Wireless

New ^ Connectivity Paradigms

from 600 to 60 GHz

living in the unlicensed world

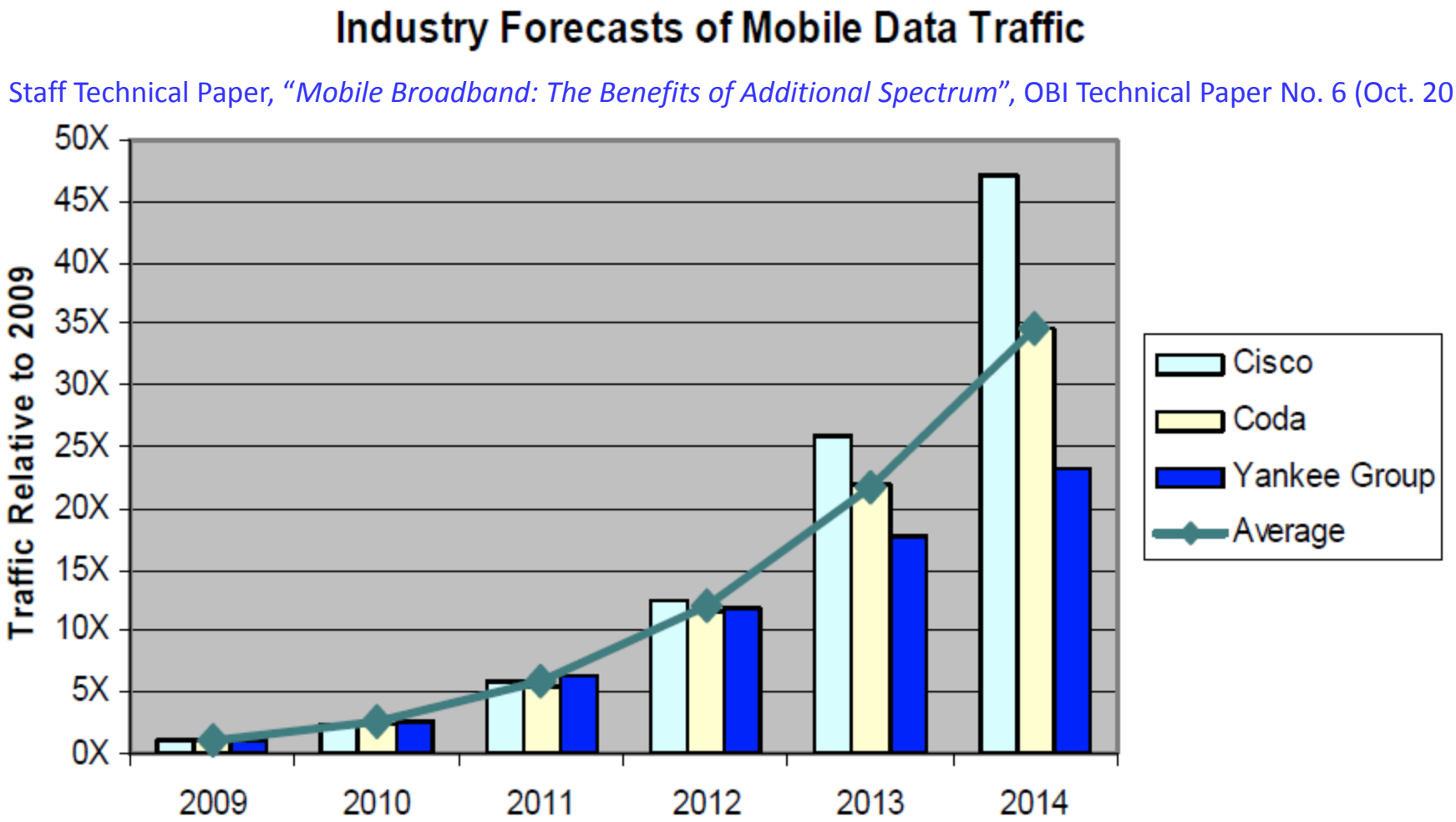
Time permitting

Victor Bahl

Mobile Computing Research Center

Microsoft Research

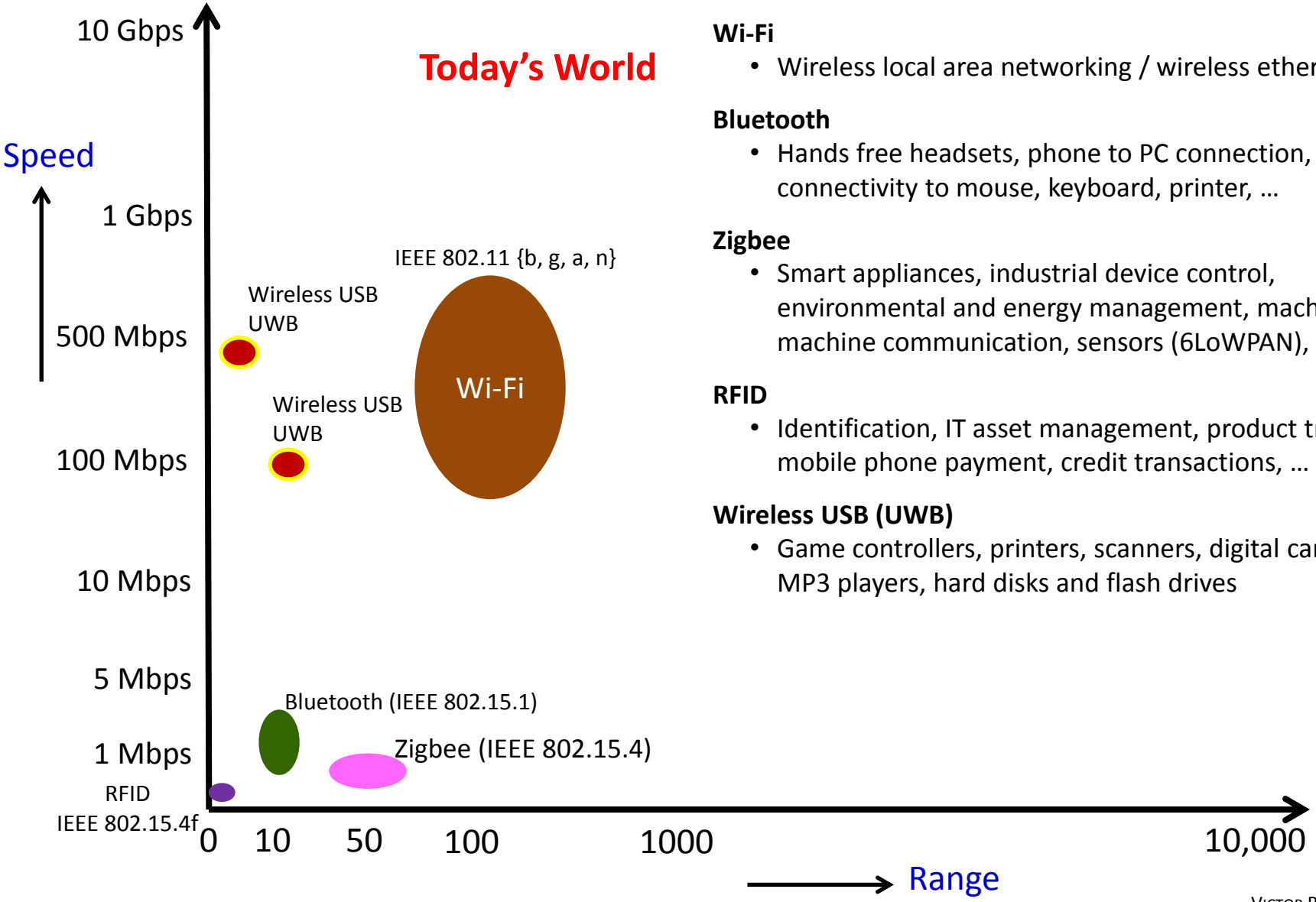
Obligatory Slide (1)



AT&T reported 106M Wi-Fi connections in 2010 Q3; versus 85M in all of 2009

AT&T's mobile data traffic has experienced a fifty-fold increase over a three year period

Connectivity Options over Unlicensed Freq.



Wi-Fi

- Wireless local area networking / wireless ethernet

Bluetooth

- Hands free headsets, phone to PC connection, ad hoc connectivity to mouse, keyboard, printer, …

Zigbee

- Smart appliances, industrial device control, environmental and energy management, machine-to-machine communication, sensors (6LoWPAN), …

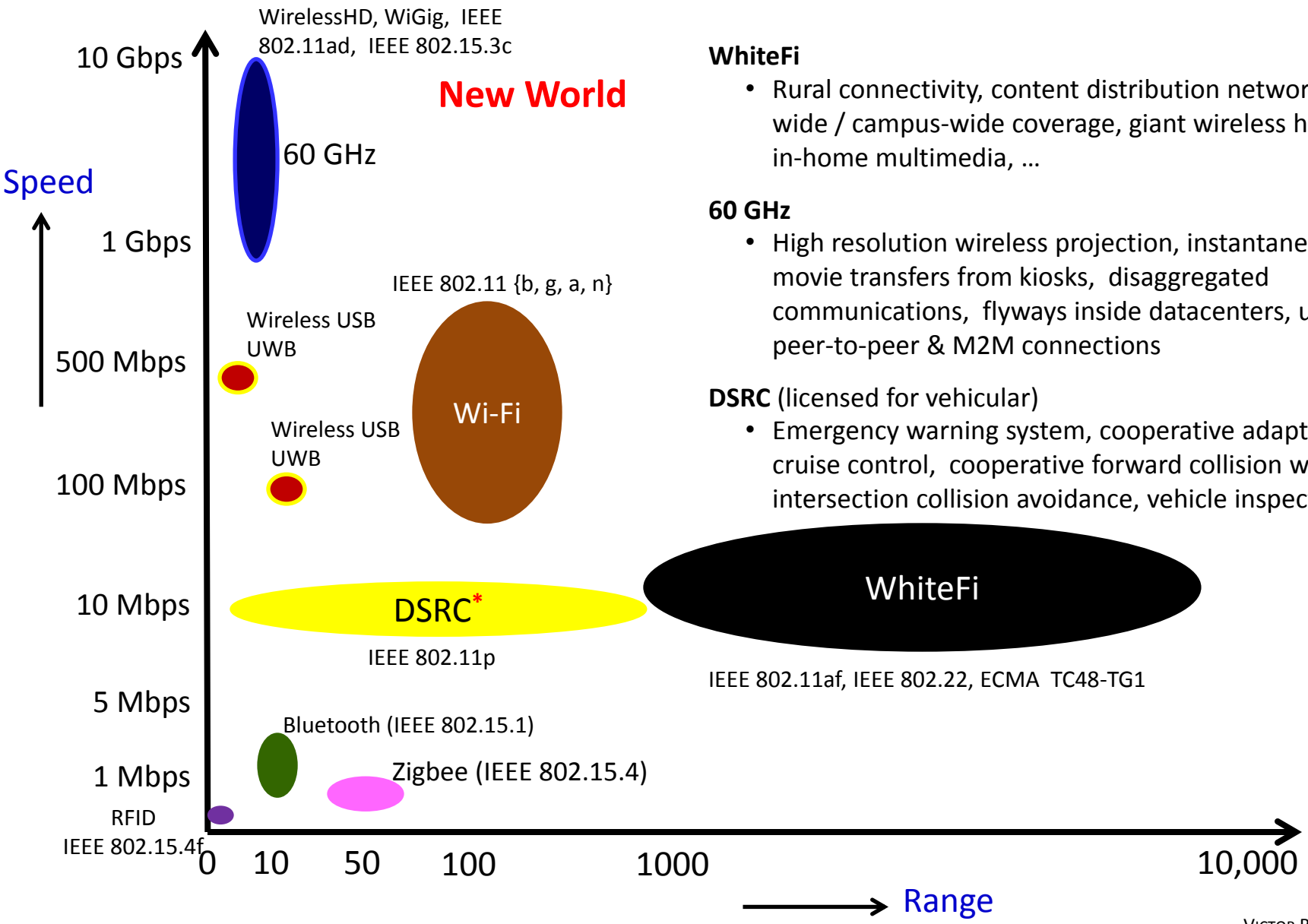
RFID

- Identification, IT asset management, product tracking, mobile phone payment, credit transactions, …

Wireless USB (UWB)

- Game controllers, printers, scanners, digital cameras, MP3 players, hard disks and flash drives

Connectivity Options over Unlicensed Freq.



WhiteFi

- Rural connectivity, content distribution networks, city-wide / campus-wide coverage, giant wireless hotspots, in-home multimedia, …

60 GHz

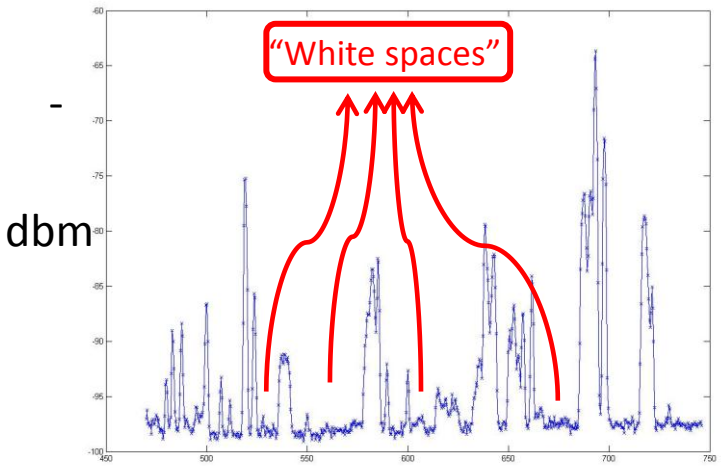
- High resolution wireless projection, instantaneous movie transfers from kiosks, disaggregated communications, flyways inside datacenters, ultra-fast peer-to-peer & M2M connections

DSRC (licensed for vehicular)

- Emergency warning system, cooperative adaptive cruise control, cooperative forward collision warning, intersection collision avoidance, vehicle inspection, ….

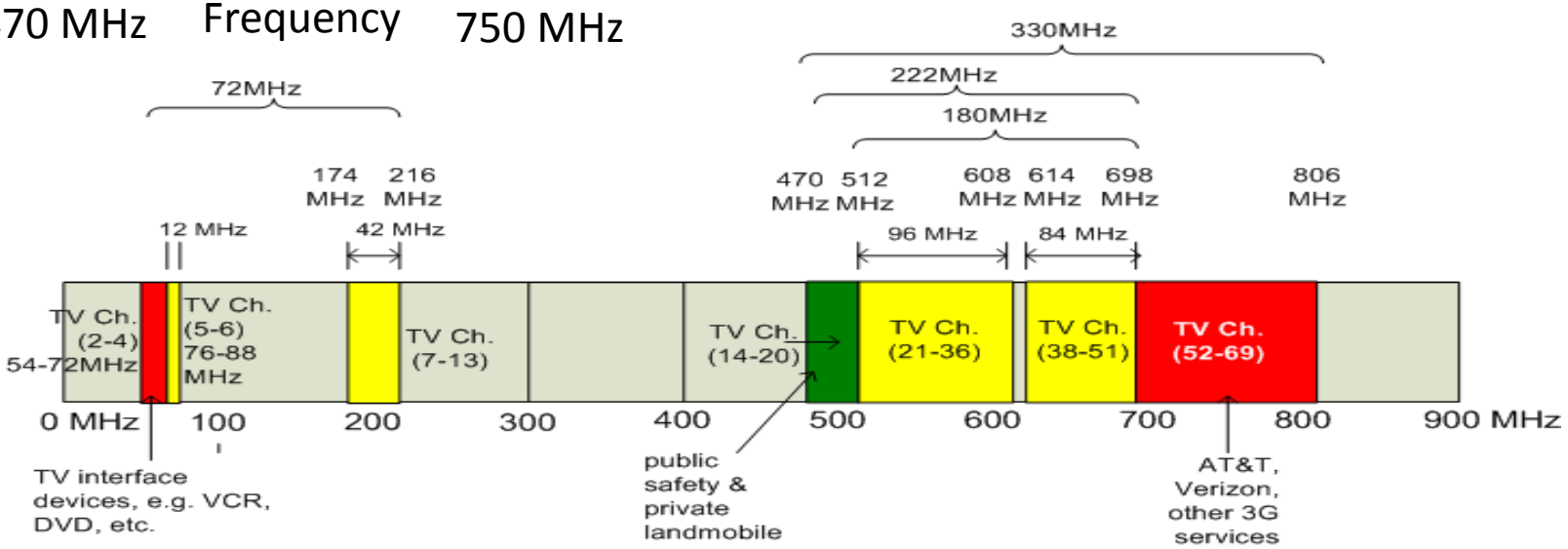
Obligatory Slide (2)

(White Spaces: Harvesting Unused Spectrum)



Properties

- Unlicensed
- Long range
- Deep penetration
- Bandwidth



How much spectrum is there?

City Hall	Available Channels	Bandwidth	Capacity Est.
Redmond	28	168 MHz	672 Mbps
Bellevue	26	156 Mhz	624 Mbps
Seattle	26	156 MHz	624 Mbps
Sammamish	28	168 MHz	672 Mbps
New York	2	12 MHz	48 Mbps
Boston	10	60 MHz	240 Mbps
San Francisco	5	30 MHz	120 Mbps
Kansas	19	114 MHz	456 Mbps
Miami	5	30 MHz	120 Mbps

Sample of bandwidth availability

Smaller cell sizes and frequency reuse is a way to manage densely populated regions with lower no. of available channels

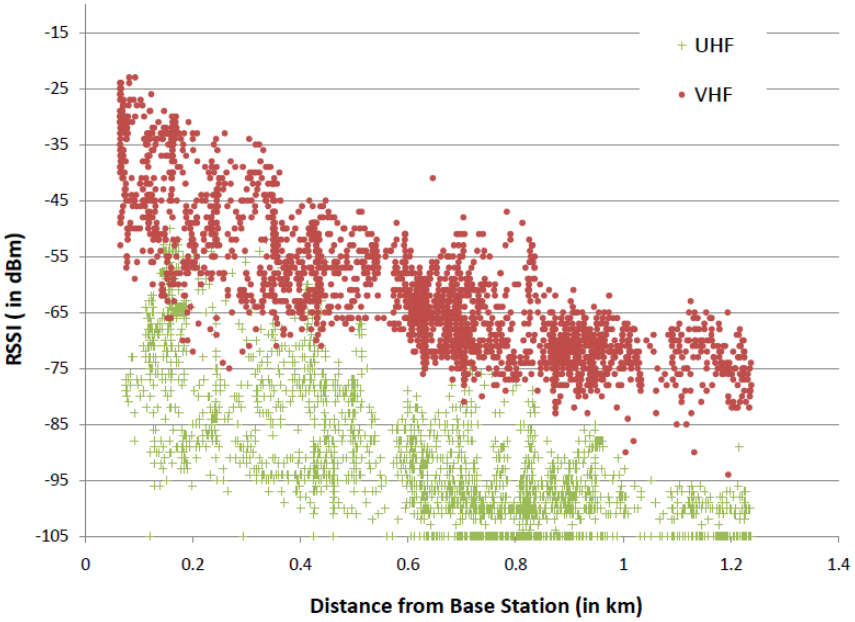
Location of incumbents

VICTOR BAHL, MICROSOFT

What range can we expect?

Microsoft Redmond Campus

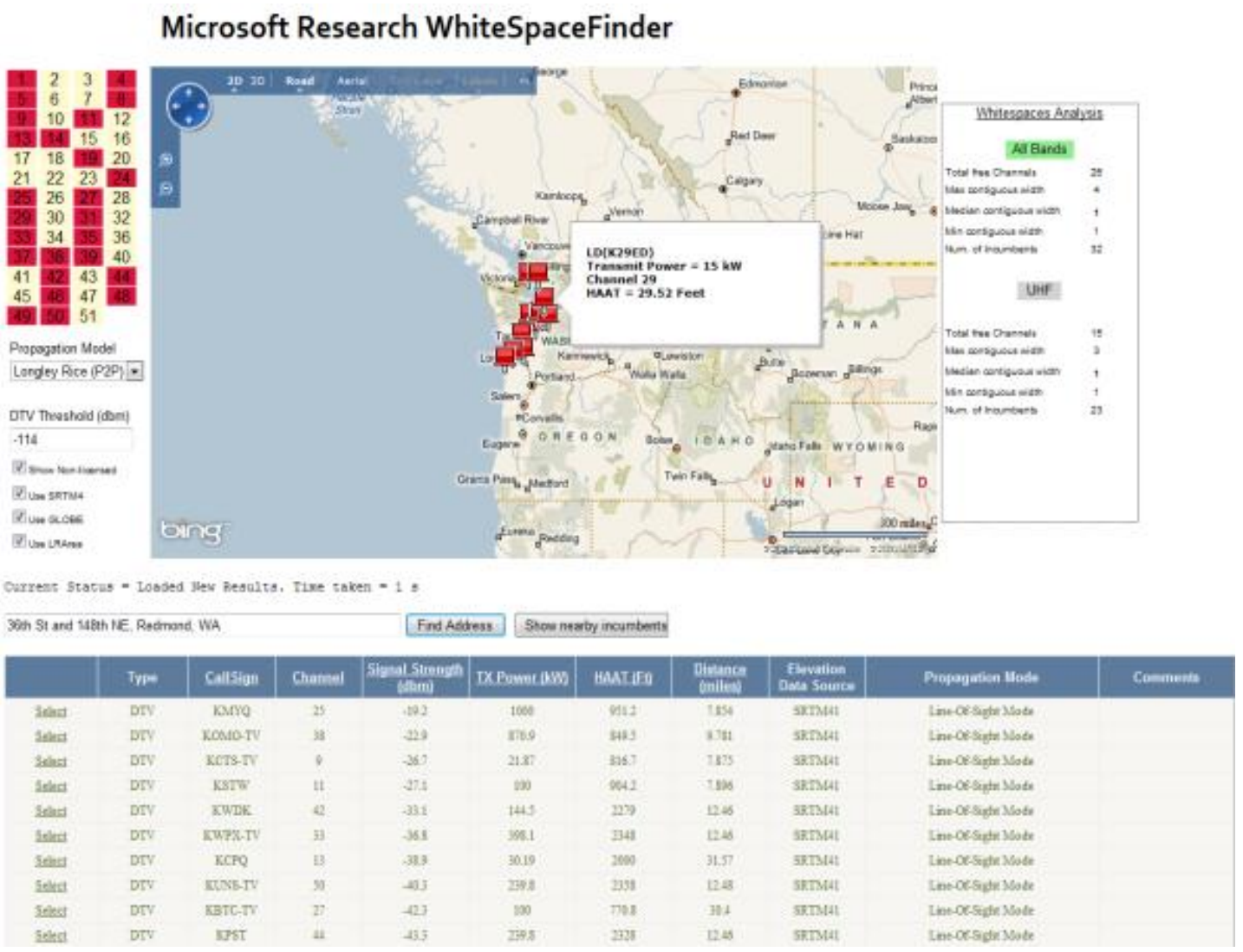
Route taken by the shuttle (0.95 miles x 0.75 miles)



Raw received power at different Distances from the transmitter

4-5 white space base stations can cover the entire Redmond campus

Database of spectrum availability



	Type	CallSign	Channel	Signal Strength (dBm)	TX Power (kW)	HAAT (Ft)	Distance (miles)	Elevation Data Source	Propagation Mode	Comments
Select	DTV	KMYQ	25	-19.2	1000	951.2	7.854	SRTM41	Line-Of-Sight Mode	
Select	DTV	KOMO-TV	38	-22.9	870.9	848.5	8.781	SRTM41	Line-Of-Sight Mode	
Select	DTV	KCTS-TV	9	-26.7	21.87	816.7	7.875	SRTM41	Line-Of-Sight Mode	
Select	DTV	KSTW	11	-27.1	100	904.2	7.896	SRTM41	Line-Of-Sight Mode	
Select	DTV	KWDK	42	-33.1	144.5	2279	12.46	SRTM41	Line-Of-Sight Mode	
Select	DTV	KWPX-TV	33	-36.8	398.1	2348	12.46	SRTM41	Line-Of-Sight Mode	
Select	DTV	KCPQ	13	-38.9	30.19	2690	31.57	SRTM41	Line-Of-Sight Mode	
Select	DTV	KUNS-TV	50	-40.3	239.8	2358	12.48	SRTM41	Line-Of-Sight Mode	
Select	DTV	KBTC-TV	27	-42.3	100	770.8	30.4	SRTM41	Line-Of-Sight Mode	
Select	DTV	KPST	44	-43.5	239.8	2328	12.46	SRTM41	Line-Of-Sight Mode	

What makes Microsoft's DB great?

TV/MIC data (FCC CDBS, others)

Location *(Latitude, Longitude)*

Terrain Data (Globe, SRTM)

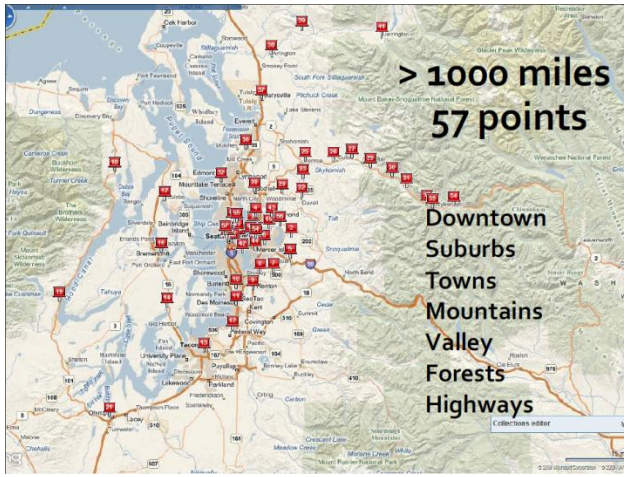
Propagation Modeling

Irregular Terrain Model (ITM)
Longley-Rice (1968)
- **20 MHz to 20 GHz**

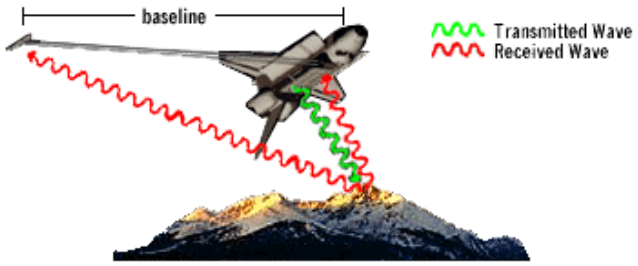
The Egli model is formally expressed as:

$$L = G_B G_M [\frac{h_B h_M}{d^2}]^2 [\frac{40}{f}]^2$$

John Egli (1957)



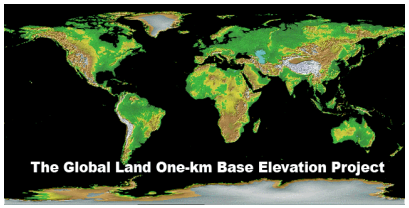
Shuttle Radar Topography Mission (SRTM)



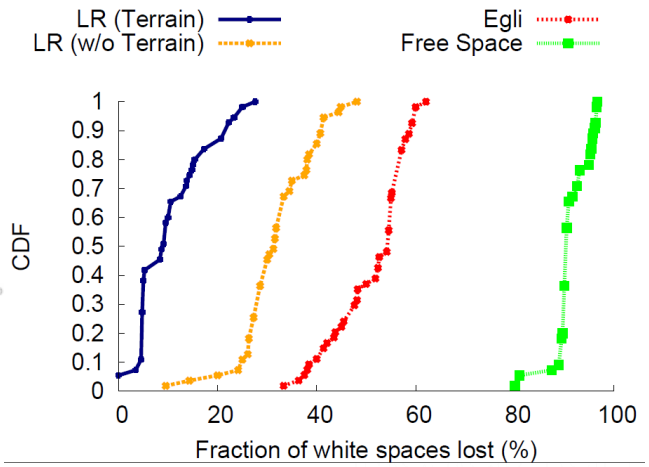
Radar signals being transmitted and recieved in the SRTM mission (image not to scale).

Joint Project between NASA and NIMA

Globe

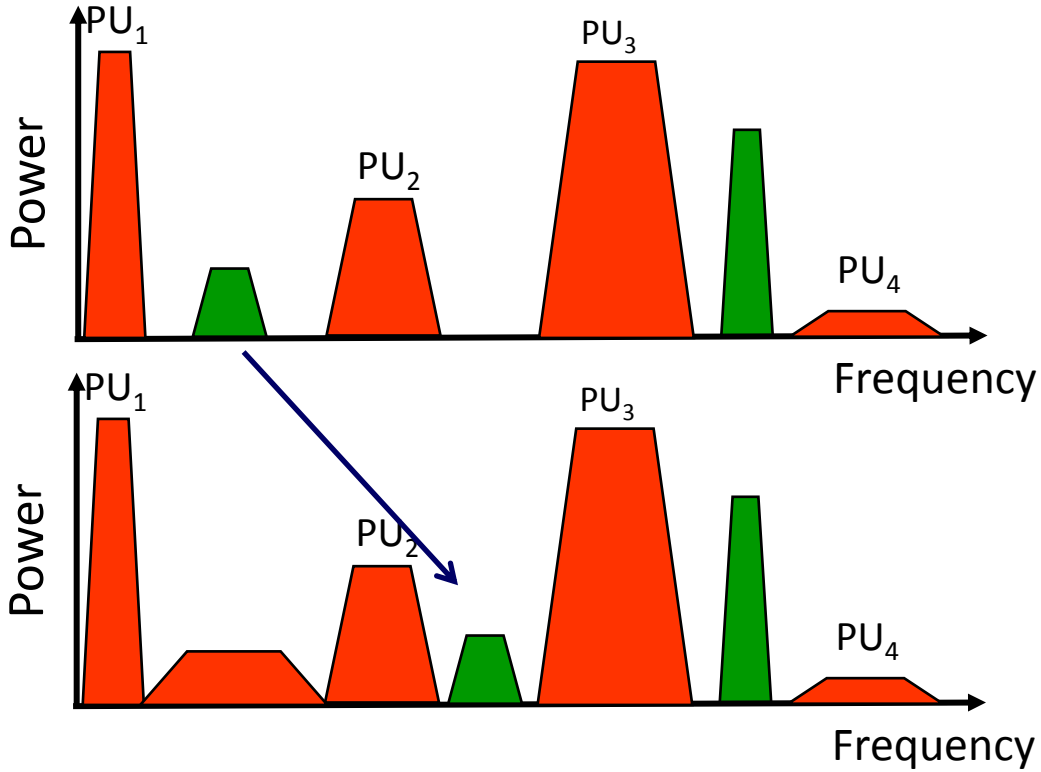


NOAA NATIONAL GEOPHYSICAL DATA CENTER



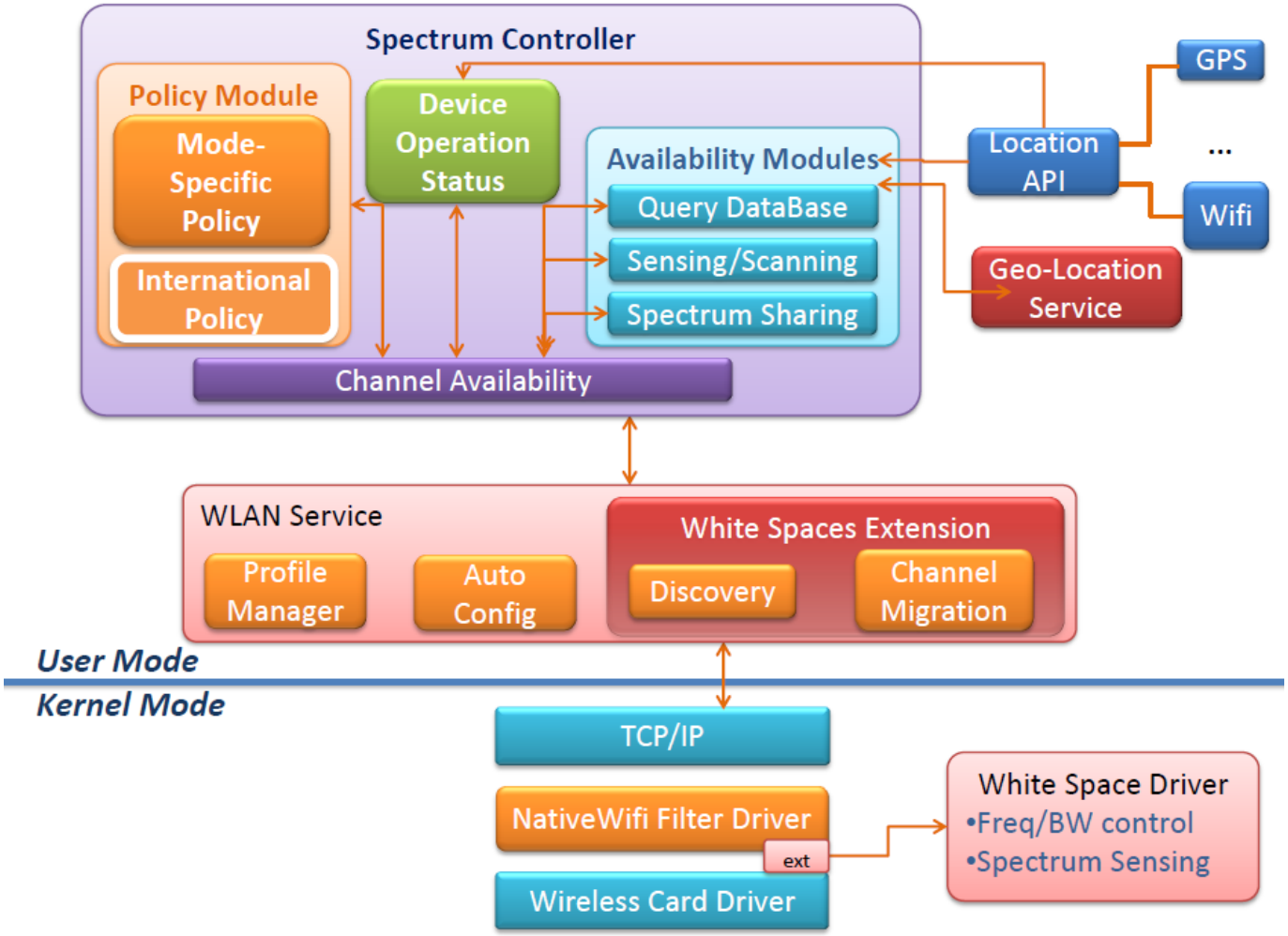
Obligatory Slide (3)

(Handling a New Networking Paradigms)



- Opportunistic use of spectrum
  - Secondary must give up to primary
- Query database to determine available channels
  - Every WS device must communicate with a DB

Implications on the Networking Stack

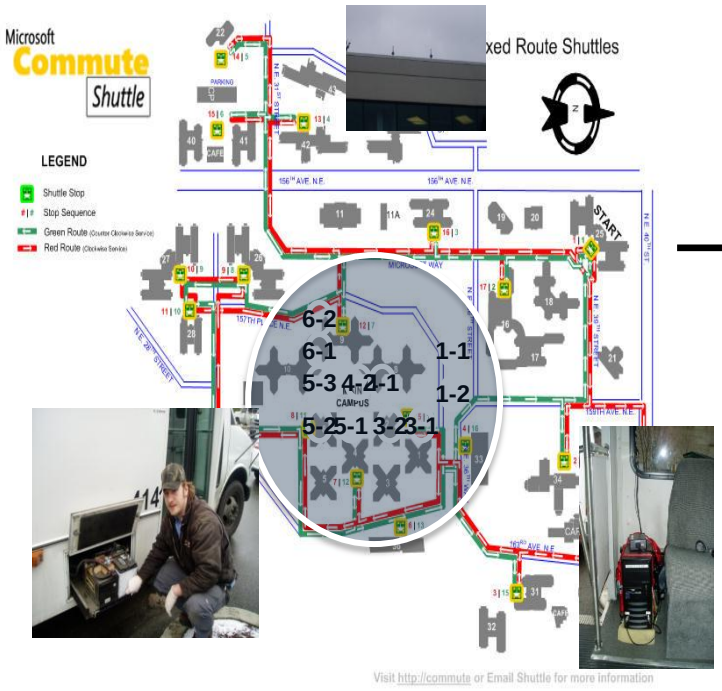


Putting it together

The world's First Urban White Space Network

Oct. 16, 2009

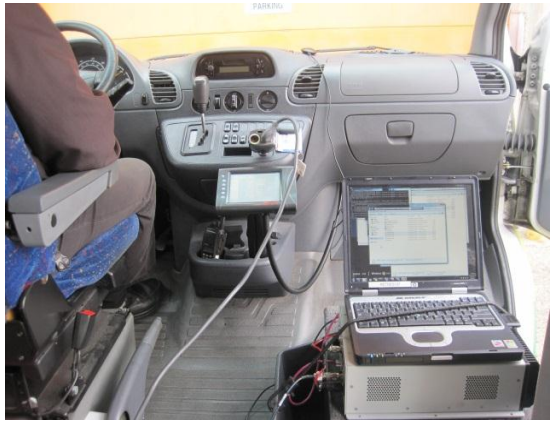
A giant white space hot-spot network on Microsoft campus



Accessing from the office

WS Antenna on Bldg 42

WS antenna on MS Shuttle



Accessing from inside a MS Shuttle

Winning over skeptics

Coexistence with TV Broadcasters

WhiteFi Antenna

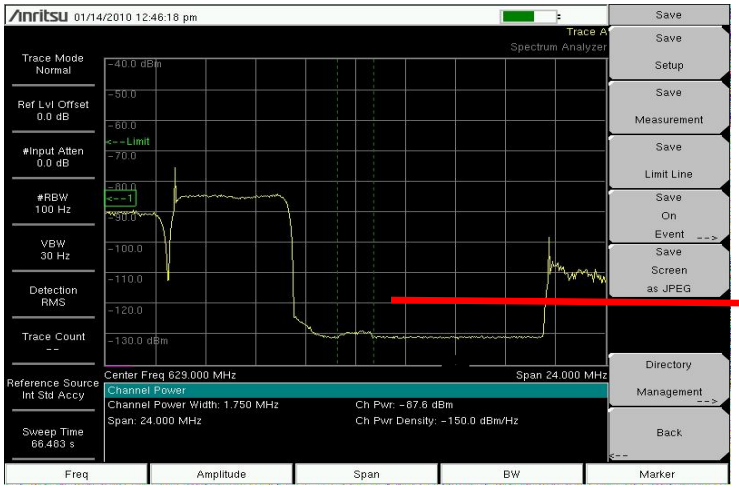
TV Antennas

KOMO (Ch. 38)

KIRO (Ch. 39)

WhiteFi (Ch. 40)

WhiteFi transmitting at 40 mW

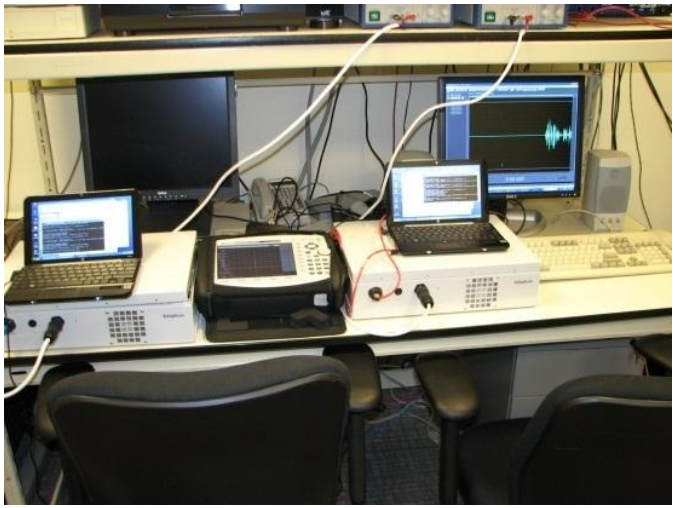


WhiteFi (Ch. 40)

Influencing critics

Co-existing with Wireless Microphones

Subcarrier Suppression setup



Microphone recording in Anechoic Chamber

Subcarrier Suppression

Results

Original

Without SCS

With SCS

Victory at last!

THE WALL STREET JOURNAL. Digital Network

MAY 11, 2010, 6:59 P.M. ET

FCC Officials Visit Microsoft To Examine Experimental Network

Aug 14, 2010

The New York Times

F.C.C. Opens Unused TV Airwaves to Broadband

By EDWARD WYATT
Published: September 23, 2010

Chairman Genachowski & Microsoft's CTO Craig Mundie, August 14, 2010

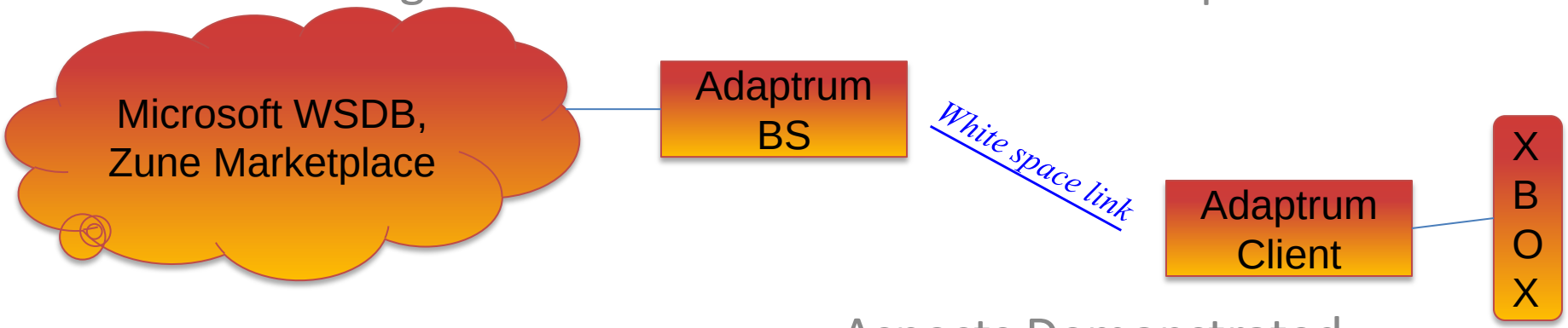
Chairman Genachowski and FCC Managing Director Steven VanRoekel Climb aboard the MS Shuttle to look at our WhiteFi Network

FCC Chairman Genachowski looks at our wireless Microphone demo In Bldg. 99, Anechoic Chamber (Room 1651)

Maintaining the Momentum

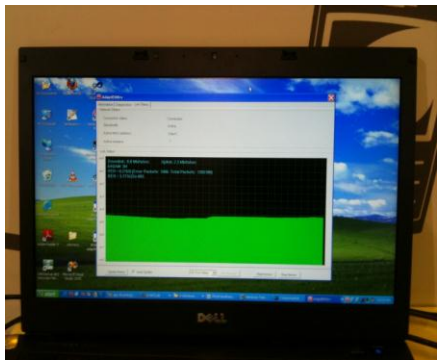
White Space at NAB 2011

Streaming HD Video to an XBOX over White Spaces



Aspects Demonstrated:

- FCC TVBD Mask compliant
- > 5 Mbps over 0.8 miles
- Interoperability with White Space DB
- Spectrum Agility with MIC entries



Global Advocacy & Evangelism

Telecom Regulatory Authority of India
(An ISO 9001-2000 Certified Organisation)

India
Oct. 22, 2009

Federal Communications Commission
Apr. 28, 2010

International Telecommunication Union

Radiocommunication Sector

iDA SINGAPORE

Singapore
Apr. 8, 2010

国家广播电影电视总局
SARFT THE STATE ADMINISTRATION OF RADIO FILM AND TELEVISION
WWW.SARFT.GOV.CN

China
Jan. 11, 2010

ANATEL
Provedor Licenciado pela Anatel

Brazil
(Feb. 2, 2010)

IEEE

Standards

KOMO 4

Fisher Communications Inc.
Jan. 14, 2010

LABS hp

Industry Partners
Jan. 5, 2010

Accolades

*The project, dubbed "White Fi," **is one of the most advanced in the field**, both dealing with the hardware side but also creating the networking protocols to handle the specific challenges.*

Softpedia (Aug. 19, 2009)

***Microsoft researchers have taken a step closer to** finally turning unused analogue TV spectrum, known as "white spaces", into unlicensed spectrum that can be used to deliver new wireless broadband service*

CNET.COM (Aug. 19, 2009)

***The Microsoft Research team has addressed many** of these issues with WhiteFi. —that early promise of "WiFi on steroids" might turn out to be surprisingly accurate, after all.*

Nate Anderson, Ars technica, August 27, 2009

*The actual engineering requirements to accomplish this frequency switch are non-trivial. Microsoft Research's "KNOWS" project **has taken up the task and made some pretty remarkable advances**.*

Scott Merrill, Crunchgear, August 28, 2009

One of the best prospects for the future** is the opening up of "white spaces," unused parts of the spectrum. **One of the most advanced research projects…..

Lucian Parfeni, Web News, August 18, 2009

***Microsoft researchers have taken the next step** toward turning old UHF analog TV spectrum into rural wireless broadband networks that would operate like Wi-Fi but with greater range.*

Simon Juran, GigaOm, August 18, 2009-09-02

Industry Landscape

Hardware Vendors (early movers)

Shared Spectrum

Adaptrum

Lyrtech

Neocific

Database Providers

Google

SPECTRUM BRIDGE

key bridge

LS telcom

neustar

WSdb

Telcordia

COMSEARCH
A CommScope Company

Standards

IEEE

Ofcom

ecma INTERNATIONAL

Trials

NOKIA
Connecting People

SPECTRUM BRIDGE

hp

Engaged

MOTOROLA

Airspan

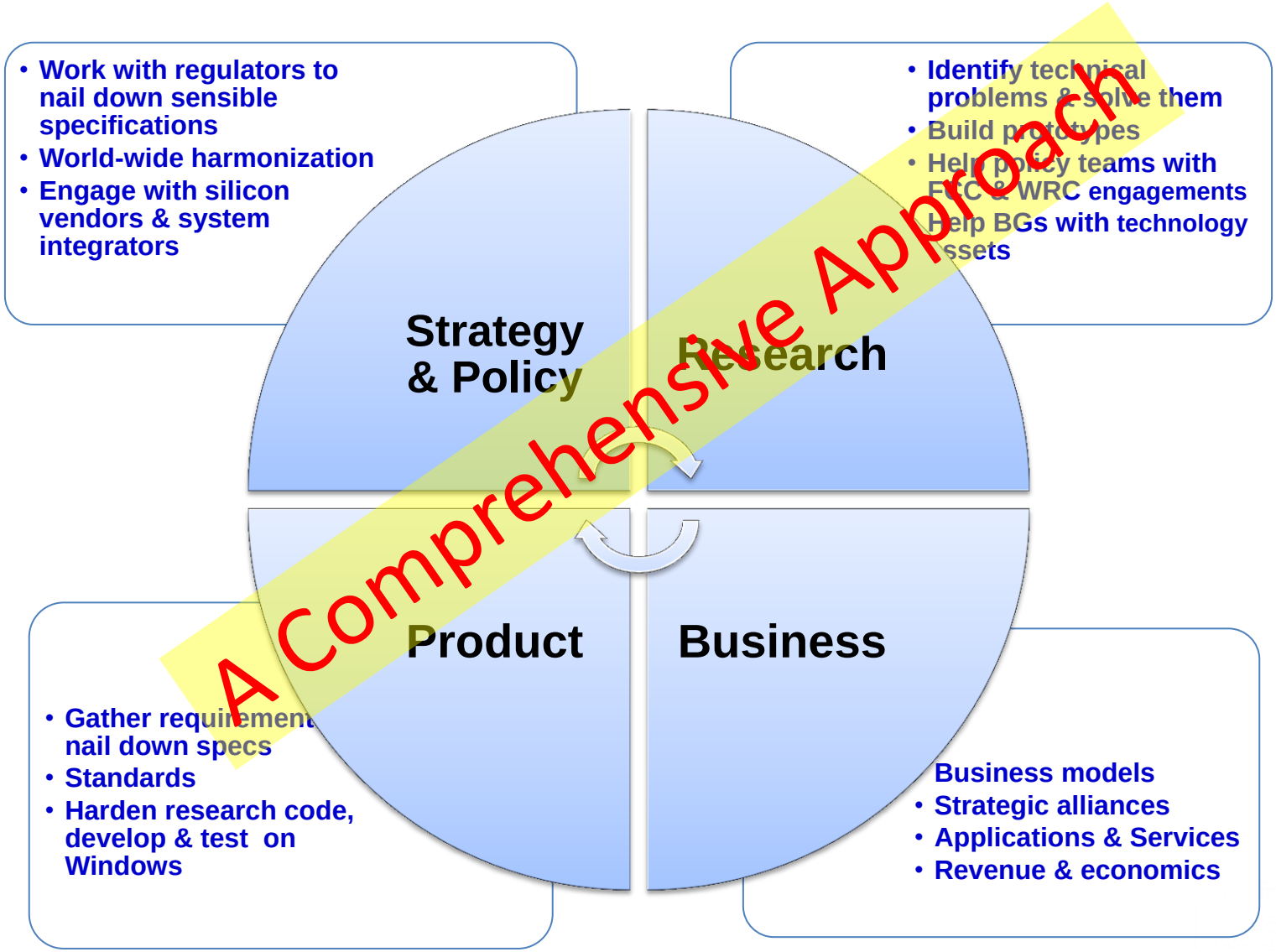
ATHEROS
There is Here

PHILIPS

LG
Life's Good

What have we learnt?

A journey that began in 2003….



Looking Ahead

Business Opportunities
- Focus on Scenarios
- What's it all good for…….no really?

Industry movement
- TV White Space Alliance
- DB providers signed up
- Standardization

Policy Positioning
- Stay on target

Research Problems
- Microphone co-location
- Heterogeneity
- Channel diversity
- Nation-wide spectrum sniffer
- Data integrity of DBs
- Software Defined Radio

Ponder over this
How long did it take to make Wi-Fi mainstream ?

Message of the day
Be patient!

Business Opportunities

- **Giant hot-spots** (to relieve spectrum congestion)
- **Content distribution networks** (should work great in suburban communities & rural America)
- **Direct connectivity to retailer portals** (without involving cellular providers)
  - E.g. BestBuy, Walmart, Home Depot, Sears, etc. put up WS BSs and provide direct access to their store up to a few mile radius
- **Campus and City wide coverage**
  - Seamless handoffs while moving between buildings in Universities, industrial parks, companies etc.
- **Home wireless multimedia**

Build, deploy, test, prove

Industry Movement: TVWS Alliance

Goal: Align industry towards a commercially feasible solution

- Develop usage models & marketing requirements
- Agree on a technical solution

Members: Microsoft, Google, Dell, Nokia, LG, Cisco, Broadcom, Intel, Atheros, Marvell, HP

- HP joined in March 2010; dropped from CogNea ☺
- Others pending

Direction

- TVWS Alliance drives WGs within Wi-Fi Alliance & IEEE 802.11
- Formed IEEE 802.11af
  - define the PHY
  - minimum MAC enhancements
- Groups in Wi-Fi Alliance
  - Develop roadmap for a certification program
  - MAC enhancements + database specifications

Industry Movement: TVDB Providers

- FCC names nine white-space database providers (Jan. 27, 2011)
  - Comsearch
  - Frequency Finder
  - Google
  - KB Enterprises
  - Key Bridge Global
  - Neustar
  - Spectrum Bridge
  - Telcordia
  - WSdb LLC
- Microsoft files with FCC to become a DB provider (April, 2011, Docket No. 04-186)

Comments due May 20, 2011

Hot topic of the day
Interoperability Discussions

PUBLIC NOTICE

Federal Communications Commission
445 12th St., S.W.
Washington, D.C. 20554

News Media Information 202 / 418-0500
Fax-On-Demand 202 / 418-2830
TTY 202 / 418-2555
Internet: http://www.fcc.gov
ftp.fcc.gov

DA 11-803
Released: April 29, 2011

Office of Engineering and Technology Seeks Comment on Microsoft Corporation Proposal to be Designated as a TV Bands Device Database Administrator

ET Docket No. 04-186

Comment Date: May 20, 2011
Reply Date: May 31, 2011

Policy: MS Response to FCC NoI on DSA

(ET Docket No. 10-237)

FCC (in cooperation with NTIA) must ensure

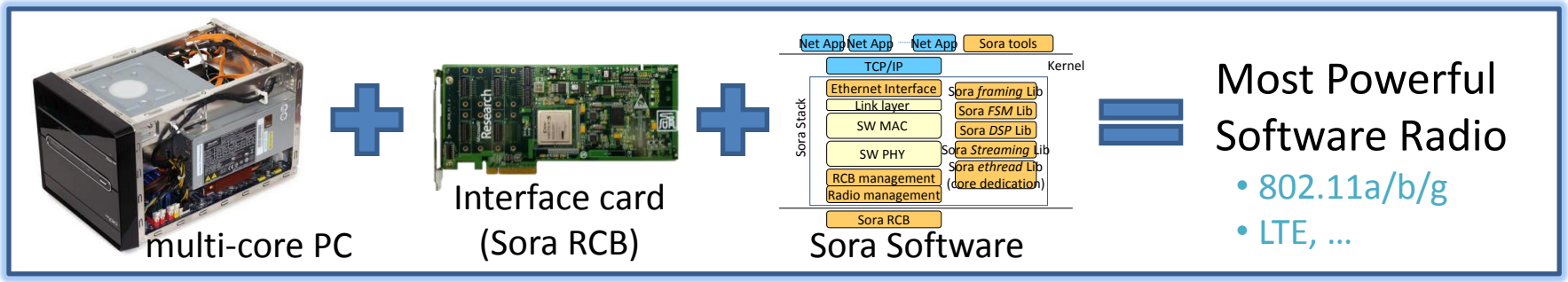
- Sufficient amount of spectrum stays available for WSN
- Underutilized spectrum, especially below 3 GHz, is made available for additional DSA

Regulatory bodies must

- Consider reallocation of additional spectrum
- Promote DSA to make better use of limited spectrum
- Realize that spectrum DBs are evolving to be able to negotiate spectrum access and usage rights in real time (*e.g.*, accounting for the cost of interference, power limits, geolocation and mobility, prioritization, and duration)

In other Development

MSR's Software Radio (Sora)



- High-performance software radio platform on standard multi-core Windows PC
  - Fast enough to support pure software implementation of the latest wireless standards (WiFi, LTE, …)

- Sora Academic Program
  - Hardware/software made available to universities
  - Over 30+ schools worldwide are using Sora in research

Research: MSR White Space Platform SDK

(Available end of this year)

KNOWS + SORA

KNOWS Software
(TV broadcast sensing,
Geo-location database,
spectrum management)

Any White Space Applications

Software

White Space Baseband (802.11a/g/n, 802.11af, etc.)

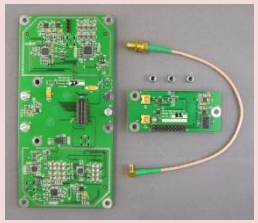
White Space Cognitive Layer (dynamic spectrum allocation, etc.)

Software Radio Layer (Sora)

Hardware

Standard
multi-core PC

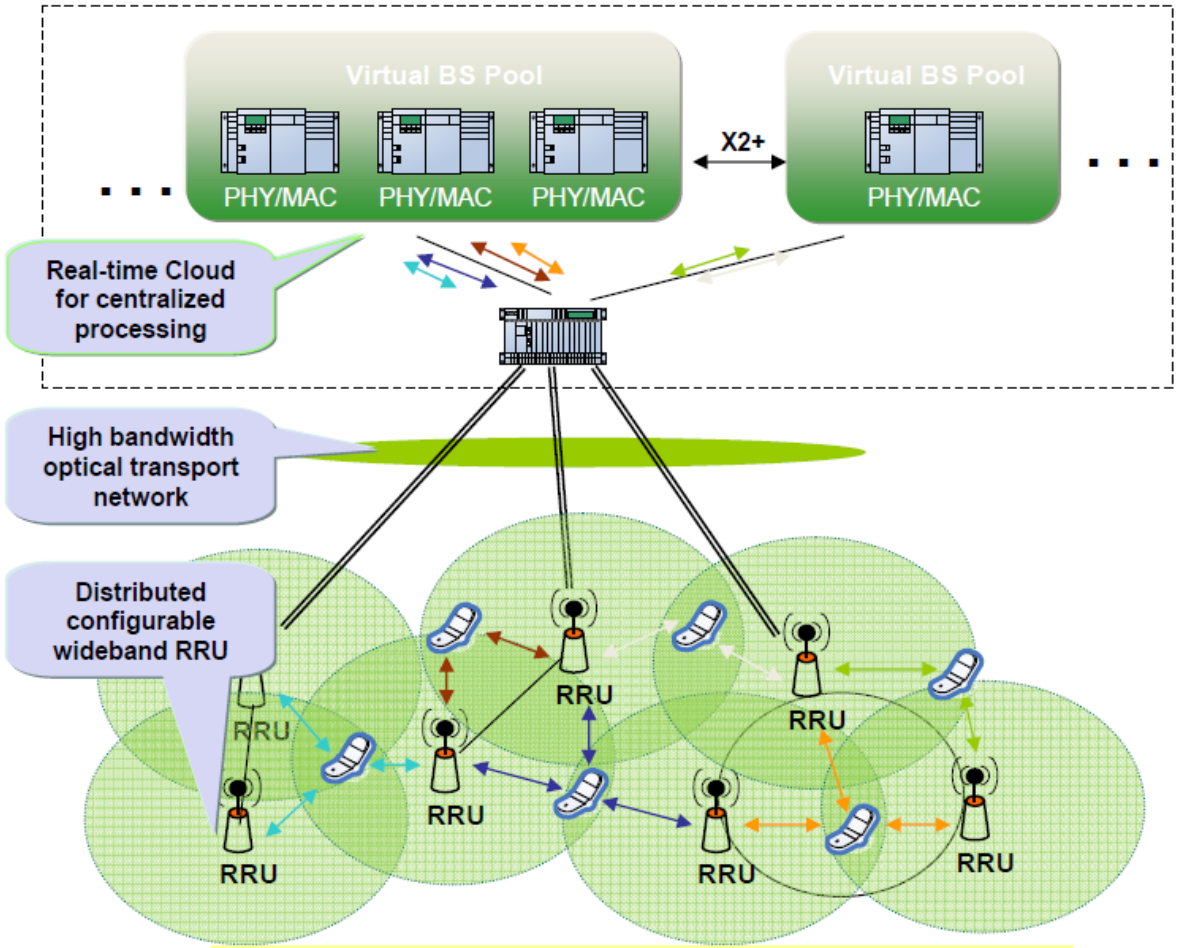
Sora hardware



WS Radio Front-end and Antenna

Example: Vision of C-RAN Architecture

Centralized Processing, Collaborative Radio, real-time Cloud Computing Infrastructure



future RAN solution that consumes less power, cost less money but has higher capacity and more flexibility

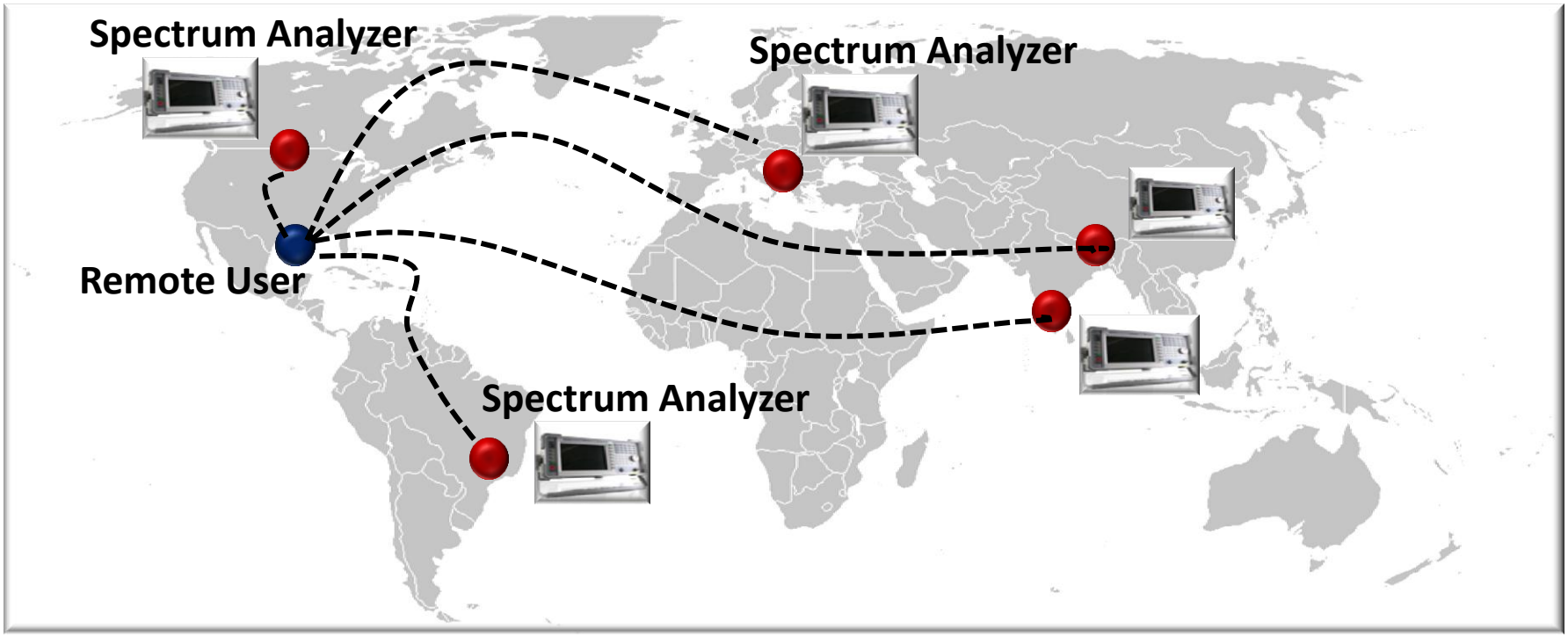
From
China Mobile Research

Green Radio Access Networks

- Reduce CAPEX/OPEX, lower MB cost
- Better allocation of resources, improved power efficiency
- Easier to implement collaborative radio technology
- Supporting multi-standard operation

Research: MSR's SpecNet Vision

(Crowd sourcing of spectrum sensing)



A first-of-its-kind platform that allows remote users to measure spectrum remotely in real-time and to implement and deploy coordinated distributed sensing applications

MSR's SpecNet Operation

Spectrum Analyzers

- Volunteering spectrum analyzer (SA) owners register and connect to SpecNet
- SA owners specify times of public usage
- Connect to SpecNet server

Users

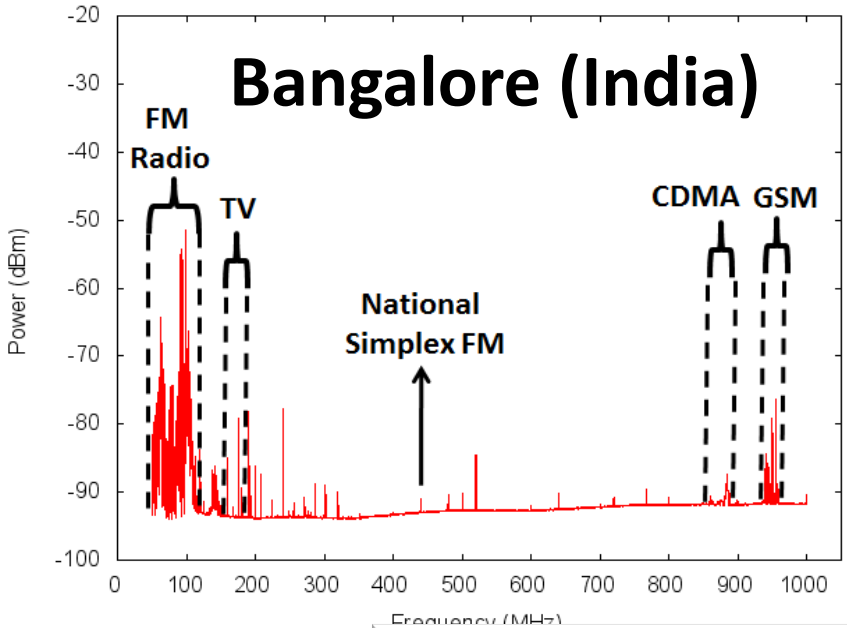
- Use SpecNet API to write applications
- SpecNet API provides an easy to use abstraction layer implemented as XML-RPC for flexibility
- Can be written in any language that supports XML_RPC , C#, Pearl etc.

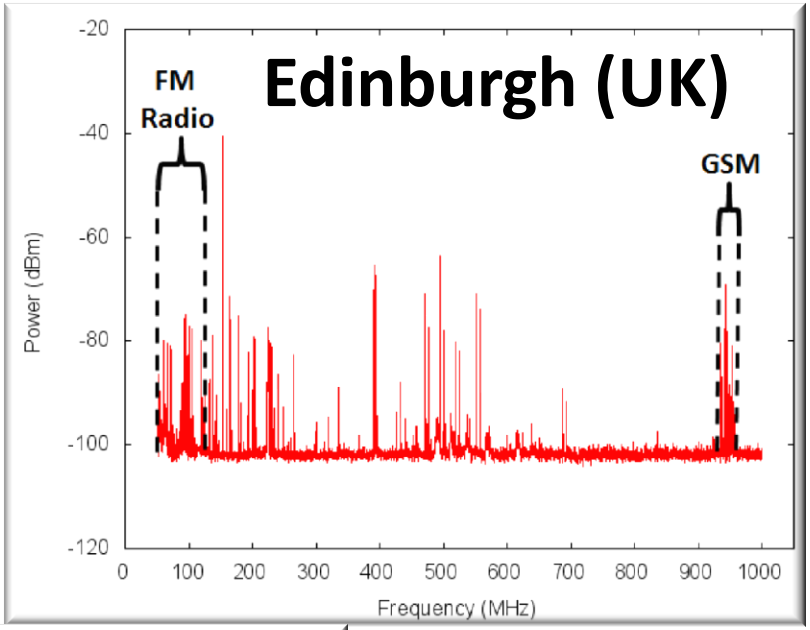
Listing 1: Code snippet for remote measurement.

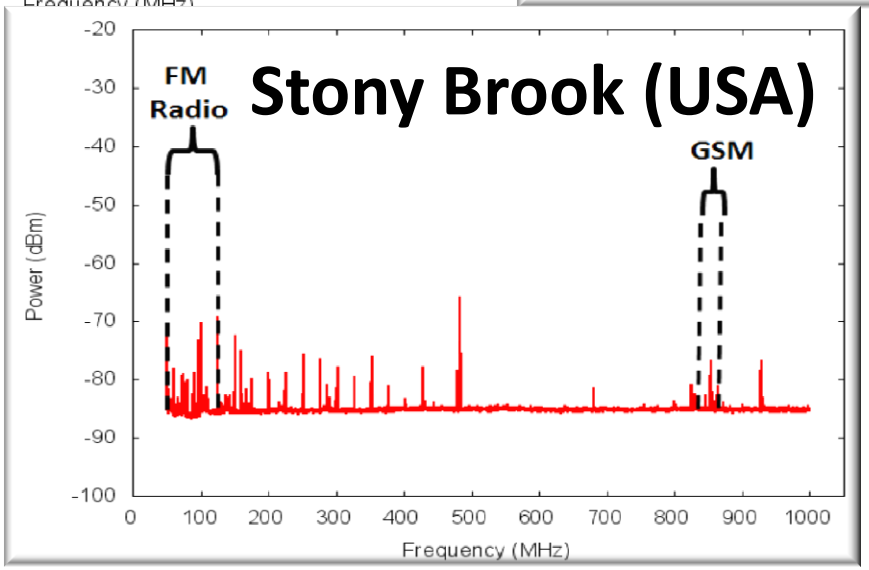
```
# connect to SpecNet server
apiServer = xmlrpclib.ServerProxy(
  "http://122.166.44.139:3000/SNAPI/API.rem",
  allow_none=True);

# Find devices from region of interest
devices = APIServer.GetDevices(
  [55.944350, -3.187745, 500.0], None);
for device in devices:
    power_vals = APIServer.GetPowerSpectrum(
     device['ID'], Fs, Fe, 1e3);
```

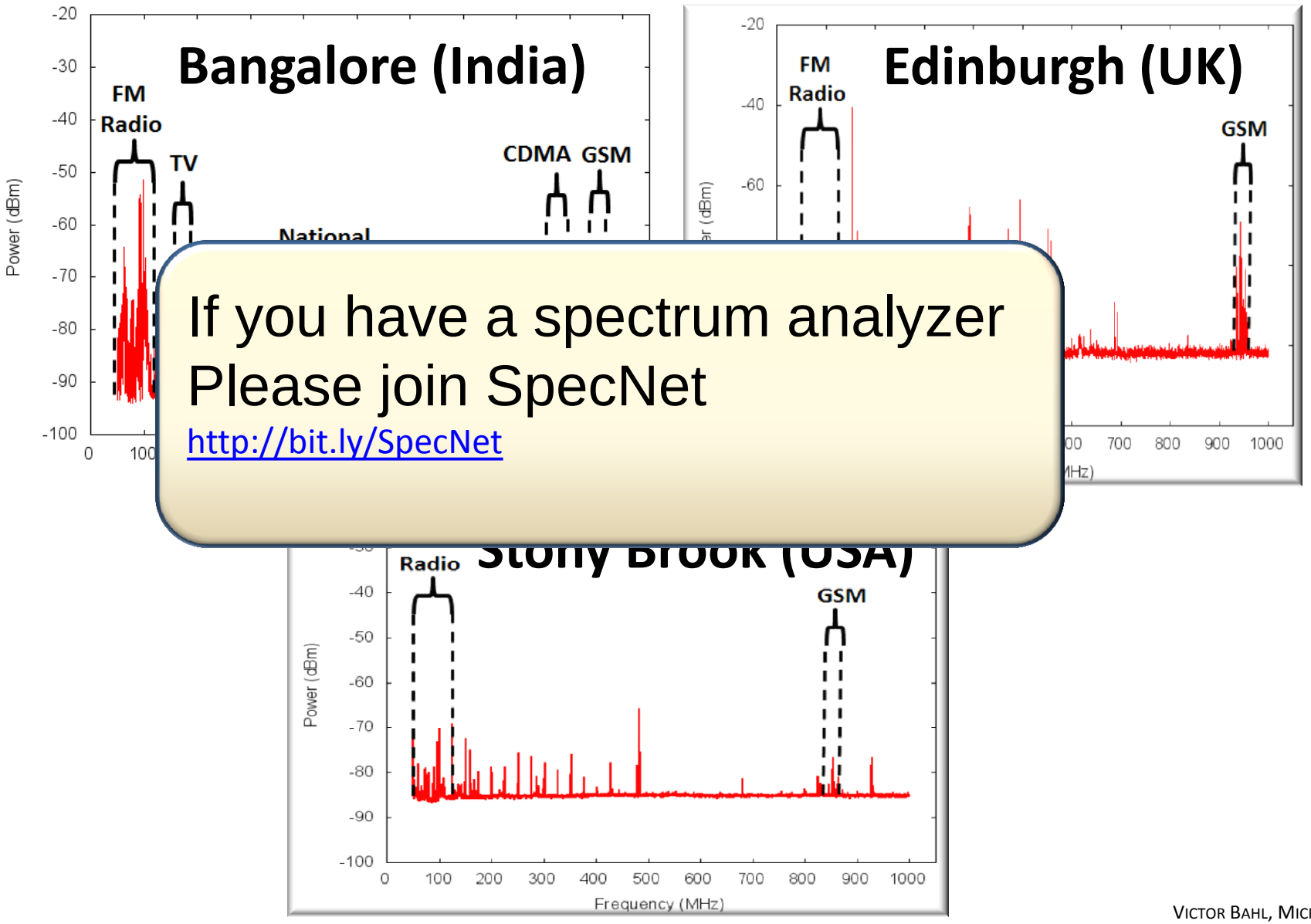
MSR's SpecNet Operation







MSR's SpecNet Operation



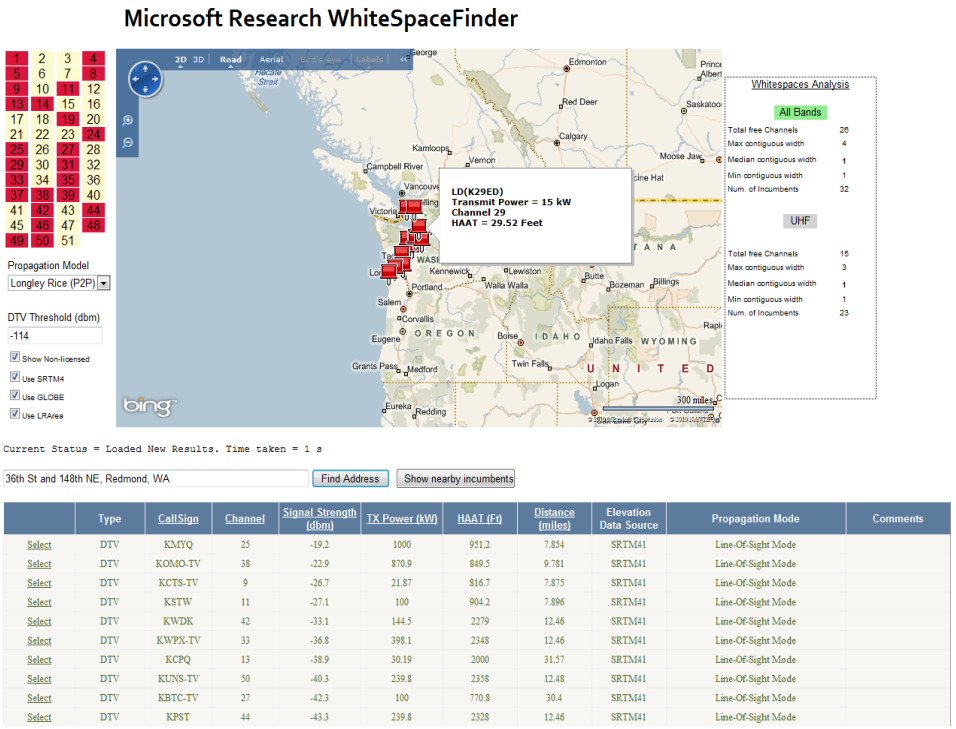
If you have a spectrum analyzer
Please join SpecNet
http://bit.ly/SpecNet

DySpan 2010 Announcement

April 7 2010

http://whitespaces.msresearch.us

<primary user[], signal strength[] at location>



Features

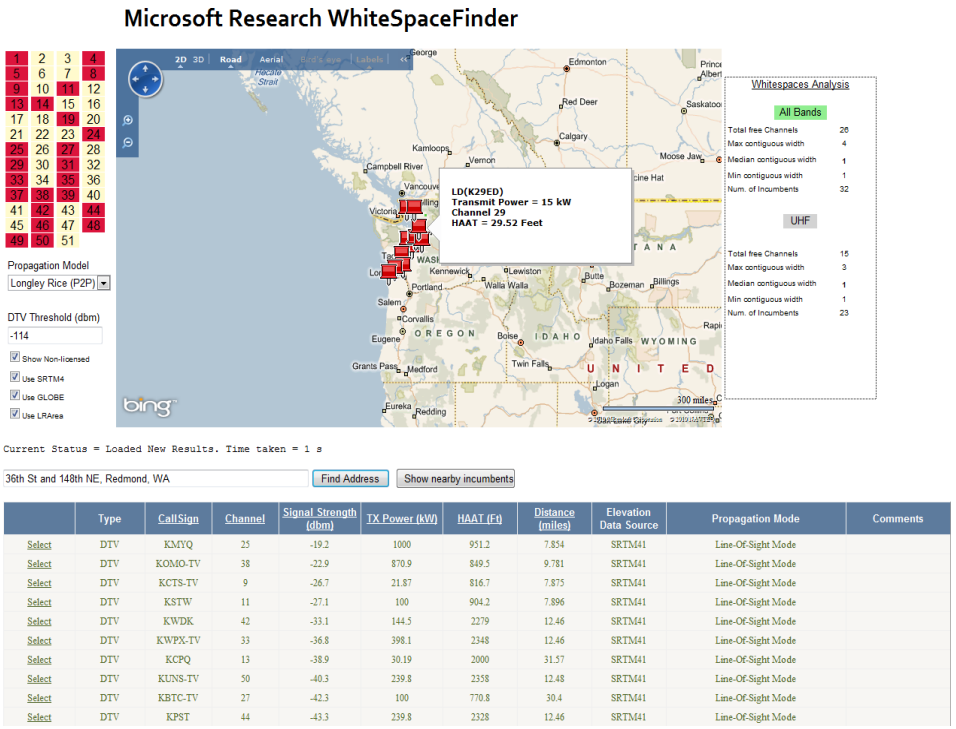
- Configurable parameters
  - —Propagation models: L-R, Free Space, Egli
  - —detection threshold (-114 dBm by default)
- Includes analysis of white space availability

DySpan 2011 Update: Internationalization

http://whitespaces.msresearch.us

<primary user[], signal strength[] at location>

Now supports UK, Finland, Singapore & Hong Kong



	Type	CallSign	Channel	Signal Strength (dbm)	TX Power (kW)	HAAT (Ft)	Distance (miles)	Elevation Data Source	Propagation Mode	Comments
Select	DTV	KMYQ	25	-19.2	1000	951.2	7.854	SRTM41	Line-Of-Sight Mode	
Select	DTV	KOMO-TV	38	-22.9	870.9	849.5	9.781	SRTM41	Line-Of-Sight Mode	
Select	DTV	KCTS-TV	9	-26.7	21.87	816.7	7.875	SRTM41	Line-Of-Sight Mode	
Select	DTV	KSTW	11	-27.1	100	904.2	7.896	SRTM41	Line-Of-Sight Mode	
Select	DTV	KWDK	42	-33.1	144.5	2279	12.46	SRTM41	Line-Of-Sight Mode	
Select	DTV	KWPX-TV	33	-36.8	398.1	2348	12.46	SRTM41	Line-Of-Sight Mode	
Select	DTV	KCPQ	13	-38.9	30.19	2000	31.57	SRTM41	Line-Of-Sight Mode	
Select	DTV	KUNS-TV	50	-40.3	239.8	2358	12.48	SRTM41	Line-Of-Sight Mode	
Select	DTV	KBTC-TV	27	-42.3	100	770.8	30.4	SRTM41	Line-Of-Sight Mode	
Select	DTV	KPST	44	-43.3	239.8	2328	12.46	SRTM41	Line-Of-Sight Mode	

Features

- Configurable parameters
  - —Propagation models: L-R, Free Space, Egli
  - —detection threshold (-114 dBm by default)
- Includes analysis of white space availability
- Internationalization of TV tower data
- Protection for MICs by adding as primary user

Collaborators

Chanel occupancy database design & related issues

White space mesh networks for rural communities

Harmonization between heterogeneous white space networks

Security & Privacy In white space networks

Now Grandma is on our side….

NAB takes fight against "white space" broadband to the airwaves

Eric Bangeman | Last updated: 3 years ago

Poor grandma's picture is breaking up due to interference from wireless broadband

First White Spaces Access Point Gives Grandma the Internet

John Cox, NetworkWorld , Apr. 19, 2011

Houston Grandma Gives White Space Broadband a Spin

Built on the shoulders of giants…

Researchers

- Ranveer Chandra
- Krishna Chintalapudi
- Thomas Moscibroda
- Bozidar Radunovic
- Kun Tan
- Yongguang Zhang

Policy & Strategy

- Paula Boyd
- Paul Garnett
- Pierre de Vries (Silicon Flatirons Center)

Students

- Rohan Narayan Murty (Harvard)
- George P. Nychis (CMU)
- Eeyore Wang (CMU)
- Yuan Yuan (UMD)

Open Source Research

Technology	Publication
1. White Space Networking without sensing	DySPAN 2011
2. Protecting integrity of WS Spectrum Measurements	NDSS 2011
3. Co-existence with wireless microphones	MSR Tech Report
4. Harmonious operation in heterogeneous environment	In-preparation
5. Enhancements to the software stack	N/A
6. Fast discovery & connectivity in ad hoc mode	In-preparation
7. Secure collaborative sensing	DySPAN 2010
8. Temporal analysis & Spectrum assignment for AP Operation	SIGCOMM 2009 (Best paper)
9. Dynamic channel width operation	SIGCOMM 2008
10. Load aware spectrum distribution	ICNP 2008
11. Dynamic time spectrum blocks	MobiHoc 2007
12. Control channel medium access protocol	DySPAN 2007
13. Spectrum leasing	DySPAN 2006
14. Separation of control & data	BroadNets 2006

Thanks!

bahl@microsoft.com

Wireless Connectivity over Unlicensed Frequencies

Popular Name	Associated Standard	Frequencies	Bandwidth	Speed	Range	Uses	World -Wide
Wi-Fi	• IEEE 802.11 {b, g, a, n}	• 2.4 – 2.4835 GHz • 5.15 – 5.35 GHz • 5. 725 – 5.825 GHz	• 83.5 MHz • 300 MHz	• 54 – 600 Mbps / 22 MHz - 40 MHz	• 100-200 m • 50 – 150 m	LAN	Yes
Bluetooth	• IEEE 802.15.1	• 2.4 – 2.4835 GHz	• 83.5 MHz	• 721 Kbps • 1 - 3 Mbps	• 10 m	Cable Repl.	Yes
Wireless USB	• WiMedia	• 3.1 – 10.6 GHz	• 7.5 GHz Underlay	• 480 Mbps • 100 Mbps	• 3 m • 10 m	Cable Repl.	US only
Zigbee	• IEEE 802.15.4	• 902–928 MHz • 2.4 – 2.4835 GHz • 833 MHz (EU)	• 26 MHz • 83.5 MHz	• 250 Kbps • 40 Kbps • 20 Kbps	• 50 m	PAN	Yes
RFID	• IEEE 802.15.4f	• UWB • 2.4 – 2.4835 GHz • 433.05 - 434.79 MHz	• 83.5 MHz • 1.75 MHz	• Very low	• 1 - 2 m	NFC	Yes
WAVE – DSRC*	• IEEE 802.11p	• 5.85 – 5.925 GHz	• 75 MHz (US) • 30 MHz (EU)	• 6 - 27 Mbps / 10 MHz	• 300 -1000 m	Vehicular	US & EU
WhiteFi	• IEEE 802.11af • IEEE 802.22 • ECMA TC48-TG1	• Opportunistic – VHF & UHF TV Bands	• 0 – 180 MHz	• 24 Mbps / 6 MHz	• 1-5 miles	WAN	US only
60 GHz	• WirelessHD • WiGig • IEEE 802.11ad • IEEE 802.15.3c	• 57 – 64 GHz	• 7 GHz	• 6-8 Gbps / 2.16 GHz	• 5 – 10 m (LOS)	Cable Repl.	Yes