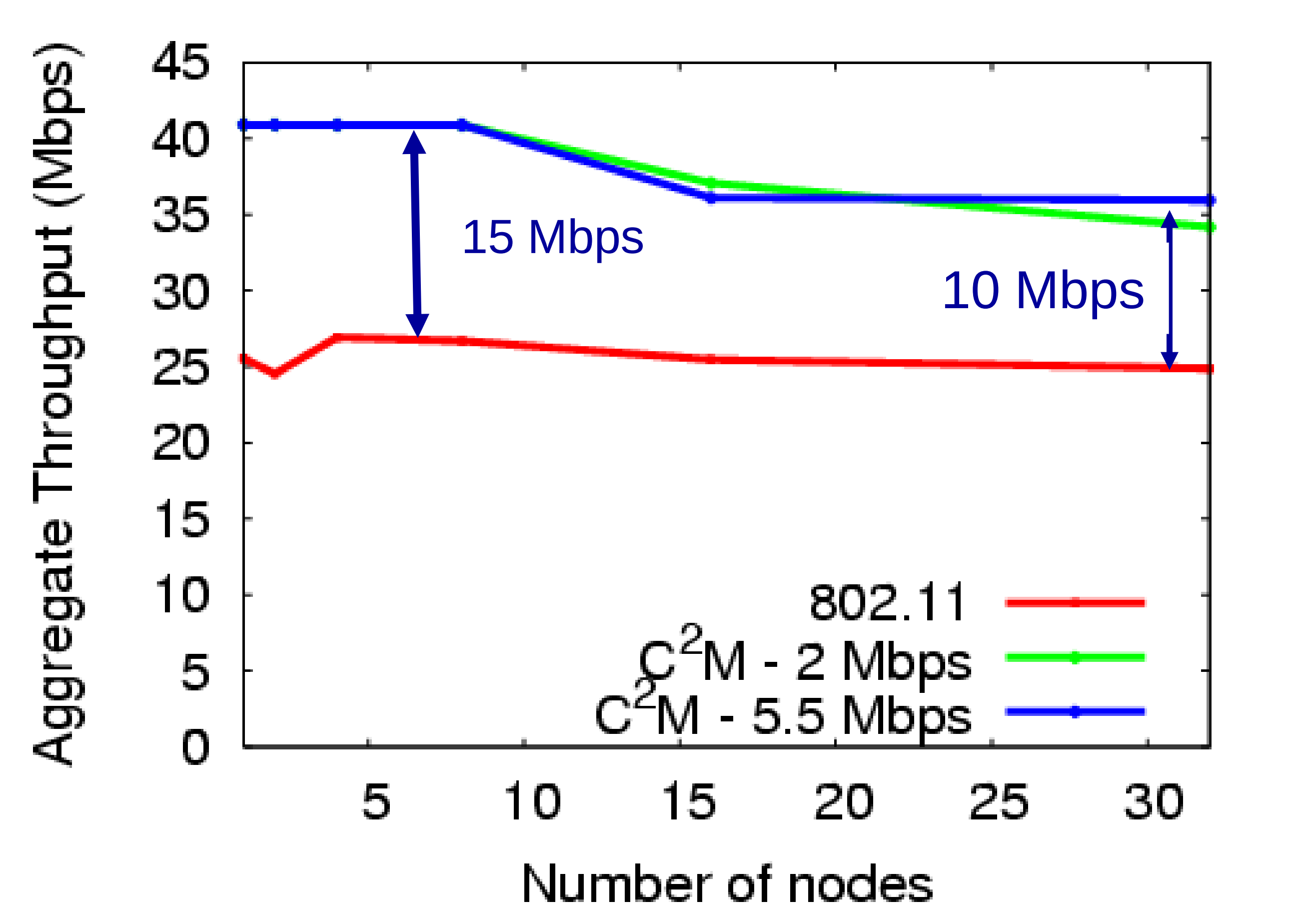
Collaborative Sensing & Access

- Common Control Channel (CCC) for rendezvous
  - Contend for spectrum access
  - Reserve a TSB
  - Exchange spectrum availability information (use scanner to listen to CCC while transmitting)
- Maintain a list of reserved TSBs
  - Overhear neighboring node's control packets
  - Generate 2D view of TSB reservations
- Distributed, adaptive, localized reconfiguration



Splitting Control and Data

Broadband 2005

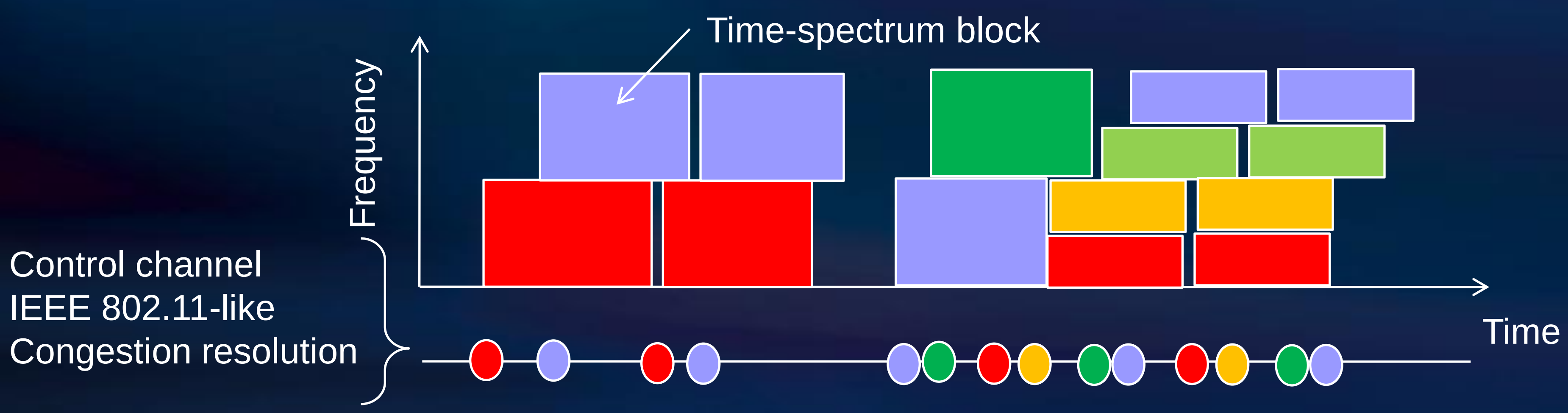


Throughput improvement more than that with data striping

Microsoft Research

Resource Allocation Matrix

Nodes record info for reserved time-spectrum blocks



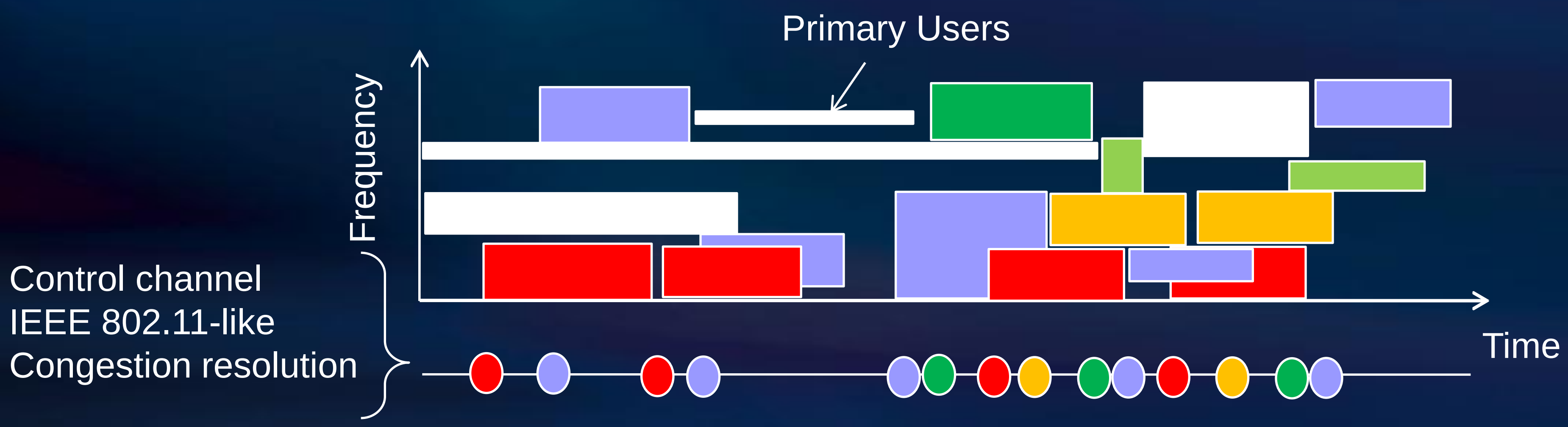
The above illustrates an ideal scenario

1) Existence of Primary Users can cause fragmentation

2) In multi-hop → neighbors have different views

Microsoft Research

Resource Allocation Matrix



Nodes record info for reserved time-spectrum blocks

b-SMART

Distributed SpectruM Allocation oveR whiTe spaces

- Which TSB should be reserved…?
  - How long…? How wide…?
- Design Principles

1. Try to assign each flow blocks of bandwidth B/N

B: Total available spectrum
N: Number of disjoint flows

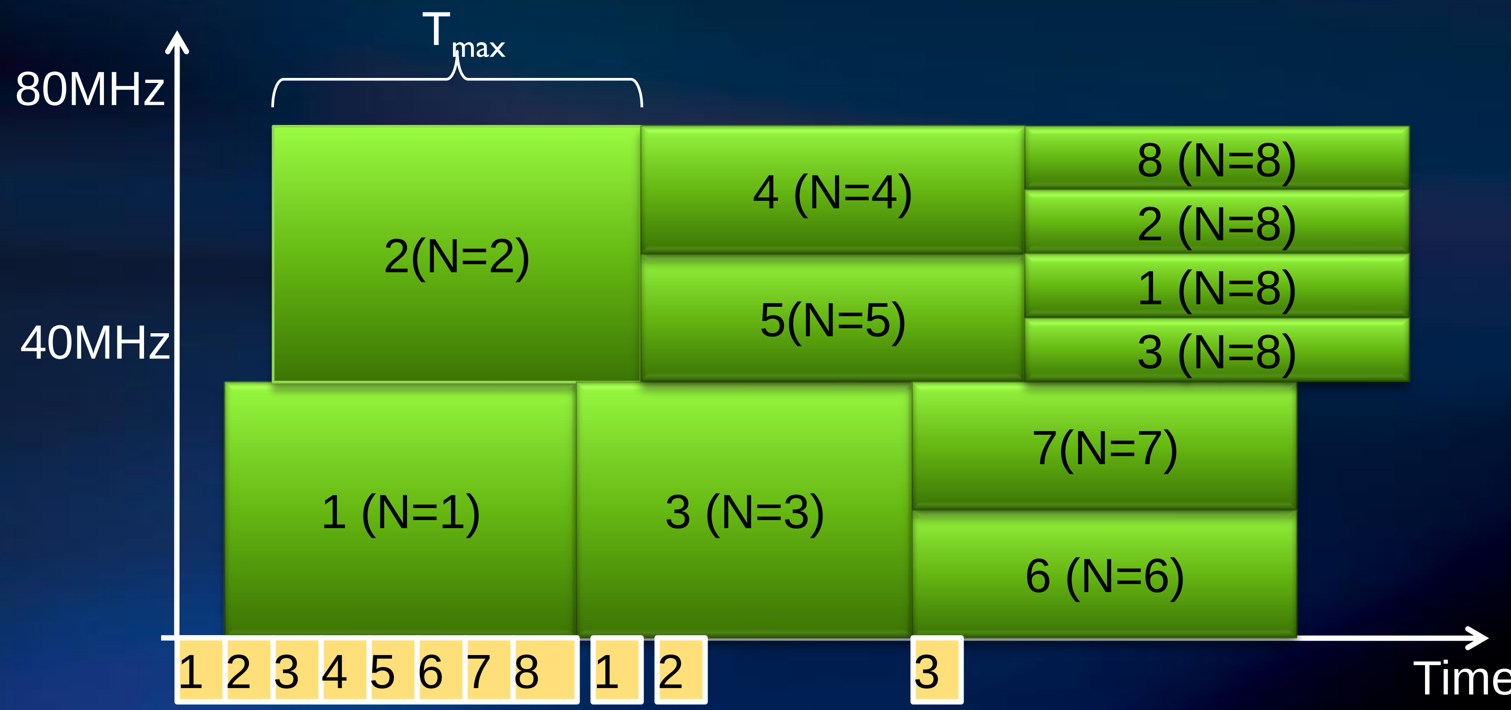
2. Choose optimal transmission duration ¢t

Long blocks: Higher delay

Short blocks: More congestion on control channel

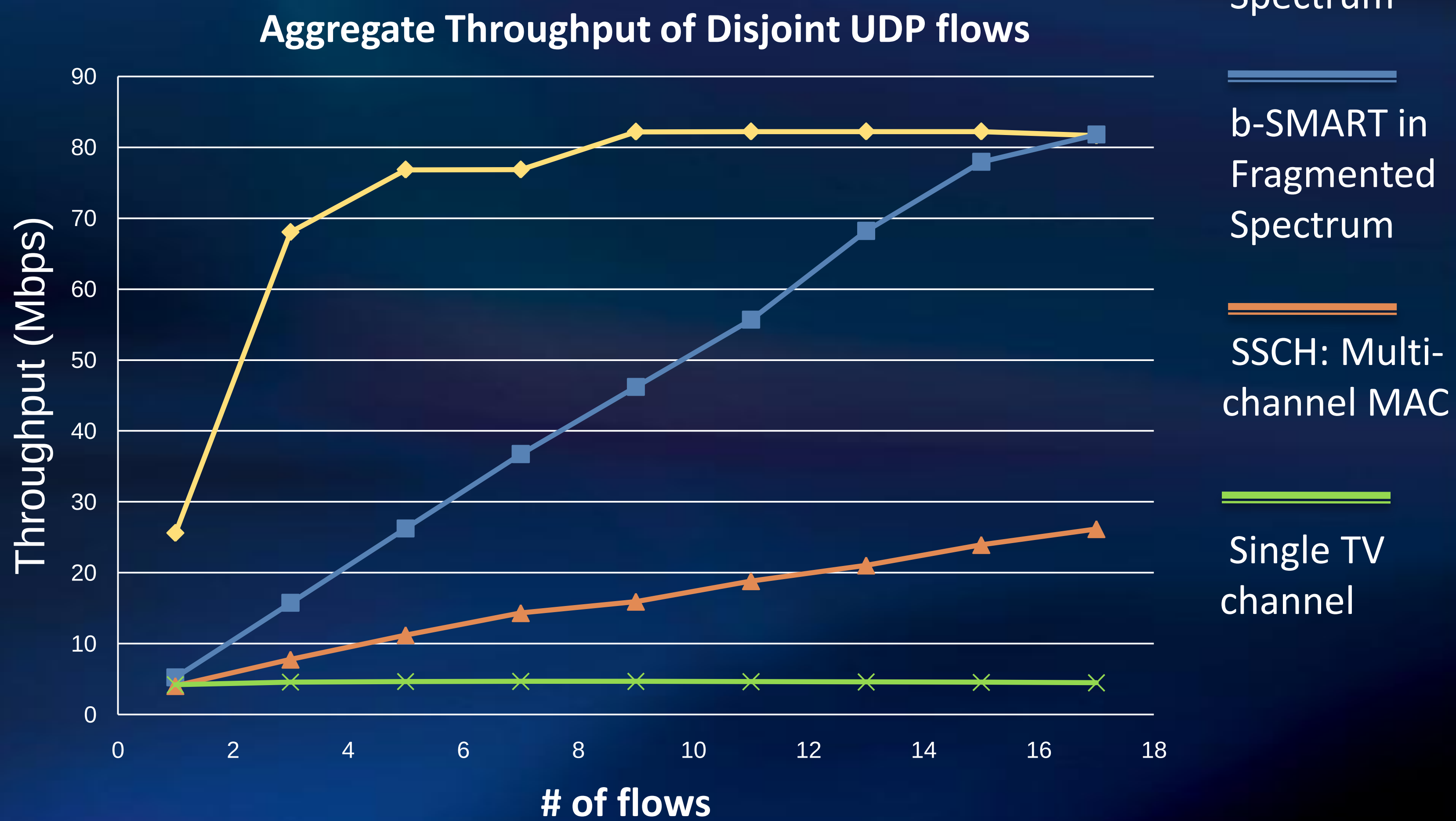
Example

- Number of valid reservations in NAM → estimate for N
- Case study: 8 backlogged single-hop flows



Does it Help?

KNOWS Performance



KNOWS significantly outperforms systems based on fixed allocations!

Microsoft Research

Challenges

Practical Challenges:

- Heterogeneity in spectrum availability
  - Range mismatch
  - Fragmentation
- Protocol must
  - Allow opportunistic use
  - Be eficient (distributed)
  - Be self regulating (Fair)
  - Be Load-aware

Modeling Challenges:

- In single/multi-channel systems,
  → graph coloring problem.
- With contiguous channels of variable channel-width, coloring is not an appropriate model!

  → Need new models!

Theoretical Challenges:

- New problem space
- Tools…? Efficient algorithms…?

Build on years of knowledge we have acquired in wireless

Microsoft Research

Cognitive Wireless Networking

Research Program

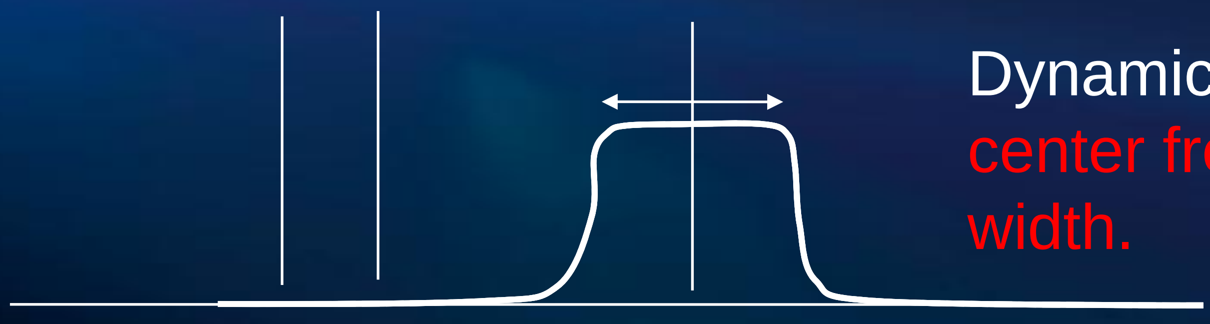
Wireless Meshes, Ubiquitous Personal Networks, Wireless Office, Wireless LANs, Vehicular networks

- Licensed Spectrum
  - White Space Networking
    - KNOWS
  - Management & Policy
    - SPARK
- Unlicensed Spectrum
  - Redesigning ISM Networks
    - CogWiFi
  - Management & Policy
    - Etiquettes
  - SDR-Wireless

Microsoft Research

Varying Channel Width – A Good Idea?

SIGCOMM 2008



Dynamically adjust center frequency and width.

Lower widths increase range while consuming less power!

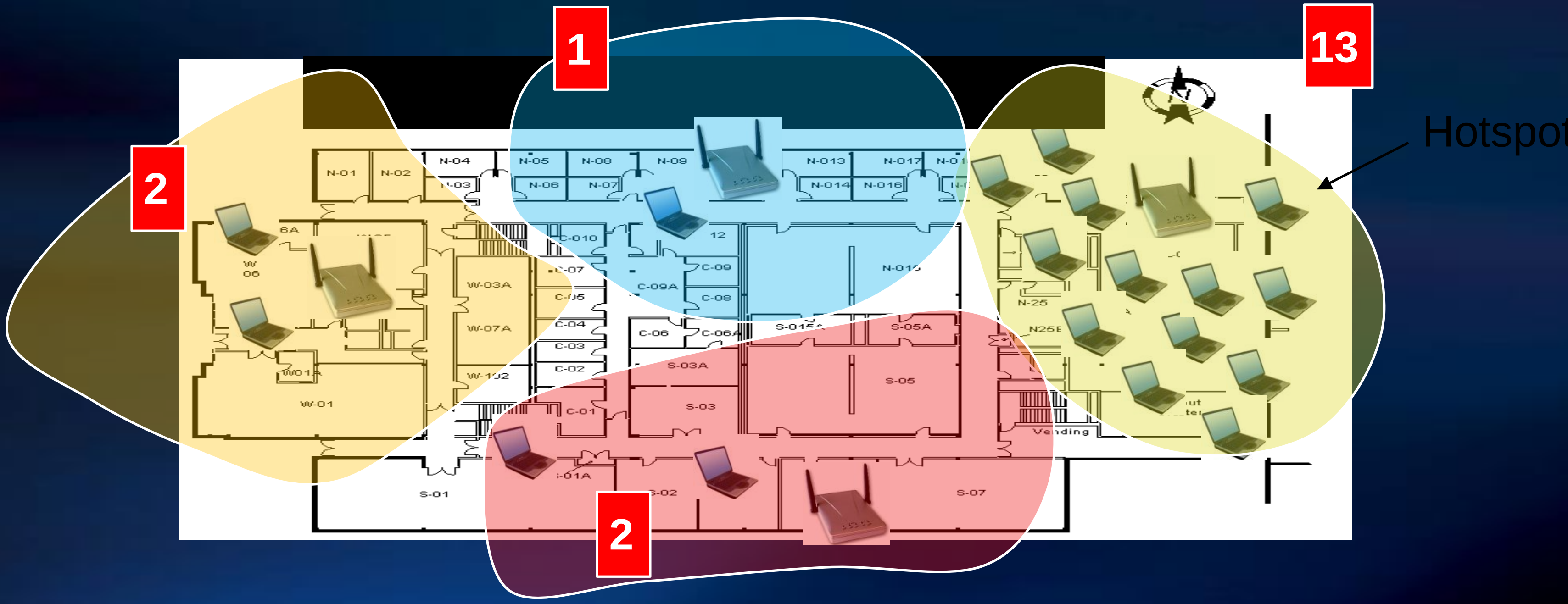
	5MHz	10MHz	20MHz	40MHz
Send	1.92	1.98	2.05	2.17
Idle	1.00	1.11	1.25	1.41
Receive	1.01	1.13	1.27	1.49

Power Drain

Microsoft Research

Application: Load Balancing in W-LANs

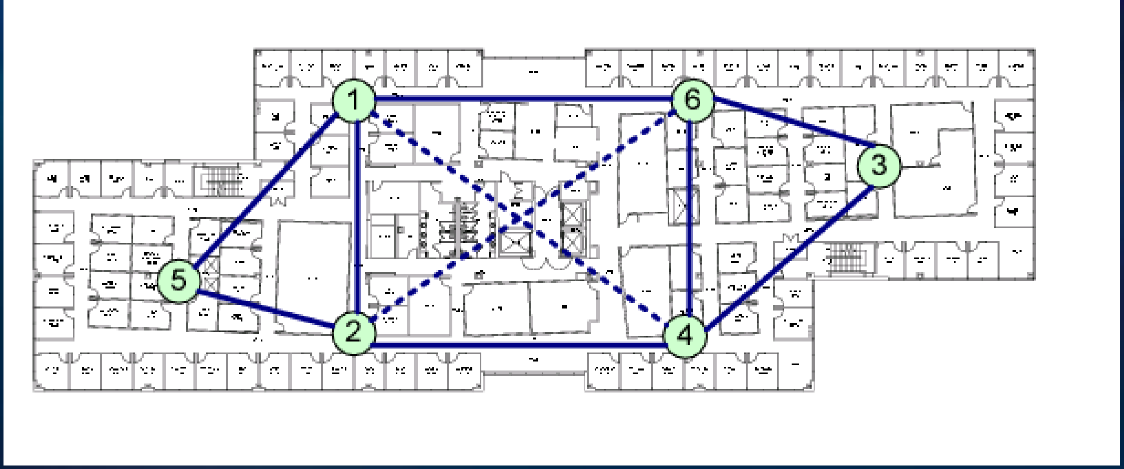
Adaptively assign wider channels to APs with high load

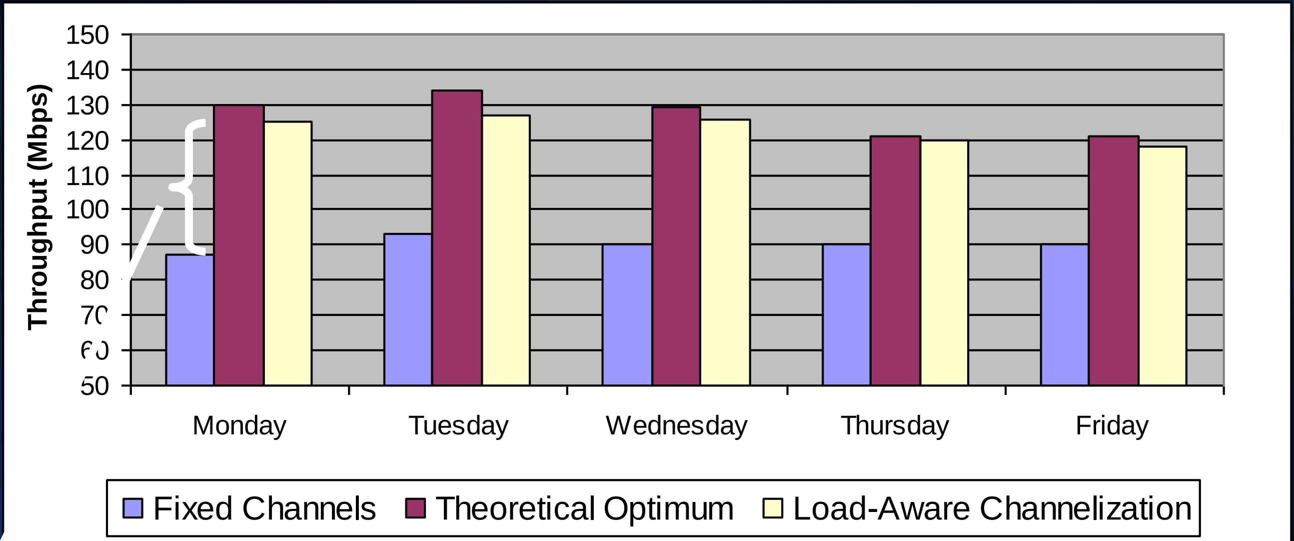


- Significantly better throughput & fairness
- Can achieve close to theoretically optimal performance

Does this help?

DySpan 2007





Significant increase in overall throughput

Microsoft Research

Looking Ahead

TI SDR SFF

- Re-visit high impact scenarios:
  - Mesh networking, all-wireless office, location-awareness,..
- Develop new scenarios with Intention Aware Networking
  - UPN, ZuneNet, Guardian Phone,..
- Push hard on the hardware-software boundary and revisit important designs

Trends Impacting Design

- Processor advancement (m-core)
- Improved Connectivity Options
  - Agile Radios
  - Software Defined Radios
  - Multi-radio platforms
  - 60 GHz, multi-gigabir connectivity
- Miniaturization
- Policy Improvements
  - Allow re-use of licensed spectrum

Microsoft Research

http://research.microsoft.com/conferences/CogNetSummit/

Microsoft Research

Cognitive Wireless Networking Summit 2008

"From thought to practice"

June 5 - 6, 2008 ✣ Salish Lodge & Spa ✣ Snoqualmie, WA

Academia

- Suman Banerjee University of Wisconsin, Madison
- Charles Bostian Virginia Tech
- Bob Brodersen University of California, Berkeley
- Joseph Evans The University of Kansas
- Andrea Goldsmith Stanford University
- Dirk Grunwald University of Colorado, Boulder
- Carl Gunter University of Illinois at Urbana-Champaign (UIUC)
- Dina Katabi Massachusetts Institute of Technology (MIT)
- Nick Laneman University of Notre Dame
- Petri Mahonen University of Aachen, Germany
- Dipankar Raychaudhuri Rutgers University
- Ashu Sabharwal Rice University
- Claudio da Silva Virgina Tech
- Dan Stancil Carnegie Mellon University (CMU)
- Vahid Tarokh Harvard University
- David Tse University of California, Berkeley
- David Wetherall University of Washington/Intel Research
- Heather Zheng University of California, Santa Barbara

Industry/Government

- Milind Buddhikot Alcatel-Lucent Bell Labs
- John Chapin Vanu
- Karen Haigh BBN Technologies
- Preston Marshall DARPA
- Haiyun Tang Adaptrum

Sample Presentations

- Four Years of "Software Radio" and Applications
  Building Cognitive Radios
- Stealing from an ongoing flow: Protocols & Prototypes
  Efficient Signal Identification using the Spectral Correlation
- Adapting Channel Widths to Improve Application Performance
- Architecture and Protocol Design for Cognitive Radio Networks
- A Networked Approach to Spectrum Sensing
- Architecture for Cognitive Networks: One Or Many,
  Network Support for Wireless Connectivity in the TV Bands
- DoS Threats for Cognitive Wireless Networks
- ADROIT: Adaptive Dynamic Radio Open-source Intelligent Team,
- Spectrum Aware Load Balancing for WLANs,
- Breaking Spectrum Gridlock via Cognitive and Cooperative Radios,
- Greedy Asynchronous Distributed Interference Avoidance
- Model-driven Optimization of Multi-hop Wireless Networks
- Collaborative Spectrum Management for Reliability and Scalability
- Cognitive Techniques and Spectrum management
- Spectrum Enforcement in a Spectrum Sharing World

Moving Forward

Revisit & Improve Regulations
Policy that stimulates innovation

Derive User & Application's Intention
Observe, model, anticipate & react

Revisit Assumptions & Designs
Push boundary between hardware & software

Cognitive Software

Vision Videos

Manufacturing Future

Healthcare Future

Microsoft Research

Thanks

http://research.microsoft.com/netres/