Opportunities and Challenges of Community Wireless Networks

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Presentation Outline

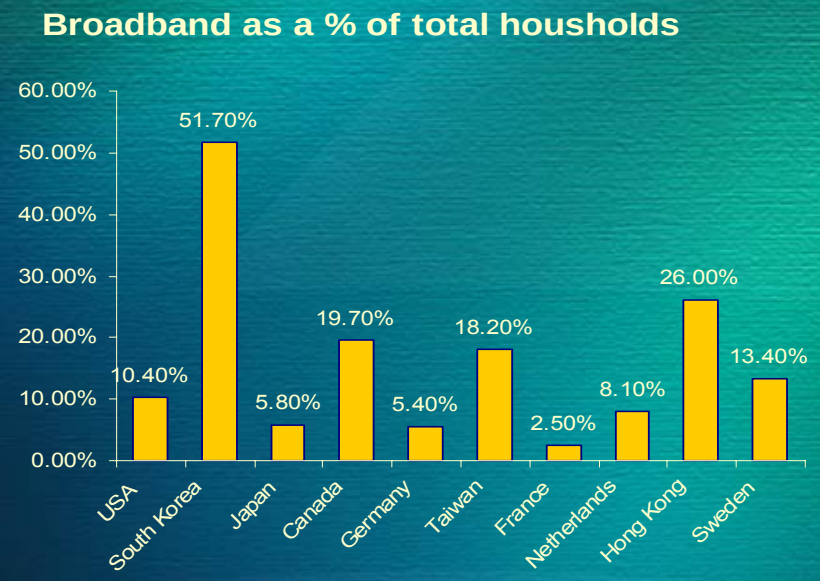
- Motivation
  - Community networking – why?
- Viability & Challenges
  - Community Network Formation Study
  - Research Challenges
- Some Solutions
  - System Architecture and Components
  - Capacity Estimation & Improvement
  - Multi-Radio Routing
  - Troubleshooting Mesh Networks
- Testbeds & Trials
- Conclusions

Motivation

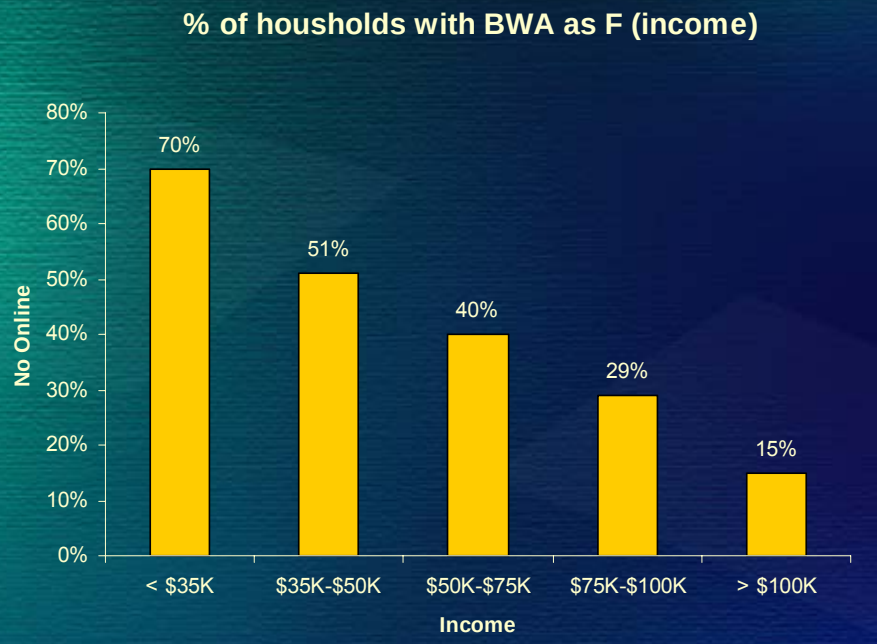
"*Residential broadband access is an under developed technology that has the potential for profound positive effect on people's lives and Nation's economy*"

Residential Broadband Revisited, NSF Report, October 23, 2003

Residential Broadband
Where are we?



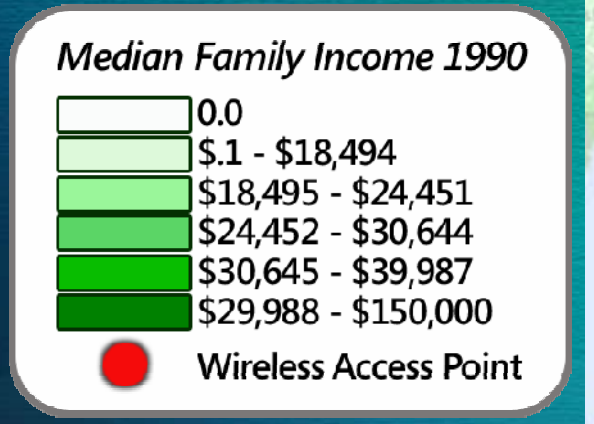
Source: *Broadband & Dial-Up Access*

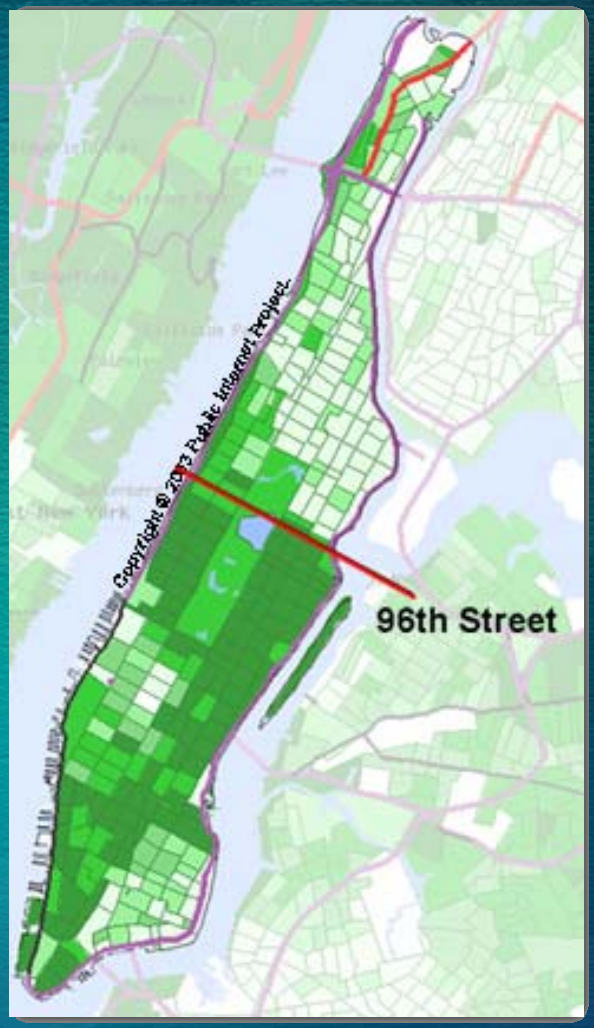


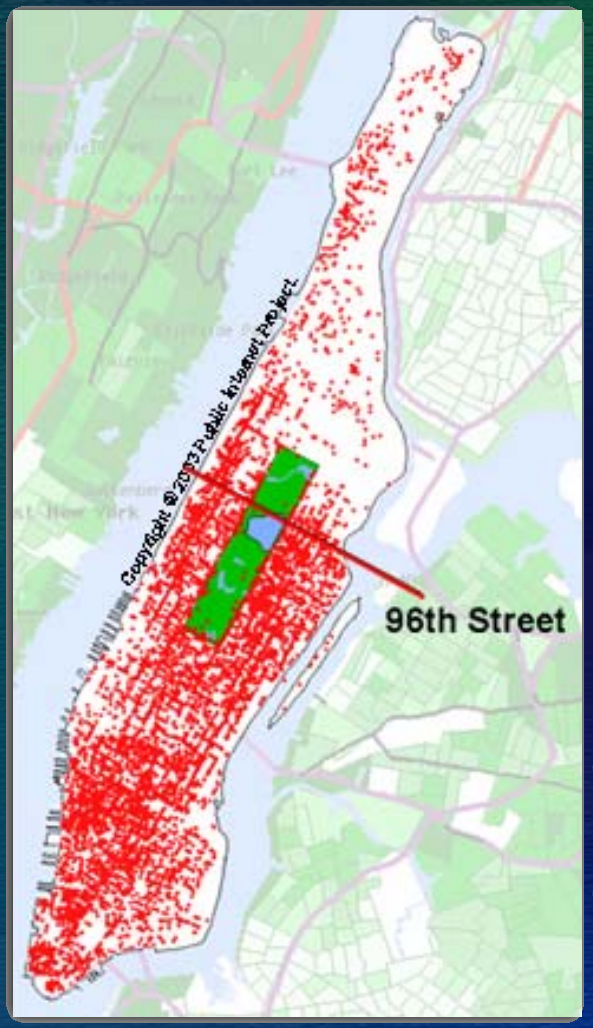
Source: *Leitchman Research Group*

Broadband Divide

- 13,707 unique nodes within Manhattan (Fall 2002)
- 91% below 96th Street



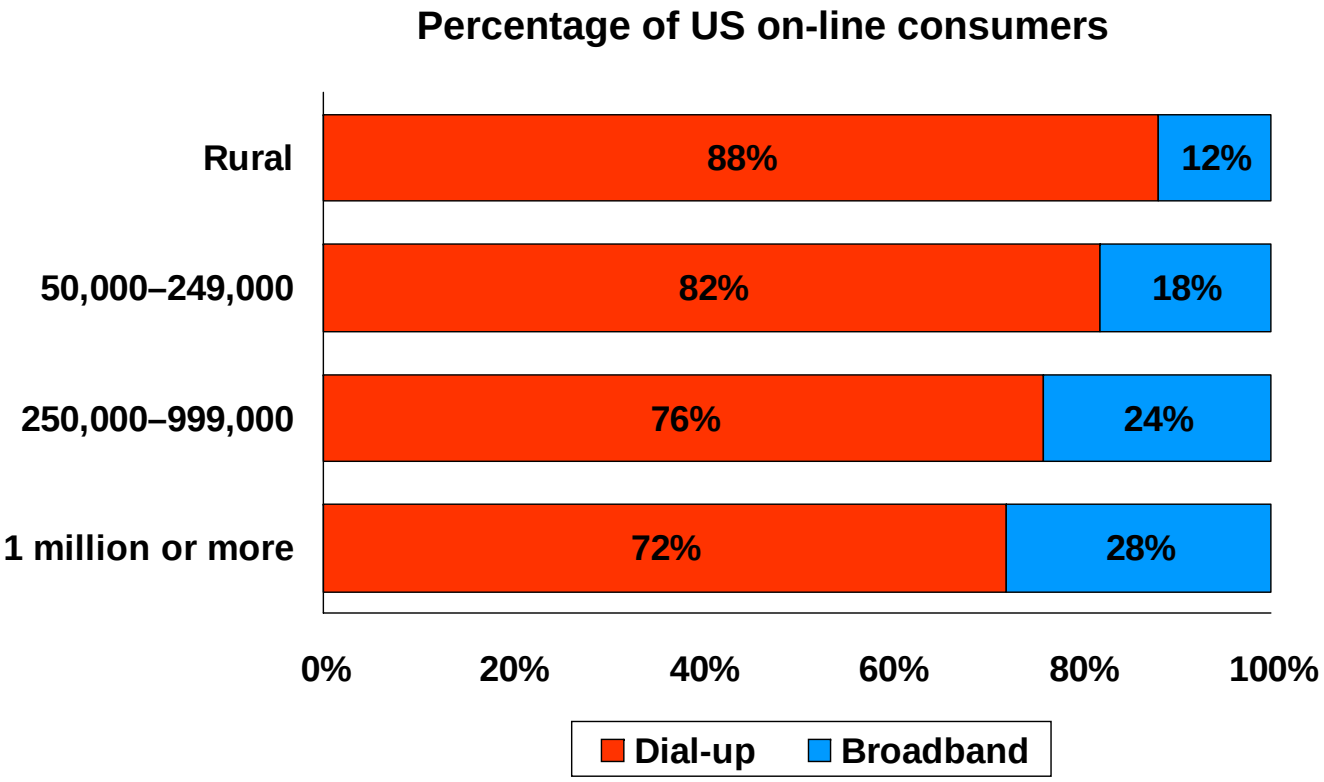




Source: http://publicinternetproject.org

Density = Broadband

Limited Broadband in Rural Areas



Source: Jupiter/Ipsos-NPD Consumer Survey (12/02), n = 2,011 (US only)

Quotes

"For Internet access, there are15 ISPs for every 100K users, for Cable or DSL there are two providers for every 100K users"

- Consumer Federation of America, July 2002

"One reason often cited for low penetration of broadband services is their high cost, typically $50 a month"

- The Mercury News

"[Broadband users] are much more likely to create content for the Web or share files, telecommute, download music, or game files, or enjoy streaming audio or video"

- Cox News Service

"Applications will drive broadband access and justify the investment for citizens, businesses and government"

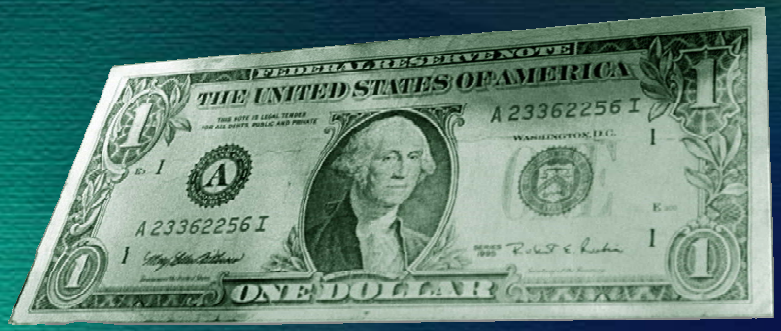
- Office of Technology Policy, US Dept. of Commerce, Sept., 2002

What can you get for a $1?

Processing
- One PC-day of computation

Storage
- 1 GB disk storage
  (2 DVD quality movies)

Interconnection
- 100 MB broadband data
  (3.5 hours of music)
- 1 MB voice telephony
  (15 minutes talk time)
- 1.6 KB SMS
  (10 messages)



Bits ≠ Value
- Broadband: 1¢ per MB
- GPRS: $1 per MB
- SMS: $600 per MB

It's the Bandwidth (and Spectrum) that's expensive

What about wiring the last mile?

The Last Mile: Connection between a home and local hub

Scale & legacy make last mile expensive

- ~ 135 million housing units in the US (U.S. Census Bureau 2001)
- POTS (legacy) network designed for voice & built over 60 years
- Cable TV networks built over last 25 years

The Truck Roll Problem: Touching each home incurs cost: customer equipment; installation & servicing; and central office equipment improvements

In our estimate building an alternate, physical last mile replacement to hit 80% of US homes will take 19 years and cost ~ US $60-150 billion

Why should you care?

The future is about rich multimedia services and information exchange

…possible only with wide-scale availability of broadband Internet access

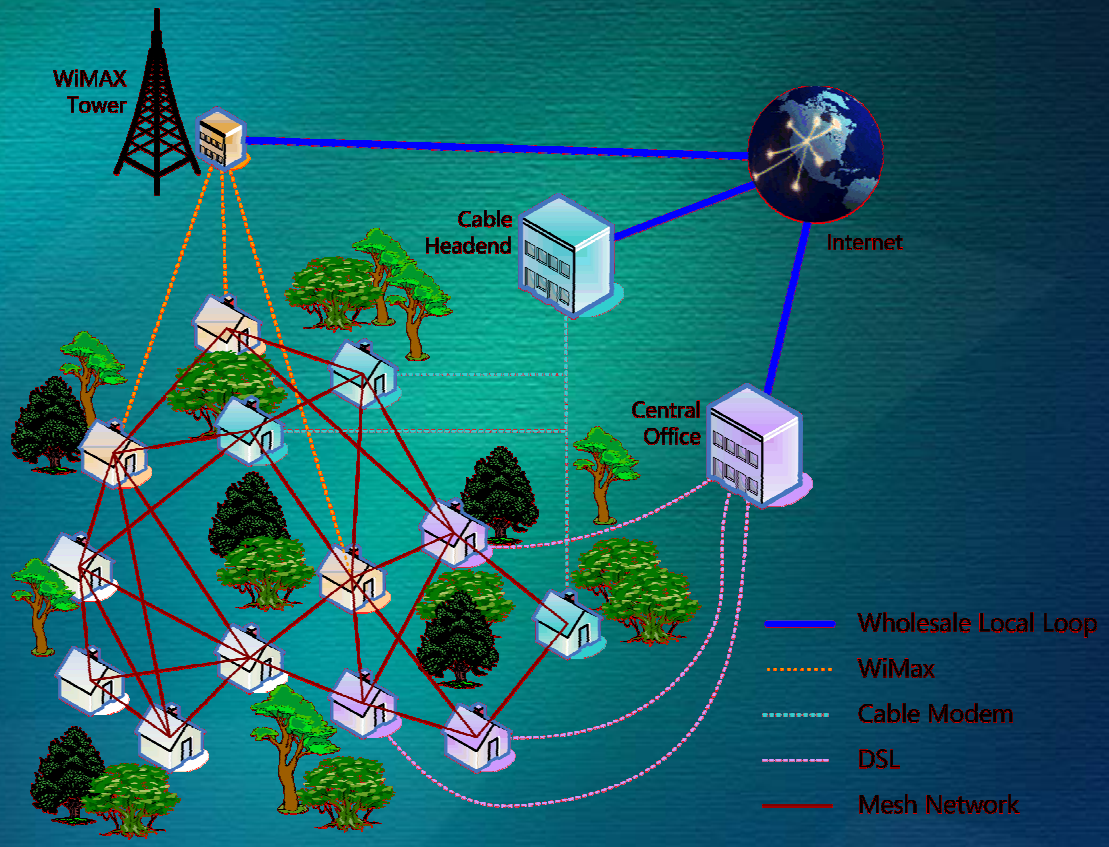
but…

Many people are still without broadband service

- Up to 30% of America (32 million homes) cannot get broadband service (rural areas, older neighbourhoods, poor neighbourhoods)
- A large majority of the developing world does not have broadband connectivity
- It is not economically feasible to provide wired connectivity to these customers

Community Mesh Network

The natural evolution of broadband connectivity



Wireless mesh networks have the potential to bridge the Broadband divide

We are not alone…

- Wi-Fi Hits the Hinterlands, BusinessWeek Online, July 5, 2004

  "Who needs DSL or cable? New "mesh" technology is turning entire small towns into broadband hot spots"

  Rio Rancho N.M., population 60,000, 500 routers covering 103 miles^2

- NYC wireless network will be unprecedented, Computerworld, June 18, 2004

  "New York City plans to build a public safety wireless network of unprecedented scale and scope, with a capacity to provide tens of thousands of mobile users"

- Rural Areas need Internet too! Newsweek, June 7, 2004 Issue

  "EZ Wireless built the country's largest regional wireless broadband network, a 600-square-mile Wi-Fi blanket, and activated it this February"

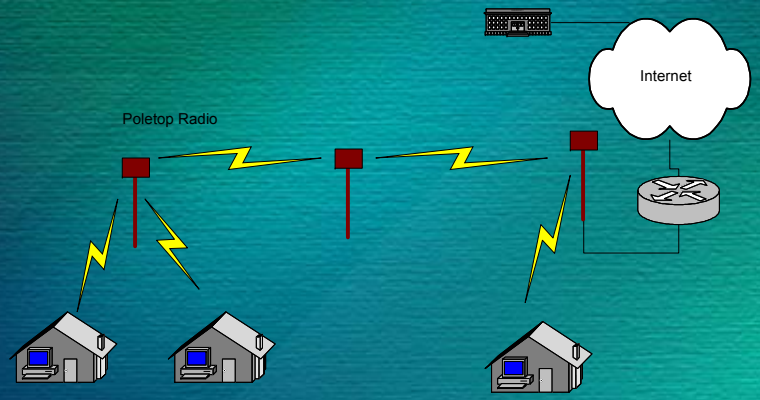
  Hermiston, Oregon, population 13,200, 35 routers with 75 antennas covering 600 miles^2

- Mesh Casts Its Net, Unstrung, January 23, 2004

  "Providing 57 miles^2 of wireless coverage for public safety personnel in Garland Texas"

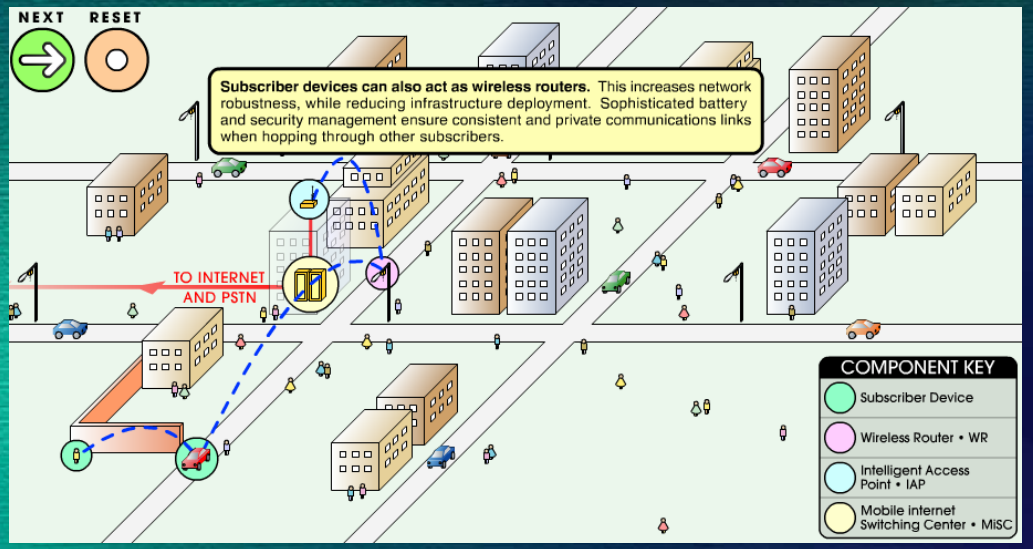
Wireless Last/First Mile Companies

Infrastructure Based



SkyPilot, Flarion, Motorola (Canopy) Invisible Networks, RoamAD, Vivato, Arraycomm, Malibu Networks, BeamReach Networks, NextNet Wireless, Navini Networks, etc.

Infrastructure-less



Meshnetworks Inc.,Radiant Networks, Invisible Networks, FHP, Green Packet Inc., LocustWorld, etc.

Architecture effects design decisions on

Capacity management, fairness, addressing & routing, mobility management, energy management, service levels, integration with the Internet, etc.

Wireless Mesh Networks

vision demo


My Storage
chen
You have new services available:
• CommunityNet Computing Services
Yes, please enroll me
No, thank you.
My Resources
Photos
PartyON

CommunityNet Sign Up

John Chen's:
Filters

Share Reciprocal Resources within Your Neighborhood

Search: GO

Favorite Filters

- Google
- Tailspin P&L
- Throckmorton Homework...
- Tailspin Home Page
- My Resources
- Chamber of Commerce
- Town Hall
- Throckmorton Junior High

Distributed Backup (*Highly Recommended*)

Never lose a precious family photo, or any other important file, even if your equipment suffers a catastrophic failure. By distributing copies across other computers, you will always be able to get your stuff... and even when you're out and about.

Capability Sharing

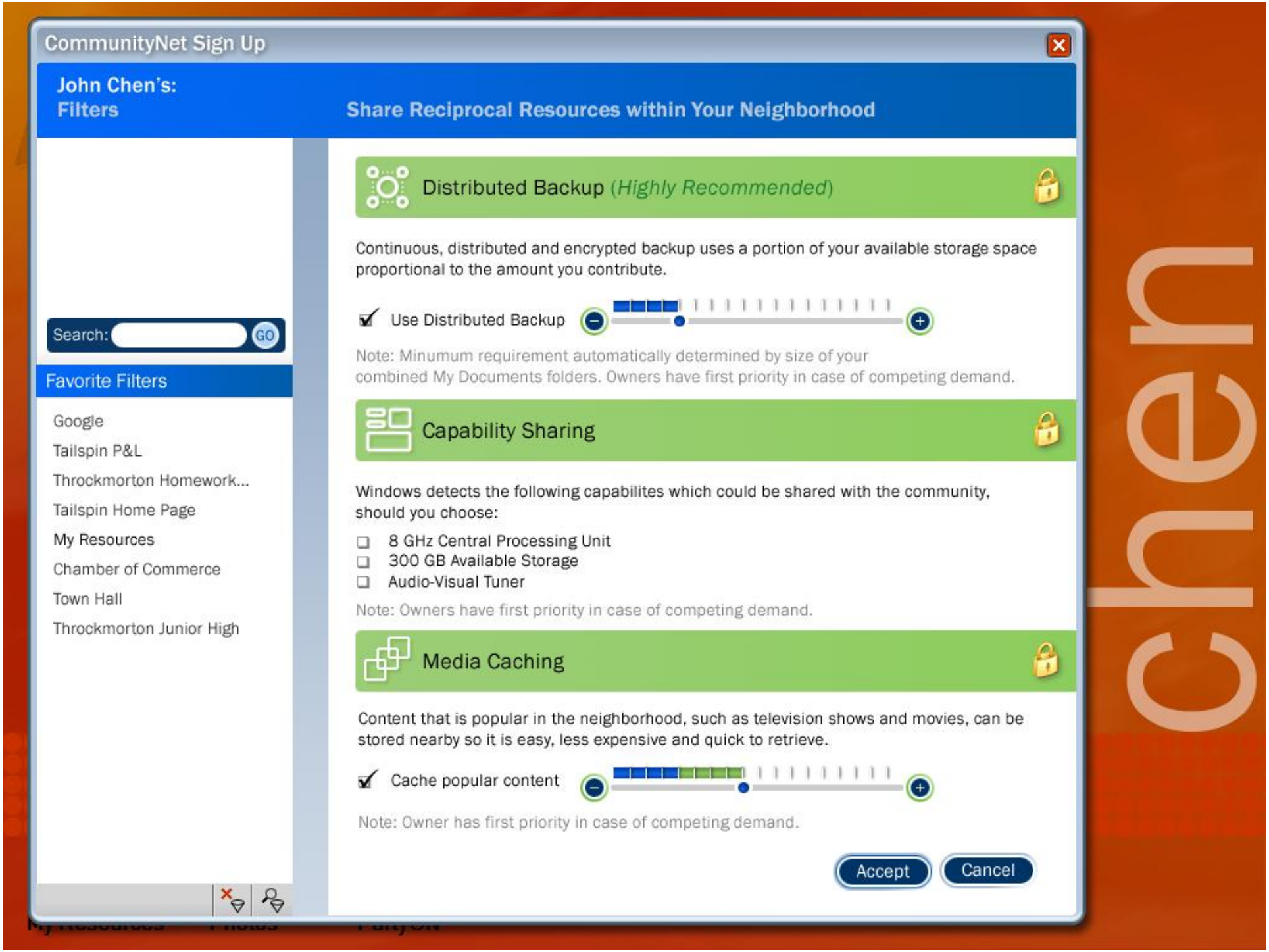
Wanted to record that show, but you were recording something else at the same time? Or simply forgot to set recording up? If anyone near by recorded it, you could still watch it.

Media Caching

Everyone's talking about that movie, but you haven't had a chance to see it yet. Finally, a quiet evening, but who wants to wait hours for it to download? If someone else in the neighborhood has already requested it, you can start watching instantly.

Curious? Dismiss

chen


CommunityNet Sign Up
John Chen's:
Filters
Share Reciprocal Resources within Your Neighborhood
Search:
GO
Favorite Filters
Google
Tailspin P&L
Throckmorton Homework...
Tailspin Home Page
My Resources
Chamber of Commerce
Town Hall
Throckmorton Junior High
Distributed Backup (Highly Recommended)
Continuous, distributed and encrypted backup uses a portion of your available storage space proportional to the amount you contribute.
Use Distributed Backup
Note: Minumum requirement automatically determined by size of your combined My Documents folders. Owners have first priority in case of competing demand.
Capability Sharing
Windows detects the following capabilites which could be shared with the community, should you choose:
8 GHz Central Processing Unit
300 GB Available Storage
Audio-Visual Tuner
Note: Owners have first priority in case of competing demand.
Media Caching
Content that is popular in the neighborhood, such as television shows and movies, can be stored nearby so it is easy, less expensive and quick to retrieve.
Cache popular content
Note: Owner has first priority in case of competing demand.
Accept
Cancel
chen

My Storage

Community Net

My Resources

Photos

PartyON

Community Web Services

These Web Services Are Available To You:

Select all

NeighborPoint – Your central connection to your community and neighbors. Information, events, schools, and community.

County Library System Online – Offers library news, online reference materials, book reservations and checkout, and the library system events calendar.

Woodmark Police Report – Recaps of recent police activity in and around the greater Woodmark area.

County Road Conditions – Traffic reports and Web cams, road conditions, road work schedules, and more that affects how you get to work or get about town.

Woodmark Weather – Live temperatures and conditions from Woodmark and vicinity. Includes water temperatures at the Lake Woodmark swimming area.

Woodmark CityPoint – Information about the city of

OK Cancel

chen

msn

File Edit View Sign Out Help & Settings

MSN Home | Favorites | Search | Mail & More | Messenger | Entertainment | Money | Shopping | People & Chat | Learning | Photos

Woodmark NeighborPoint Community Services

lists | discussions | site help | site moderator | site contacts

search GO

this site | this community | the web

Join the current Party Line! *All audio, all the time*

- Rick & Ann
- **Joe M.**
- Sylvia and Leslie
- Susan
- Alex
- Stefan
- Alan H.
- Dave
- Laura
- Jill
- Perez Family
- Jones Family
- Carole and Bill
- Kim Family

Woodmark Motocross

View All Security Cams

Cam Hill Cougars

Parade Planning

Announcements

- **Found: Siamese cat, "Ting" on license** **NEW!**
- Special at Tailspin Toys, Woodmark residents Only!
- Thank you from residents of Hale House

(more...)

Calendar

- Lake Woodmark Cleanup Sunday 1 pm
- Council Meeting, Tuesday 7 pm
- Neighborhood Watch Thursday 7 pm

(more...)

Quick Links

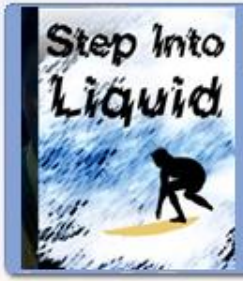
Add new item...

- Babysitters
- Yard Sales
- Missing Pets
- Lost & Found
- Rockwall Elementary
- Throckmorton Middle Sch.
- Cam Hill High School

MOVIE SEARCH RESULTS

Any screen. Any time.
SOUTHWIND VIDEO MOVIE SEARCH

Drama, romance and action movies, with more than 10 Woodmark Great! votes:

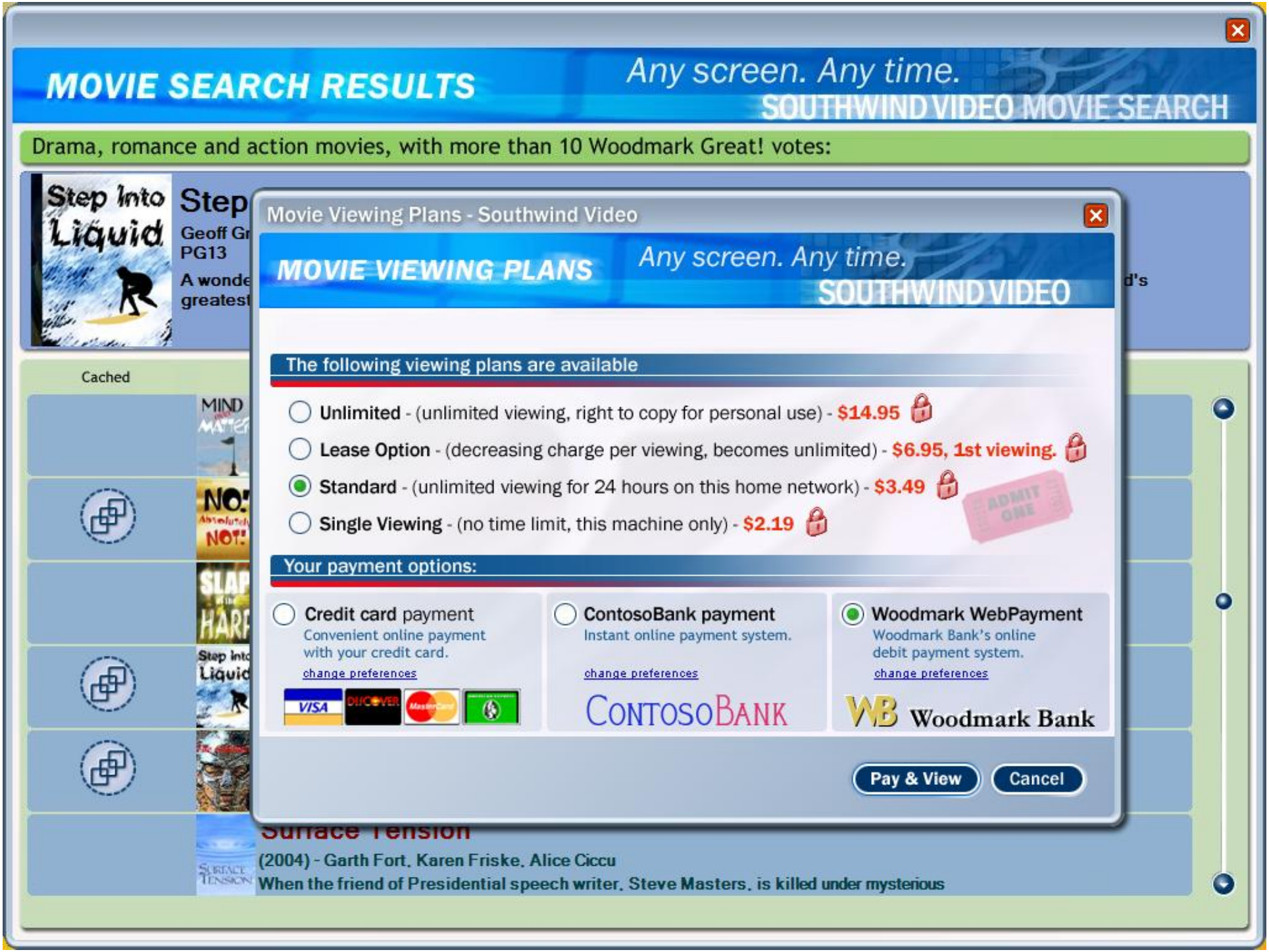


Step Into Liquid

Geoff Grisso, Rob Verhoff, Andrew Dixon, Janice Galvin, Mary E. Gibson
PG13

A wonderful love store set against a backdrop of a hotly contested surfing contest. The story unfolds in the world's greatest surfing locations.

Cached		Title
		**Mind Over Matter** (2005) - Raquel Mello, Linda Mitchell, Kok-Ho Lo For lonely undergrad Misty Shock, life on campus is a series of humiliations and disappointments
		**No! Absolutely Not!** (2003) - Imtiaz Khan, Laura Norman, Amy S. Recker Failing serial entrepreuner, Seymour Slayton, strains to nurture his struggling business. At the
		**Slap of the Harp** (2004) - Magnus Hedlund, Jossej Goldberg, Shane DeSeranno There's a dire problem in the pit. The musicians of the famed Eastern Philharmonic Symphony
		**Step Into Liquid** (2002) - Geoff Grisso, Rob Verhoff, Andrew Dixon A wonderful love store set against a backdrop of a hotly contested surfing contest. The story
		**St Gladiator** (2003) - Jane Clayton, Chris Norred, Jeff Pike Everyone thought he would die at his first appearance in the arena. Not only does he go on to win
		**Surface Tension** (2004) - Garth Fort, Karen Friske, Alice Ciccu When the friend of Presidential speech writer, Steve Masters, is killed under mysterious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Drama, romance and action movies, with more than 10 Woodmark Great! votes:
Step Into Liquid
Step
Geoff Gr
PG13
A wonde
greatest
d's
Movie Viewing Plans - Southwind Video
MOVIE VIEWING PLANS
Any screen. Any time.
SOUTHWIND VIDEO
The following viewing plans are available
Unlimited - (unlimited viewing, right to copy for personal use) - $14.95
Lease Option - (decreasing charge per viewing, becomes unlimited) - $6.95, 1st viewing.
Standard - (unlimited viewing for 24 hours on this home network) - $3.49
Single Viewing - (no time limit, this machine only) - $2.19
ADMIT ONE
Your payment options:
Credit card payment
Convenient online payment with your credit card.
change preferences
VISA
DISCOVER
ContosoBank payment
Instant online payment system.
change preferences
CONTOSOBANK
Woodmark WebPayment
Woodmark Bank's online debit payment system.
change preferences
WB Woodmark Bank
Pay & View
Cancel
Cached
Surface Tension
(2004) - Garth Fort, Karen Friske, Alice Ciccu
When the friend of Presidential speech writer, Steve Masters, is killed under mysterious

Community Network Applications

Internet use in communities increased social contact, public participation and size of social network. (social capital - access to people, information and resources)

Keith N. Hampton, MIT (author of "Netville Neighborhood Study")

URL: http://www.asanet.org/media/neville.html

- Shared Broadband Internet Access
- Ubiquitous Access (roaming solved: one "true" network)
- Neighborhood Gaming
- Medical & emergency response
- Neighborhood watchdog (e.g. video surveillance)
- Shared Community Resource
  - Media repository
  - Distributed backup

Mesh Viability & Challenges

Community Network Formation

Question

How many homes in the neighborhood have to sign up before a viable mesh forms?

Answer depends on

- Definition of “viable”
- Wireless range
- Neighborhood topology
- Probability of participation by a given houshold

Example Scenario

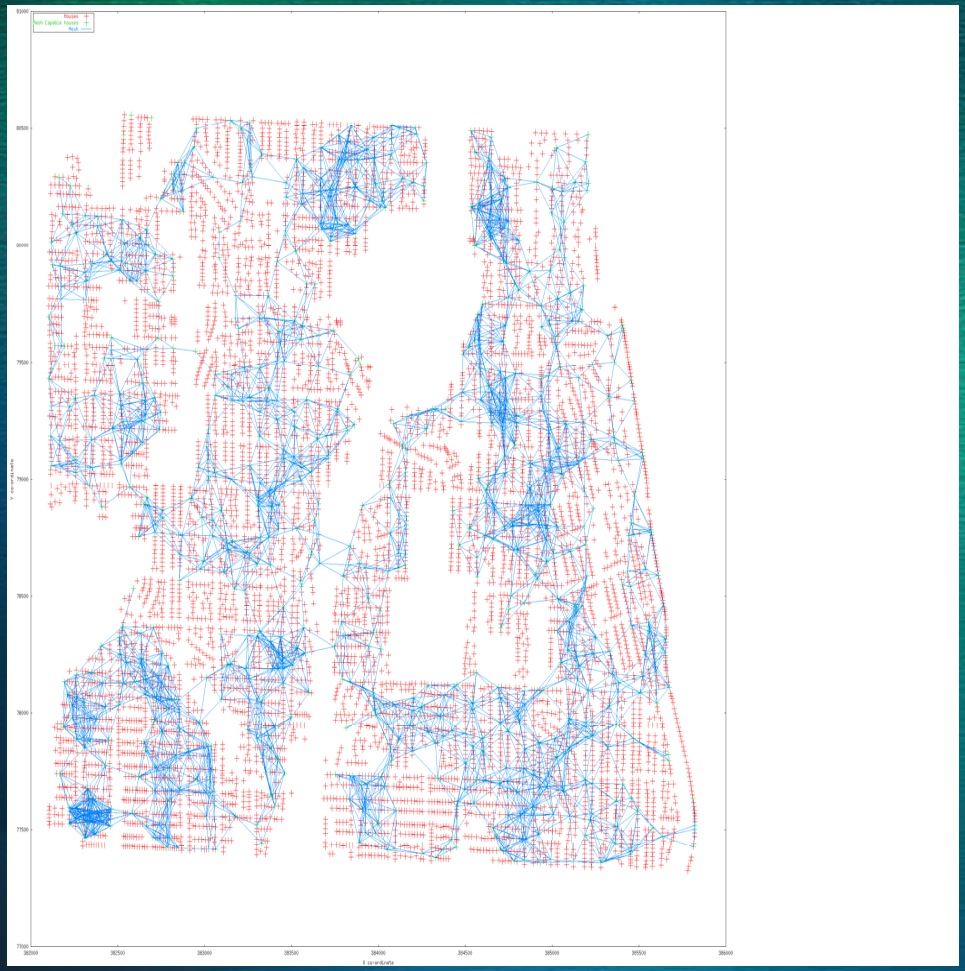
Viable mesh: group of at least 25 houses that form a connected graph

Topology: A North Seattle Neighborhood. 8214 houses, 4Km x 4Km

Wireless range: 50, 100, 200 and 1000 meters

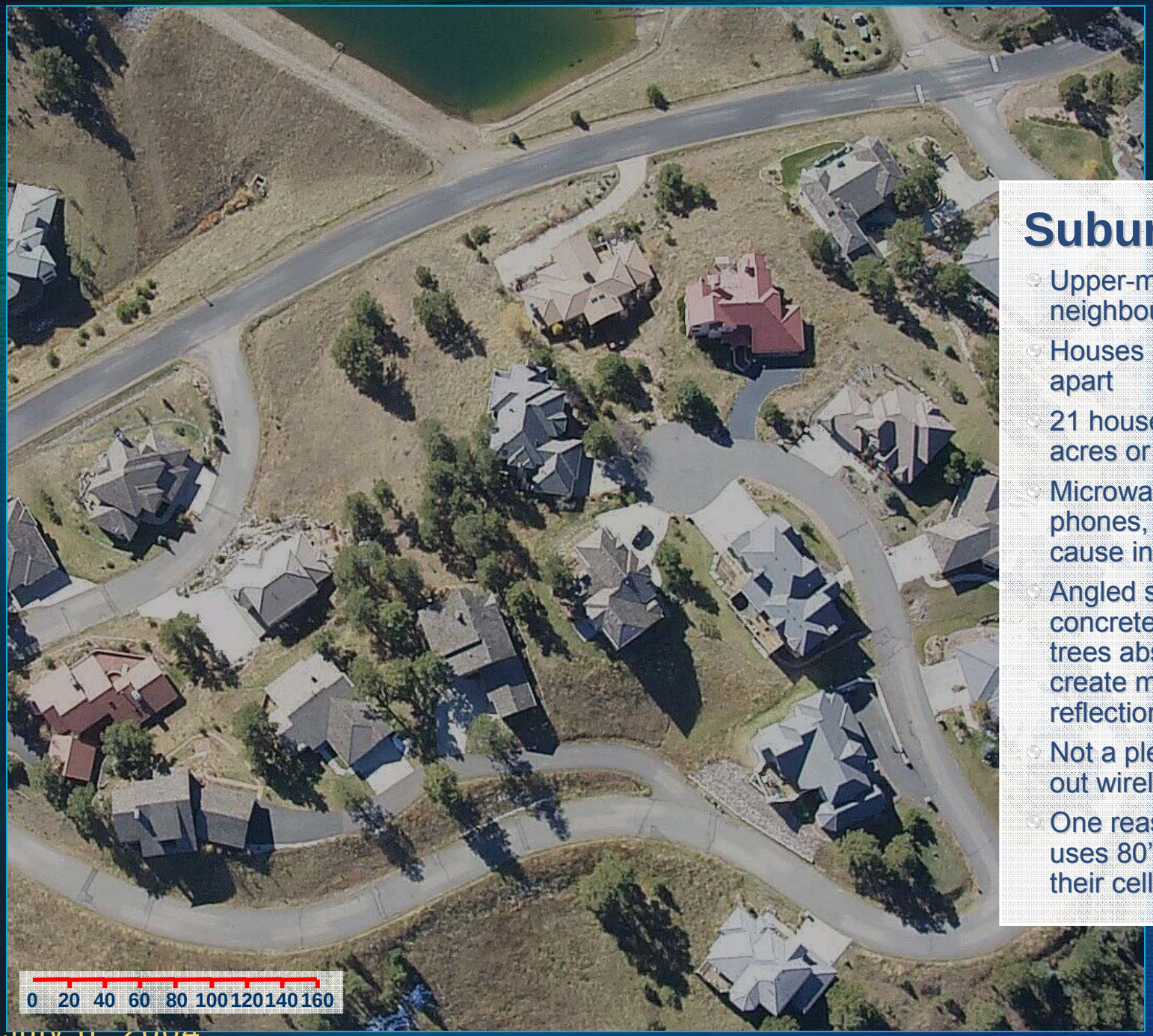
Houses decide to join at random, independent of each other. We consider 0.1% to 10% participation rates.

Mesh Formation



- 5-10% subscription rate needed for suburban topologies with documented wireless ranges
- 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 will be important

Increasing range is key for good mesh connectivity



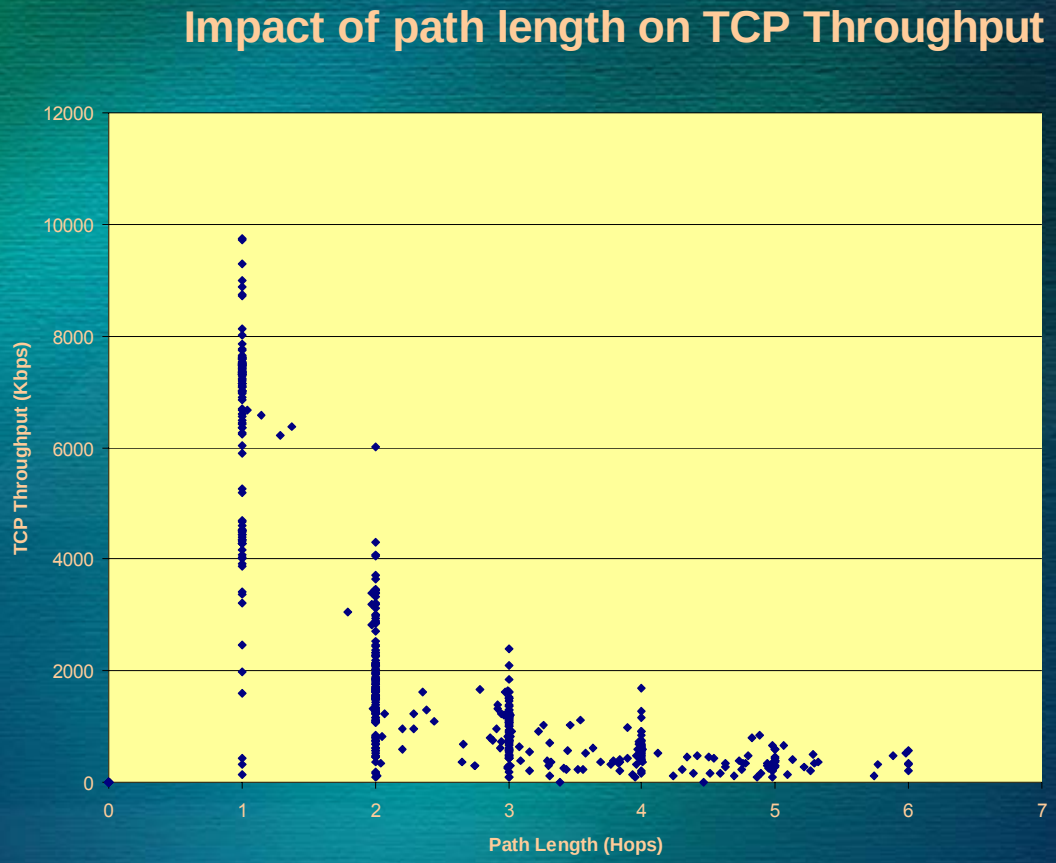
Suburbia

- Upper-middle class neighbourhood
- Houses about 40-120’ apart
- 21 houses covering 7.8 acres or ~1/3 acre lots
- Microwave ovens, cordless phones, televisions etc. cause interference
- Angled sheetrock and concrete walls, hills and trees absorb signal and create multi-path reflections
- Not a pleasant place to roll out wireless
- One reason why cellular uses 80’-100’ masts for their cell towers

5 GHz:

- Bandwidth is good, provided you can get a mesh to form
- Published 802.11a ranges led us to believe we could achieve the yellow circle
- Measured range from the apartment trial is the red circle
- Range is not sufficient to bootstrap mesh until installed % is quite high (in this diagram ~50%)

802.11a in a Multihop Network

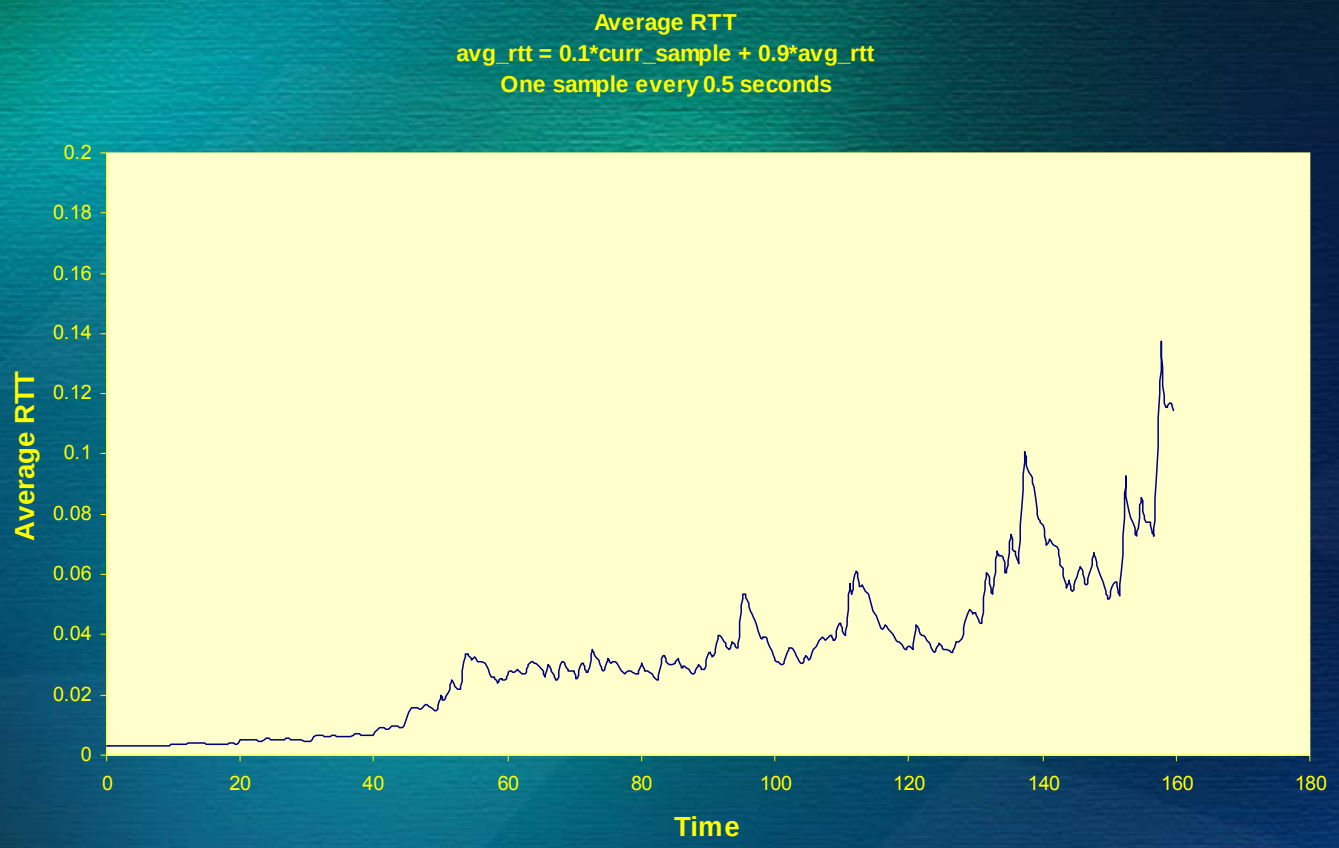


R. Draves, J. Padhye, and B. Zill

Comparison of Routing Metrics for Static Multi-Hop Wireless Networks

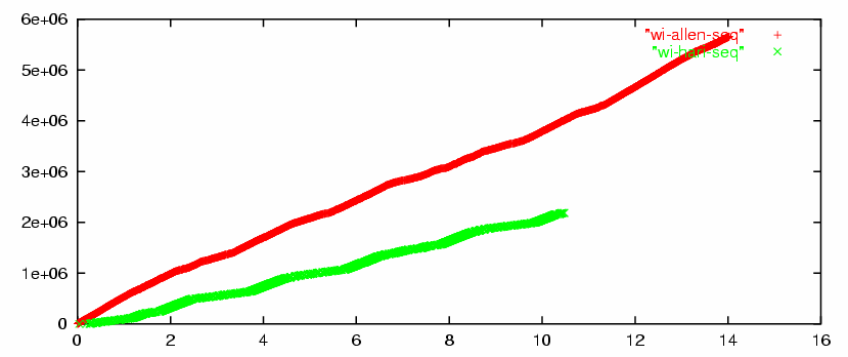
ACM SIGCOMM 2004 (also Technical Report, MSR-TR-2004-18, March 2004)

Round Trip Delay

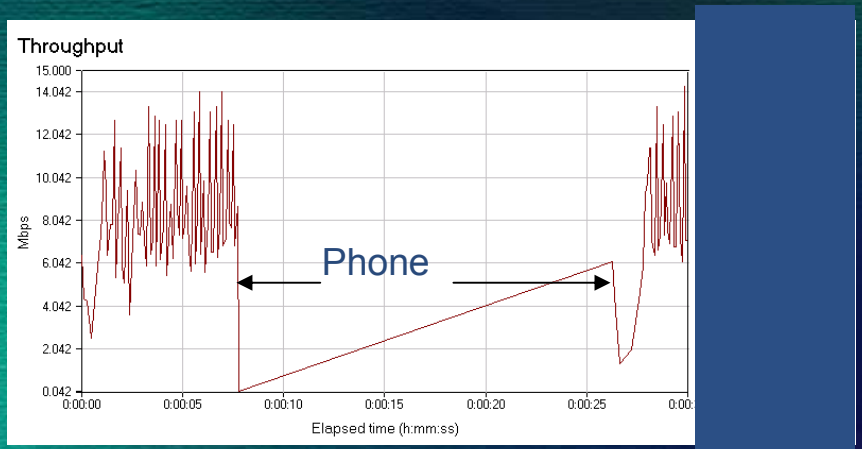


A new 100Kbps CBR connection starts every 10 seconds, between a new pair of nodes. All nodes hear each other.

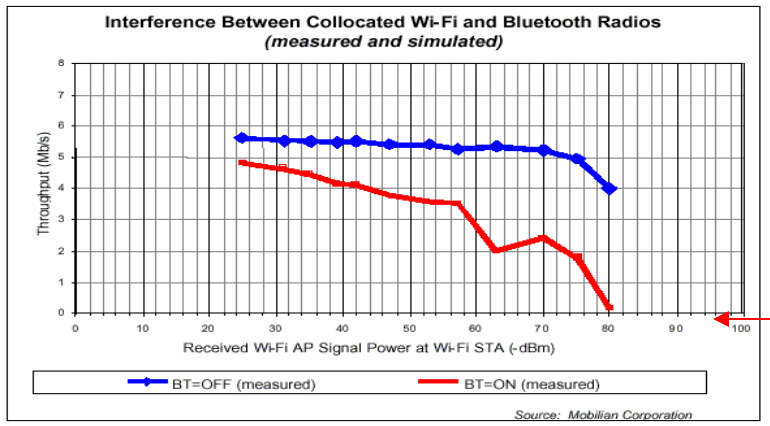
Colliding Communications



TCP download from a 802.11 AP



Panasonic 2.4GHz Spread Spectrum
Phone 5 m and 1 wall from receiver



Performance worsens when there are large number of short-range radios in the vicinity

Badly written rules: Colliding standards

Victor Bahl, Amer Hassan, Pierre De Vries, **Spectrum Etiquettes for Short Range Wireless Devices Operating in the Unlicensed Band**, White paper, Spectrum Policy: Property or Commons, Stanford Law School

Conclusion

Meshes are viable

existing technologies are inadequate

To make them real

Identify and solve key problems

build & deploy meshes

in a variety of RF environments

Problem Space

Range and Capacity

- Inexpensive electronically steerable directional antenna or MIMO for range enhancement
- Multiple frequency meshes
- Multi-radio hardware for capacity enhancement via greater spectrum utilization
- New data channel MAC with Interference management or higher throughput

Multihop Routing

- L2.5 on-demand source routing with link quality based routes selection
- Route selection with multiple radios (multiple channels)

Security, Privacy, and Fairness

- Guard against malicious users (and freeloaders)
- EAP-TLS between MeshBoxes, PEAPv2 or EAP-TLS between clients and MeshBoxes
- Priority based admission control, Secure traceroute

Self Management & Self Healing

- Minimal human intervention - avoid network operator
- Watchdog mechanism with data cleaning and liar detection
- Online simulation based fault isolation and diagnosis

Problem Space (Cont.)

Smart Spectrum Utilization

- Spectrum etiquettes and/or rules
- Agile radios, cognitive radios, 60 GHz radio, underlay technologies
- Cognitive software & applications

Analytical Tools

- Information theoretic tools that predict network viability & performance with practical constraints, based on experimental data

Ease of use (Plug and play, HCI)

- Pleasant, hassle-free user experience
- QoS protocols to improve content delivery

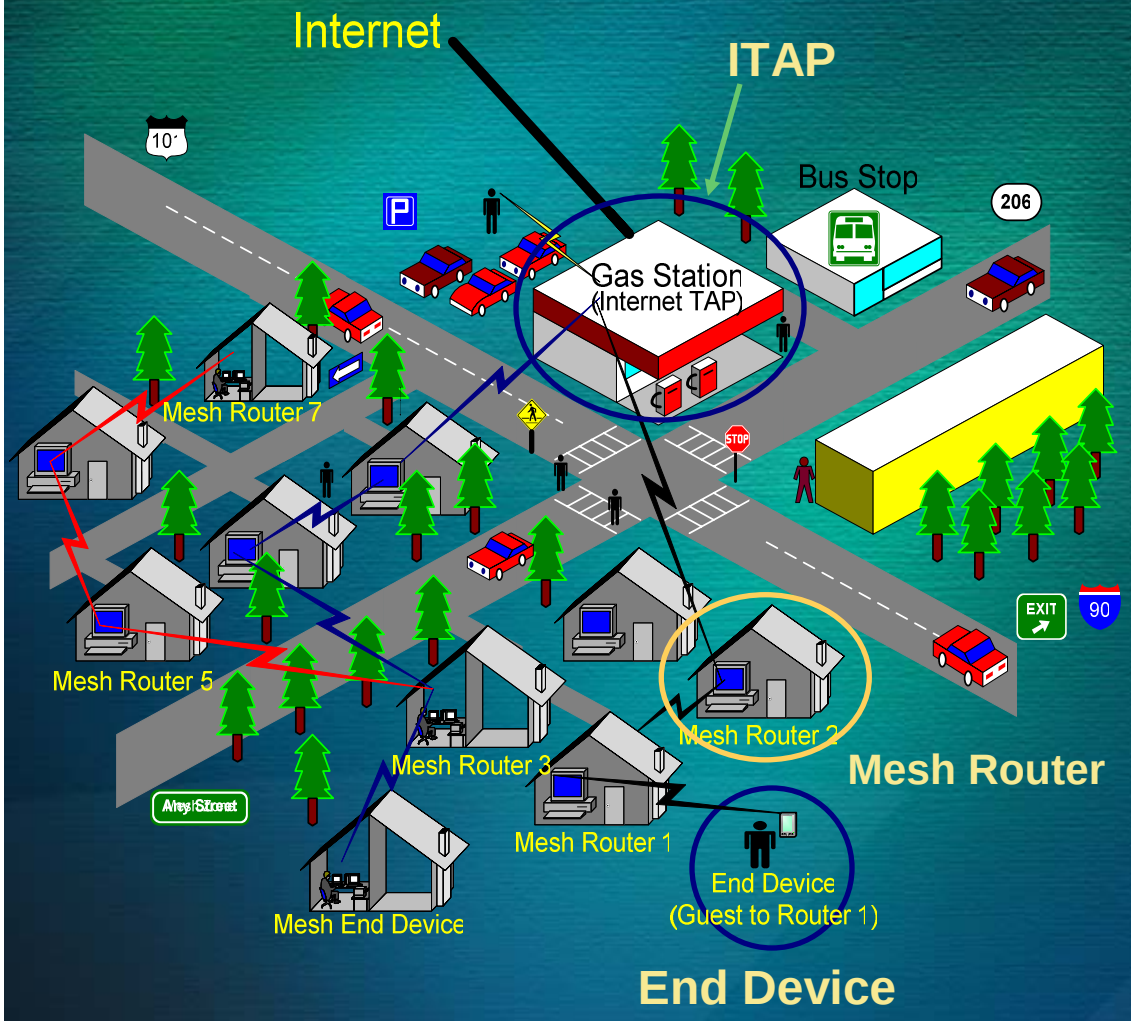
Digital Rights Management (DRM)

- Broadband access popularity related to expanded digital content.
- Increase the value proposition for end-users/subscribers

Proof of concept via rapid prototyping and testbed deployments

Mesh Architecture

Scenario: Neighborhood Wireless Meshes



End Device

- Connects to a Mesh Router
- Standards Compliant Network Interface

Mesh Router / MeshBox

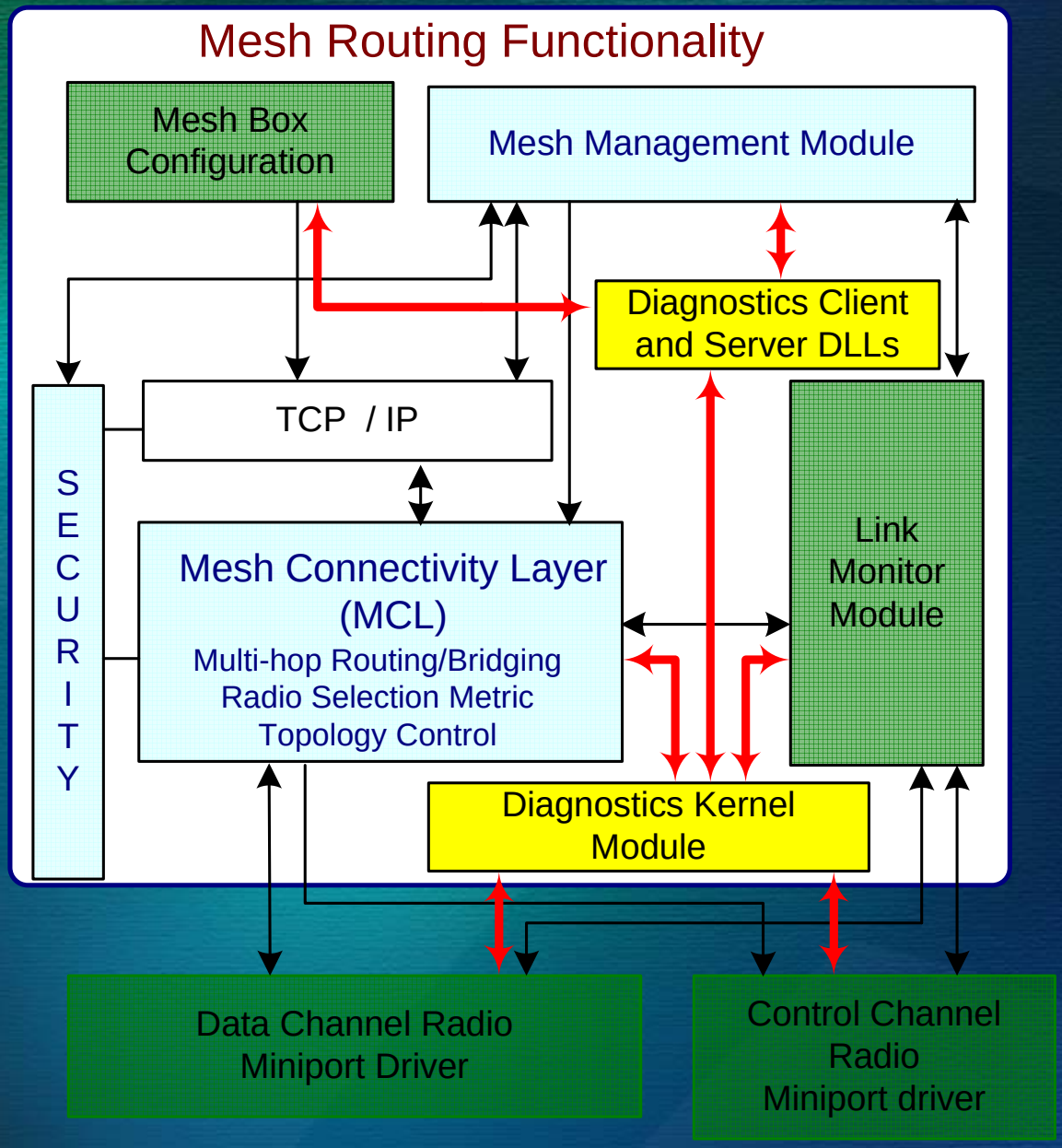
- Routes traffic within the mesh and to the neighborhood Internet Gateway
- Serves as access point for End Devices

Neighborhood Internet Gateway

- Gateway between the mesh nodes and the Internet

Key: Multiple radios, cognitive software

Mesh Routing Functionality



Capacity Estimation & Improvement

K. Jain, J. Padhye, V. Padmanabhan, L. Qiu.
Impact of Interference on Multi-hop Wireless Network Performance
ACM Mobicom, San Diego, CA, September 2003

Victor Bahl, Ranveer Chandra, John Dunagan,
***SSCH: Slotted Seeded Channel Hopping for Capacity Improvement in IEEE 802.11 Ad-Hoc Wireless Networks*,**
ACM MobiCom 2004,Philadelphia, PA, September 2004

Calculating Mesh Capacity

Previous work focused on determining asymptotic, pessimistic bounds

- Gupta and Kumar 2000: O(1/sqrt(N))

We focus on achievable capacity of specific topologies with specific technologies and traffic patterns

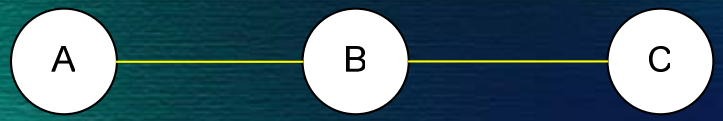
Example: 4 houses talk to the central ITAP. What is the maximum possible throughput?

Asymptotic analysis is not useful in this case

Analytical Framework

Connectivity Graph

- Models node connectivity
- Incorporates capacity of each link



Conflict Graph

- Captures interference among links

Tool

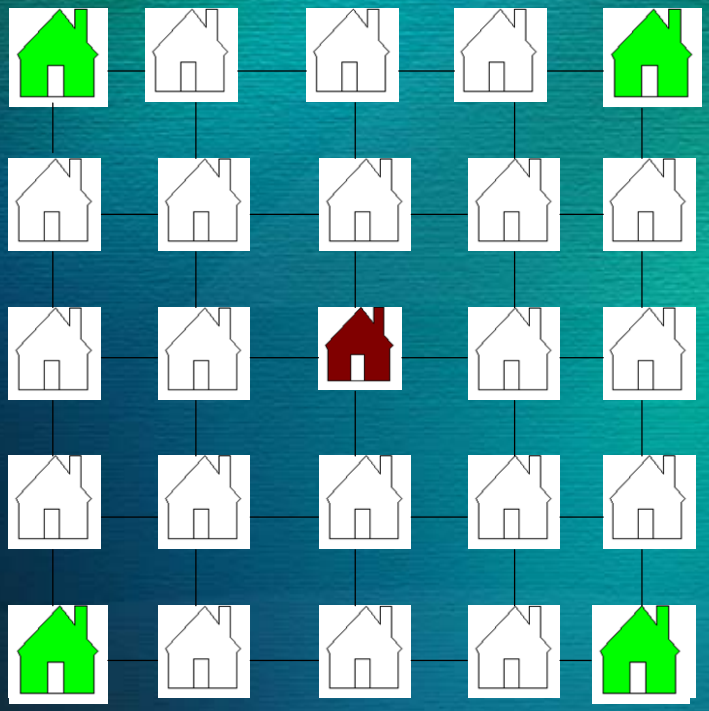
- Solves MAXFLOW problem on the connectivity graph with constraints drawn from the conflict graph

“What-if” Analysis

- Scenario based numbers instead of asymptotic bounds
- Allows evaluation of different wireless technologies

Sample Results: What-if Analysis

Example: 4 houses talk to the central ITAP. What is the maximum possible throughput?



Scenario	Aggregate Throughput
Baseline	0.5
Double range	0.5
Two Radios	1

Conclusion
Two radios are better than one

Houses talk to immediate neighbors, **All links have capacity 1**, 802.11 MAC, Multipath routing.

Question:
Are 3 radios better than 2? What is the optimum number?

Capacity Improvement

Problem

Improve throughput via better utilization of the spectrum

Design Constraints

Require only a single radio per node

Use unmodified IEEE 802.11 protocol

Do not depend on existence of a rendezvous channel

Assumption

Node is equipped with an omni-direction antenna

- MIMO technology is OK

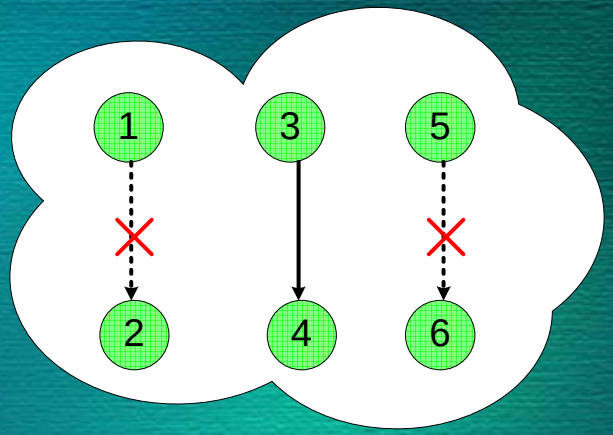
Multiple orthogonal channels are available

Channel switching time is 80 usecs.

- current speeds 150 microseconds

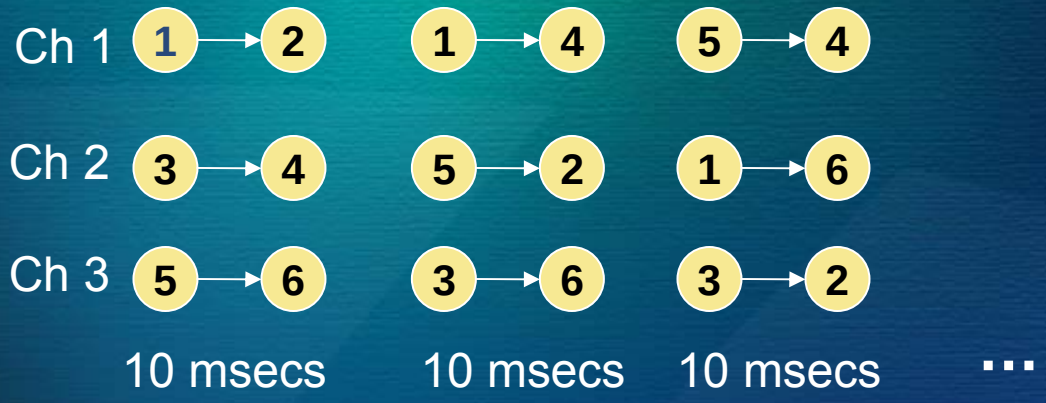
Capacity Improvement

In current IEEE 802.11 meshes



Only one of 3 pairs is active @ any given time

With MSR's SSCH enabled meshes



Slotted Seeded Channel Hopping

Approach

- Divide time into slots
- At each slot, node hops to a different channel (to distribute traffic)
- Senders and receiver probabilistically meet and exchange schedule
- Senders loosely synchronize hopping schedule to receivers
- Implement as a layer 2.5 protocol (works over MultiNet)

Features

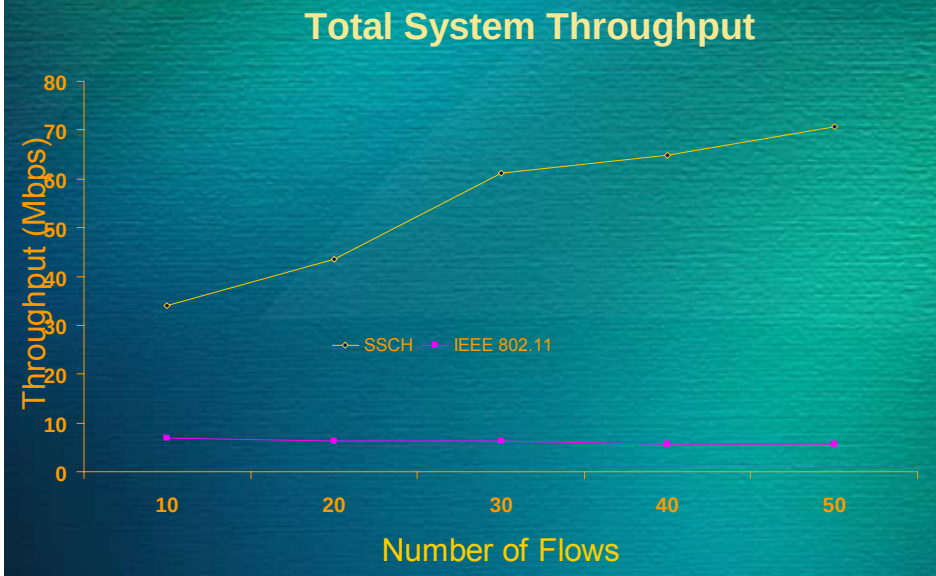
- Distributed: every node makes independent choices
- Optimistic: exploits common case that nodes know each others' channel hopping schedules
- Traffic-driven: nodes repeatedly overlap when they have packets to exchange

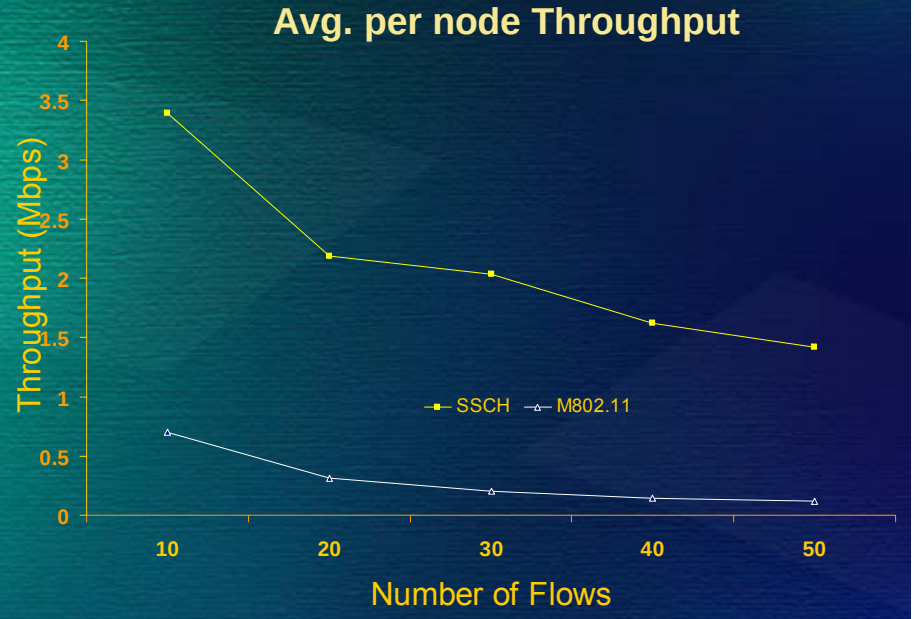
Prior Work

- SEEDEX (MobiHoc '01), TSMA (ToN '97), multi-channel MAC (VTC '00, MobiHoc '04),

Performance

QualNet Simulation: 100 nodes, IEEE 802.11a, 13 channels, every flow is multihop





Significant capacity improvement when traffic load is on multiple separate flows

Routing in Wireless Meshes

Richard Draves, Jitendra Padhye, and Brian Zill
Routing in Multi-radio Multi-hop in Wireless Meshes
ACM MobiCom 2004, September 2004

Atul Adya, Victor Bahl, Jitendra Padhye, Alec Wolman, and Lidong Zhou.
A Multi-Radio Unification Protocol for IEEE 802.11 Wireless Networks
IEEE BroadNets 2004 (also Technical Report, MSR-TR-2003-41, June 2003)

Mesh Connectivity Layer (MCL)

Design

Multi-hop routing at layer 2.5

Framework

- NDIS miniport – provides virtual adapter on virtual link
- NDIS protocol – binds to physical adapters that provide next-hop connectivity
- Inserts a new L2.5 header

Features

- Works over heterogeneous links (e.g. wireless, powerline)
- Implements DSR-like routing with optimizations at virtual link layer
  We call it **Link Quality Source Routing (LQSR)**
- Incorporates Link metrics: hop count, MIT's ETX, MSR's WCETT
- Transparent to higher layer protocols. Works equally well with IPv4, IPv6, Netbeui, IPX, …

Source & Binary Download

Available @ http://research.microsoft.com/mesh

Radio Selection Metric

State-of-art metrics (shortest path, RTT, MIT's ETX) not suitable for multiple radio / node

- Do not leverage channel, range, data rate diversity

Multi-Radio Link Quality Source Routing (MR-LQSR)

- Link metric: **Expected Transmission Time (ETT)**
  - Takes bandwidth and loss rate of the link into account
- Path metric: **Weighted Cumulative ETTs (WCETT)**
  - Combine link ETTs of links along the path
  - Takes channel diversity into account
- Incorporates into source routing

Expected Transmission Time

Given:

- Loss rate *p*
- Bandwidth B
- Mean packet size S
- Min backoff window CW_{min}

$$ETT = ET_{xmit} + ET_{backoff}$$

Where:

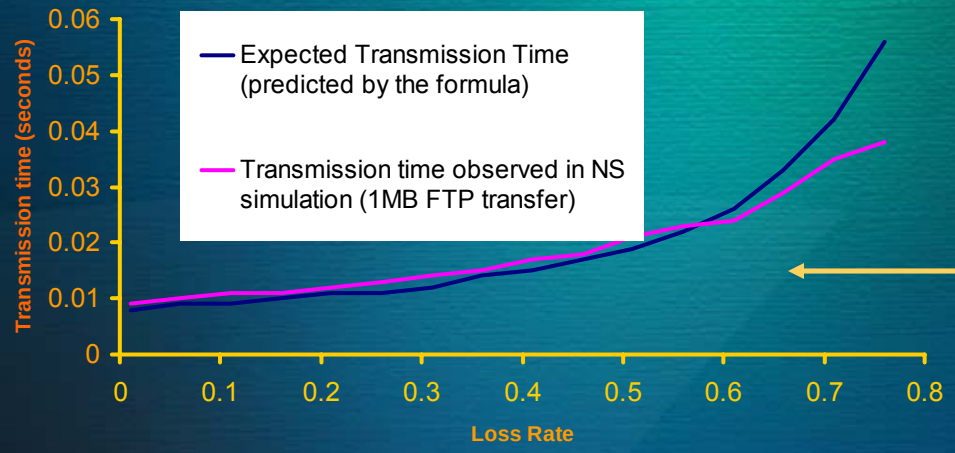
$$ET_{xmit} = \frac{S}{B(1-p)}$$

$$ET_{backoff} = \frac{CW_{min} f(p)}{2(1-p)}$$

Where:

$$f(p) = 1 + \sum_{i=0}^{i=7} 2^{(i-1)} p^i$$

Expected and Simulated Transmission times
S = 1000 Bytes, B = 1Mbps, CWmin = 320 microsec



Formula matches simulations

WCETT = Combining link ETTs

Need to avoid unnecessarily long paths

- bad for TCP performance
- bad for global resources

All hops on a path on the same channel interfere

- Add ETTs of hops that are on the same channel
- Path throughput is dominated by the maximum of these sums

Given a *n* hop path, where each hop can be on any one of *k* channels, and two tuning parameters, *a* and *b*:

$$WCETT = \frac{\left(a * \sum_{i=1}^{n} ETT_i\right) + \left(b * \max_{1 \le j \le k} X_j\right)}{a+b}$$

where

$$X_j = \sum_{\text{hop } i \text{ is on channel } j} ETT_i$$

Select the path with **min WCETT**

Results

Test Configuration

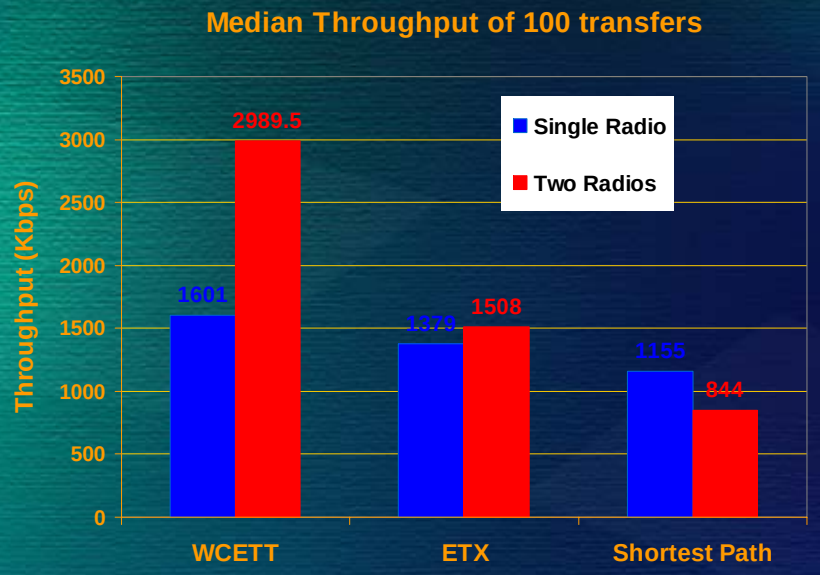
- Randomly selected 100 sender-receiver pairs (out of 23x22 = 506)
- 2 minute TCP transfer

Two scenarios:

- Baseline (Single radio):
  - 802.11a NetGear cards
- Two radios
  - 802.11a NetGear cards
  - 802.11g Proxim cards

Repeat for

- Shortest path
- MIT's ETX metric
- MSR's WCETT metric



WCETT utilizes 2nd radio better than ETX or shortest path

Troubleshooting Mesh Networks

Lili Qiu, Victor Bahl, Ananth Rao, Lidong Zhou,
A Novel Framework for Troubleshooting Multihop Wireless Networks
September 2003, *MSR Tech Report*

Goals

"Network management is a process of controlling a complex data network so as to maximize its efficiency and productivity"

Reactive and Pro-active Troubleshooting

Investigate reported performance problems

- Time-series analysis to detect deviation from normal behavior

Localize and isolate trouble spots

- Collect and analyze traffic reports from mesh nodes

Determine possible causes for the trouble spots

- Interference, or hardware problems, or network congestion, or malicious nodes ….

Respond to troubled spots

- Re-route traffic
- Rate limit
- Change topology via power control & directional antenna control
- Flag environmental changes & problems

Challenges in Fault agnosis

Characteristics of multi-hop wireless networks

- Unpredictable physical medium, prone to link errors
- Network topology is dynamic
- Resource limitation calls for a diagnosis approach with low overhead
- Vulnerable to link attacks

Identifying root causes

- Just knowing link statistics is insufficient
- Signature based techniques don't work well
  - Determining normal behavior is hard

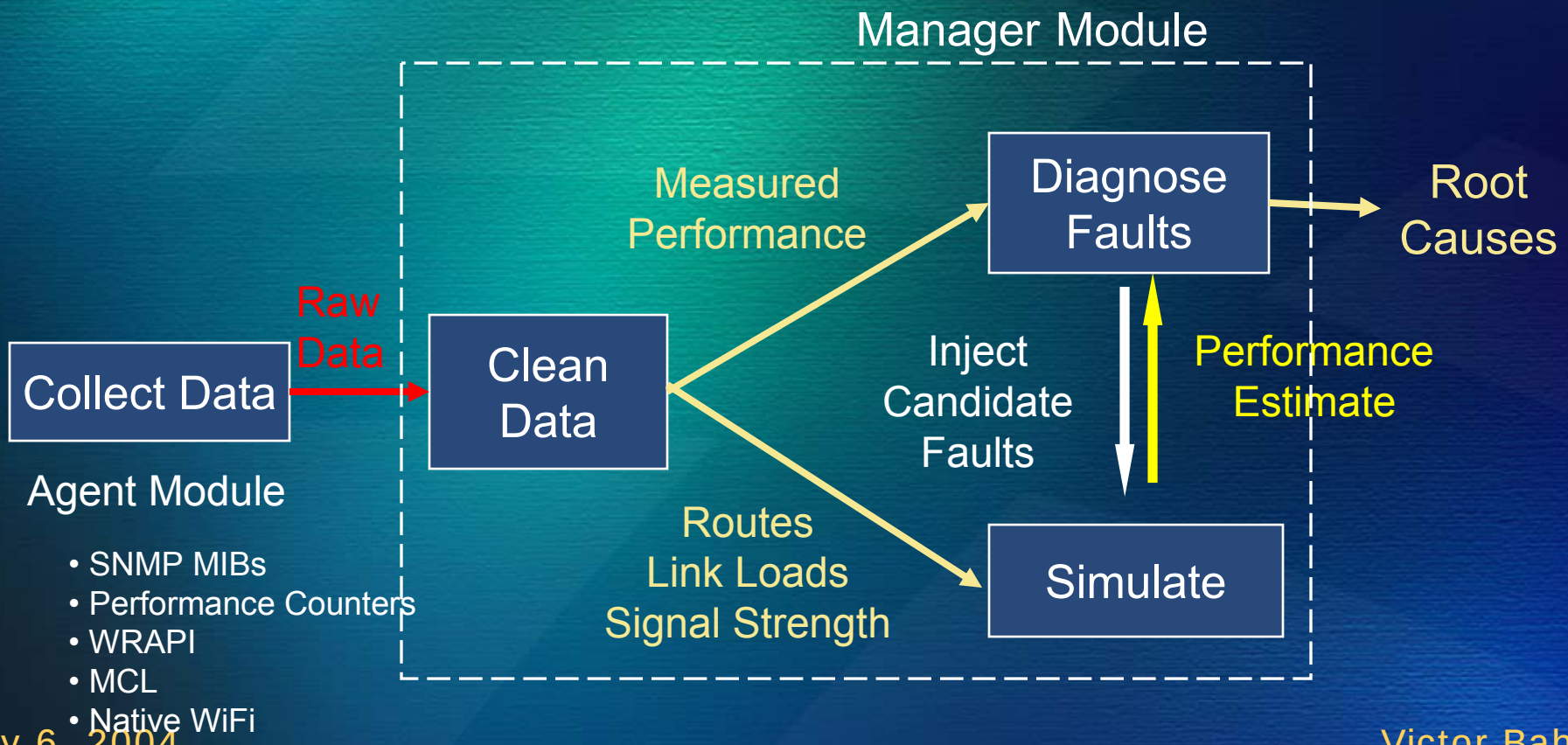
Handling multiple faults

- Complicated interactions between faults and traffic, and among faults themselves

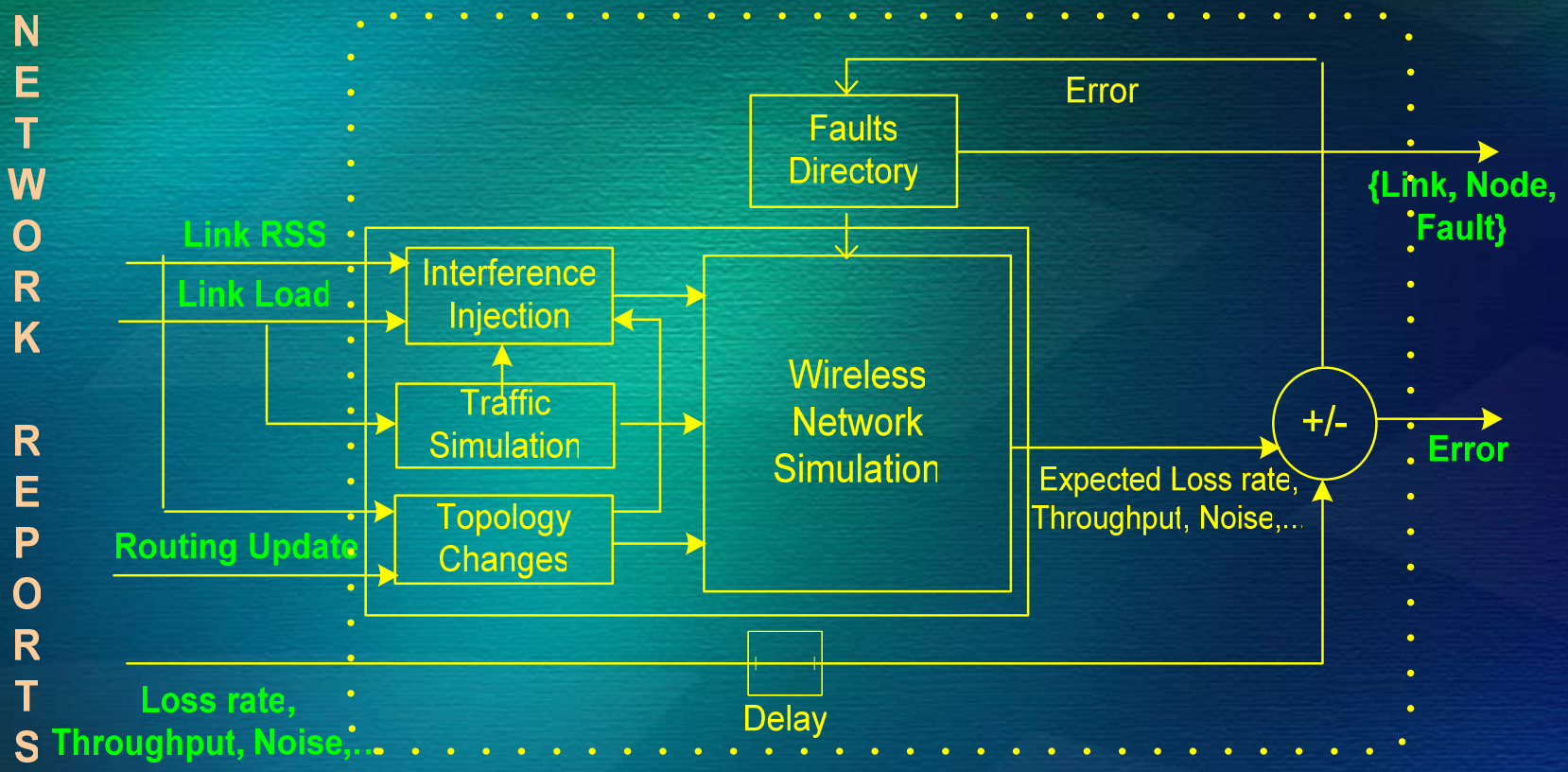
Our Approach

Steps to diagnose faults

- Establish normal behavior
- Deviation from the normal behavior indicates a potential fault
- Identify root causes by efficiently searching over fault space to re-produce faulty symptoms



Root Cause Analysis Module



Diagnosis Performances

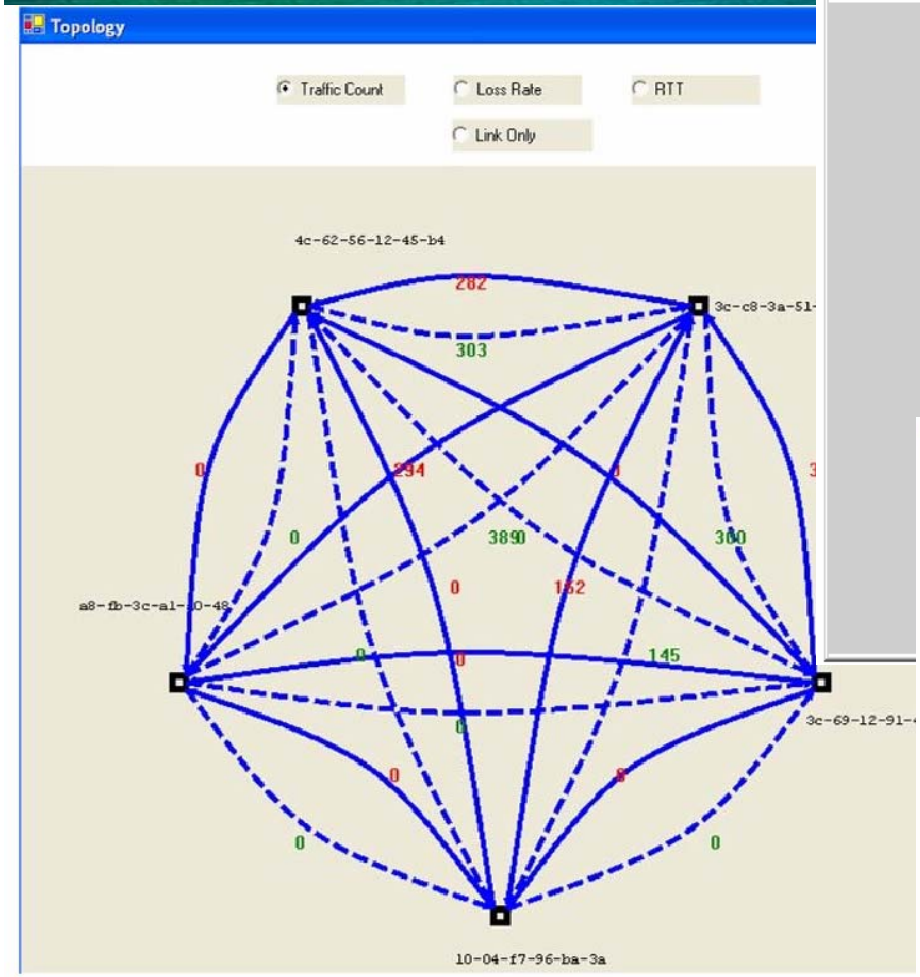
25 node random topology

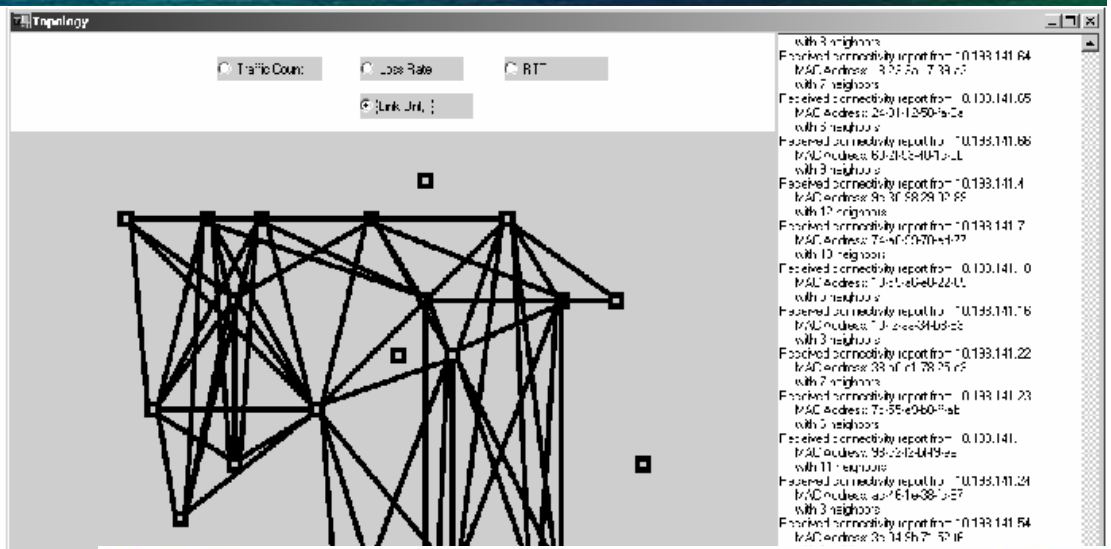
Number of faults	4	6	8	10	12	14
Coverage	1	1	0.75	0.7	0.92	0.86
False Positive	0	0	0	0	0.25	0.29

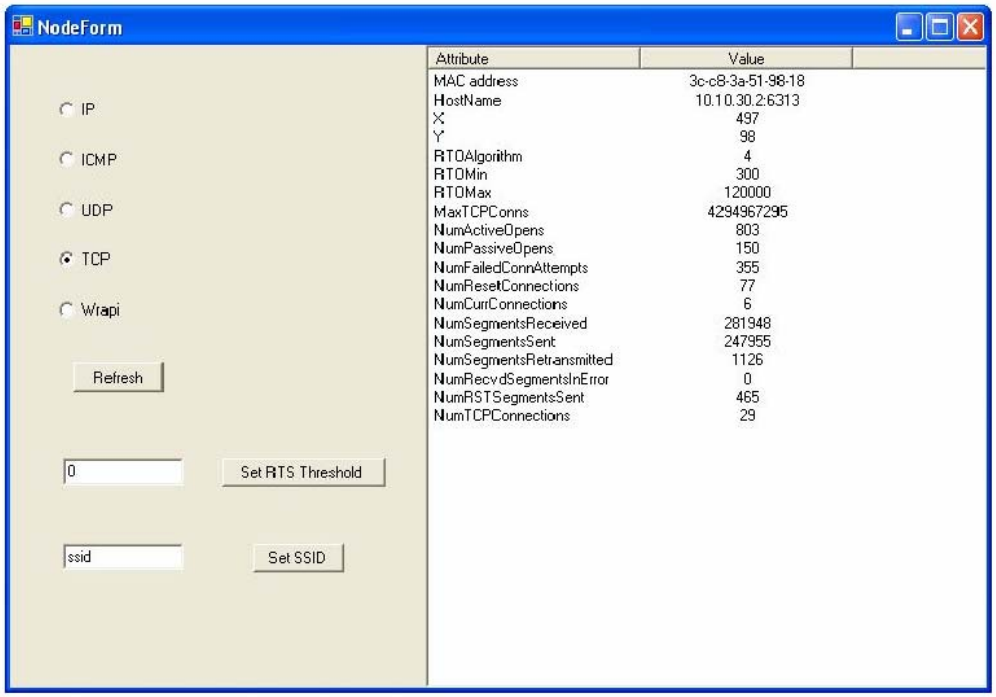
Faults detected:

- Random packet dropping
- MAC misbehavior
- External noise

Mesh Visualization Module







Testbeds & Trials

Testbeds

Details

25 to 30 nodes

Inexpensive desktops (HP d530 SF)

Two 802.11 radios in each node

- NetGear WAG or WAB, Proxim OriNOCO
- Cards can operate in a, b or g mode.

Purpose

Verification of the mesh software stack

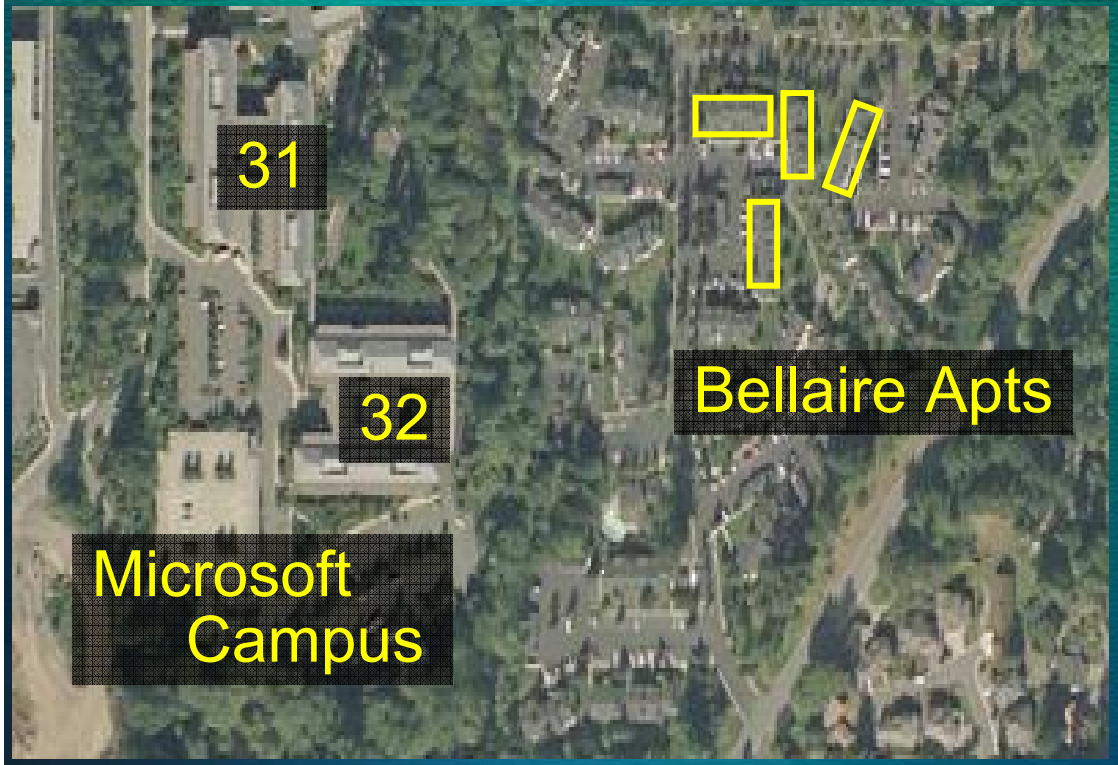
- Routing protocol behavior
- Fault diagnosis and mesh management algorithms
- Security and privacy architecture
- Range and robustness @ 5 GHz with different 802.11a hardware

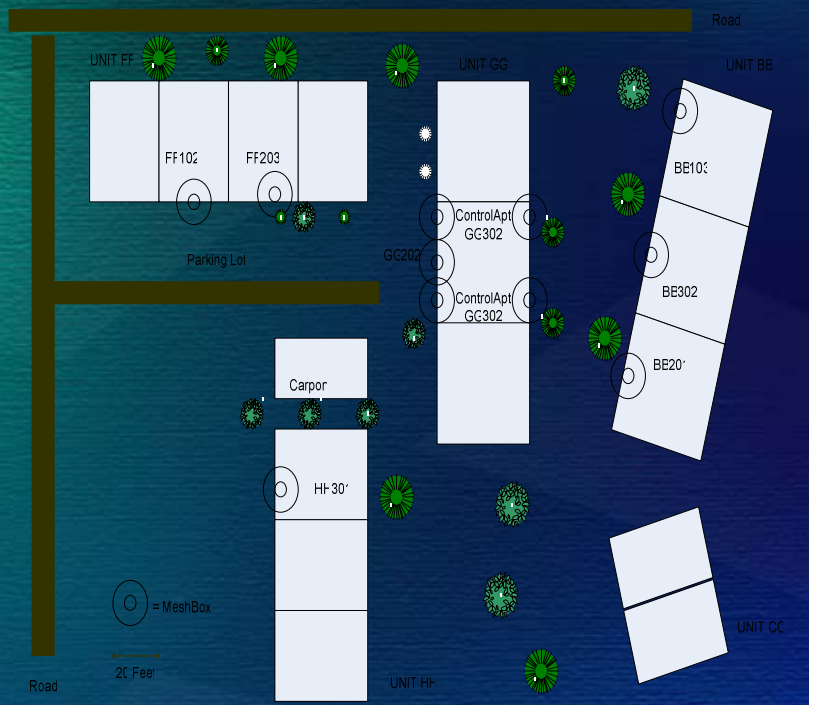
Stress Testing

Various methods of loading testbed:

- Harpoon traffic generator (University of Wisconsin)
- Peer Metric traffic generator
- Ad-hoc use by researchers

Redmond Apartment Trials





Redmond Apartment Trial


Control Apt GG302


Mesh Box


Apt FF201


Mesh Hall (Kitchen)

Cambridge UK Trial

Venice

Deployed by The Venice Team

Working with *ehome* to create a media sharing demo in collaboration with ZCast DVB trial

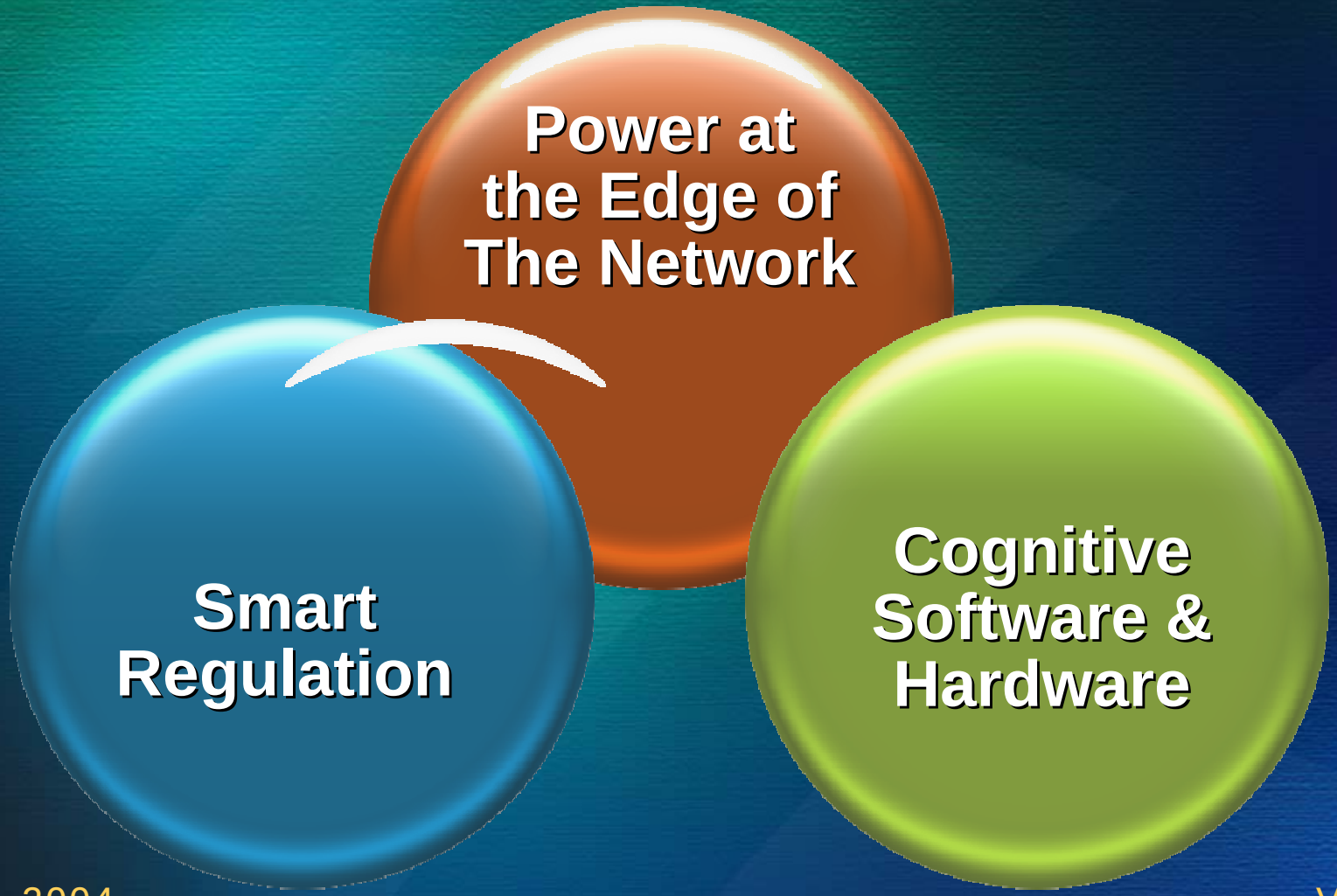
10 node mesh

Latest Mesbox

Victor Bahl

Going Forward

Elements of the converging Digital Future



July 6, 2004

Victor Bahl

Call To Action

Together academia, government, and industry must develop common vision

Perform scenario & systems based research tackling hard problems

Partner in building and deploying real-world test beds

Resources

Software, Papers, Presentations, articles etc.

- URL: http://research.microsoft.com/mesh/

Contact

- Victor Bahl, bahl@microsoft.com

Mesh Networking Summit 2004

- Videos, Presentations, Notes etc.

  URL: http://research.microsoft.com/meshsummit/