User Provided & Community Networks as *μ*-Operators in *Cognitive* Dynamic Spectrum Access

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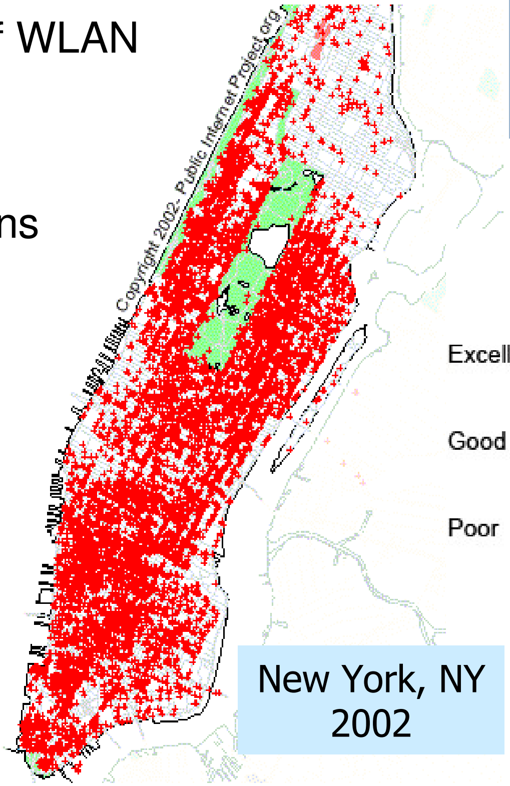
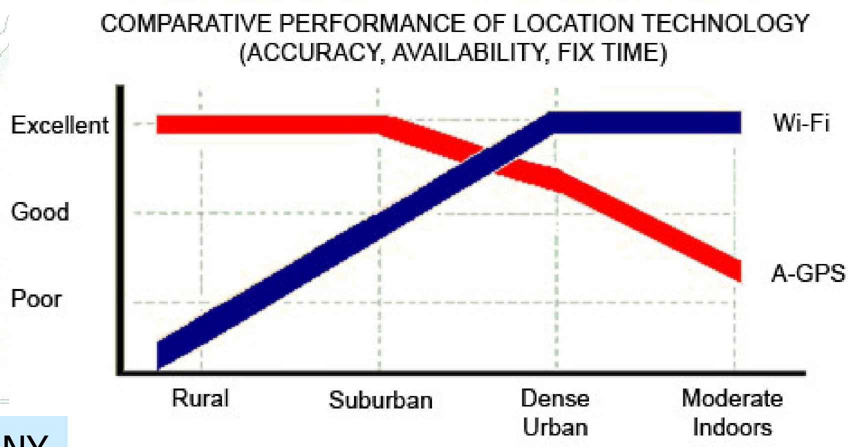
Cognition and Cooperation in the Mobile Internet

Numerous Wireless Nets in Metropolitan Areas…

- So many Wi-Fi’s that…
  you can base a business on their existence…
- The case of Skyhook Wireless, Inc.
  - Wi-Fi Positioning System: a GPS-like service
  - Relies on database of WLAN beacon signals
  - 70% of US, CDN, & Australian populations
  - by the end of 2007:
    - top 50 metropolitan areas in Europe &
    - top 15 cities in Asia





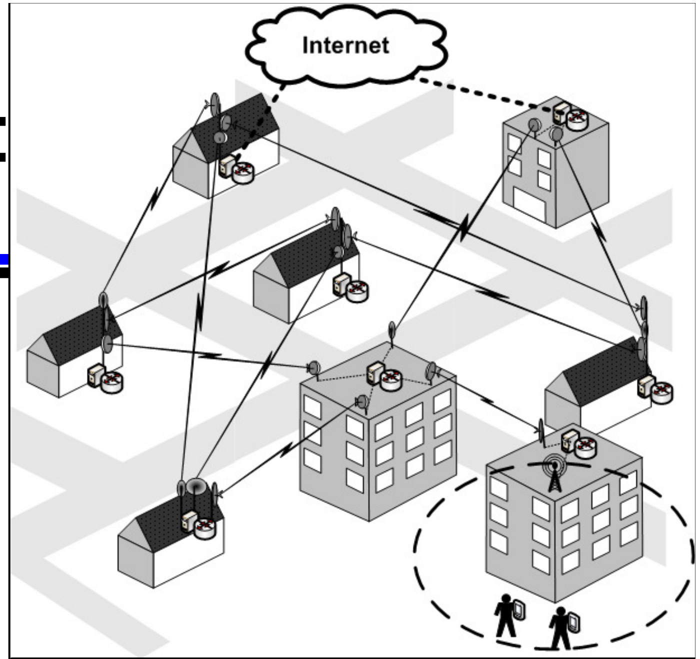
Wireless Community Networks (WCNs)

Wireless Community Network History

- Birth [late 90s, early 00s]
  - Fixed broadband: expensive and scarce
  - Experiments with Wi-Fi-based long distance links
  - First WCNs:
    - SeattleWireless (2000)
    - NYCWireless (2001)
    - Athens Wireless Metropolitan Network (2002)
  - In Greece: community-wide broadband services in the dial-up era!

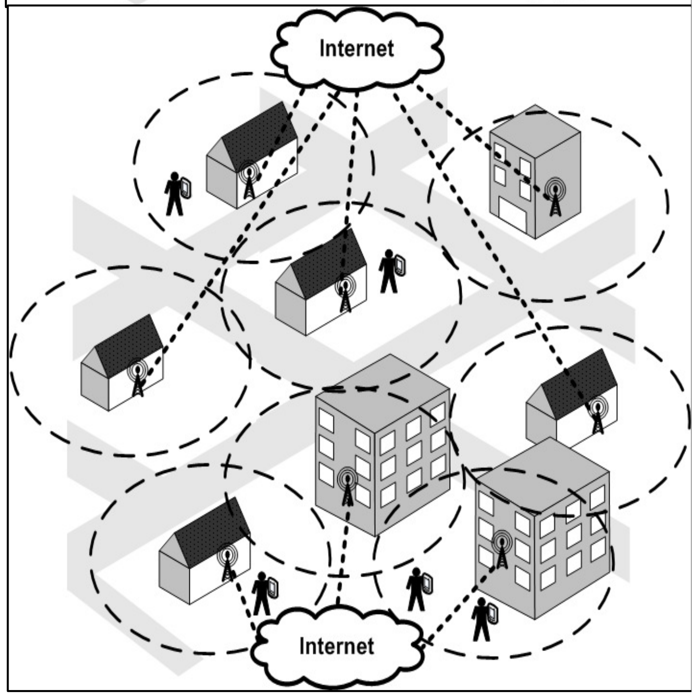
- Growth factors
  - Low broadband penetration
  - Enthusiasm in the academic community
    - Universities deploy/participate in WCNs for experimentation
  - New Wi-Fi standards: 802.11a
    - Higher throughput, less interference → more interfaces per node
    - Replaced 802.11b at the backhaul

Wireless Community Networks:
Technologies & Architectures



- Technologies
  - Based on Wi-Fi / IEEE 802.11
  - Modifications for PtP links
  - Open hardware and software platforms
    - Hand-made hardware (antennas)

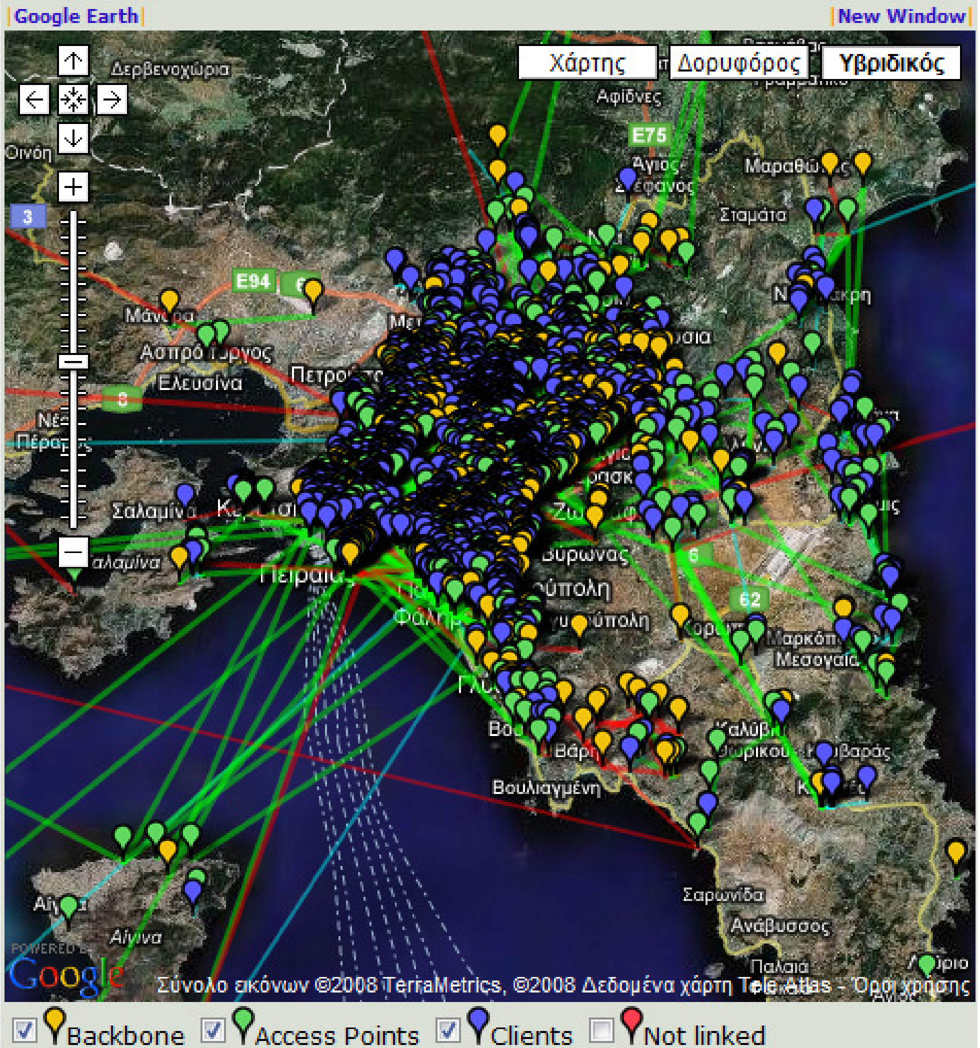
- Architectures
  - Mesh based
    - All-wireless backhaul – IEEE 802.11a
    - Access points (optional) – IEEE 802.11b/g
    - Focus on network autonomy
  - Hotspot based
    - Community-owned(?) WLAN Access Points
    - APs attached to fixed wired broadband lines
    - Focus on Internet access



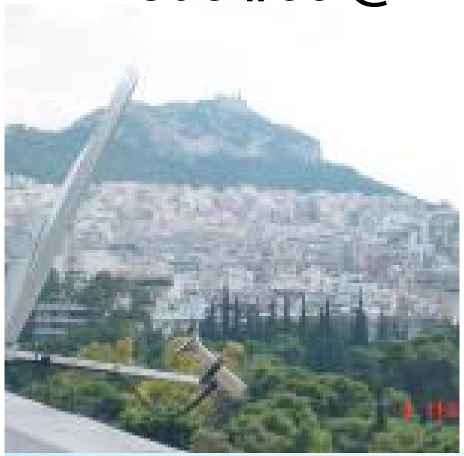
Wireless Community Networks…

Seattle Wireless	**Seattle, US**	**75 nodes**	**Mesh**
AWMN	**Athens, GR**	**2331 nodes**	**Mesh**
CUWiN	**Urbana, US**	**48 nodes**	**Mesh**
Berlin's Freifunk	**Berlin, DE**	**316 nodes**	**Mesh**
NYCWireless	**NYC, US**	**149 nodes**	**Hotspot-based**
Wireless Philadelphia	**Philadelphia, US**	**15 $miles^2$**	**Hotspot-based**
FON	**Worldwide**	**~210 000 registered APs**	**Hotspot-based**

Athens Wireless Metropolitan Network



- **among the largest, globally**
  - **2331 active nodes**
  - **2786 links**
  - **791 active services**
- **Node #66 @ MMlab**



Who runs a WCN?

- **Volunteers**
  - Tech-savvy Wi-Fi enthusiasts
  - Free interconnection
  - Bypassing wired ISPs

- **State initiatives**
  - Municipalities offer Wi-Fi access at low/no cost
  - Athens Wi-Fi, Wireless Philadelphia, The Cloud (London)

- **Private companies**
  - Mediation services for the creation of Wireless Communities
  - FON, NetShare
  - 'Micro-WISPs' share Wi-Fi for profit

WCN Operation

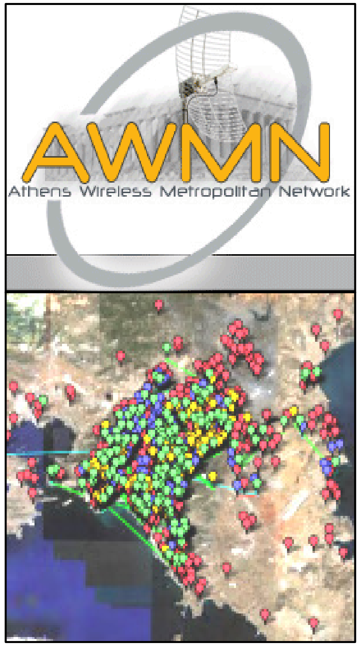
- **Incentives** for participation
  - Altruism – "Warm glow" effect
  - Promise of Wi-Fi access when mobile

- Enforcing contribution and **compliance**
  - Implicit or explicit rules in the community
  - (Fear of) **exclusion**
    - PtP link maintenance: "**tit-for-tat**"
    - Exclusion is easy for mesh → isolate a node by tearing down all links to it

- Building **reputation**
  - Contributing to collective knowledge/expertise
  - Contributing to the routing process
    - Usually nodes with many interfaces – "hubs"
  - Senior community members have better standing

W(LA)N / Wi-Fi Technology of Yesterday… Tomorrow?

- Access bandwidth: 11-54 Mbps (IEEE 802.11a/b/g)
- Backhaul bandwidth
  - Internet connections: DSL now up to many **10s** Mb/s
  - Wireless Community Networks: 54 Mb/s backbone in AWMN
- Wi-Fi phones



- uP W(LA)Ns: An **alternative to** (Telecom) **cellular**?
  - Faster
  - < max. RF power: 100 –200 mW
  - Handovers still an issue
    - but not a problem for **low-mobility** video, audio, browsing

Sharing Wireless Access P2P-style

(User) Wireless Networks & their Backhaul … have Excess Capacity (when there is no excessive interference)

- Technically, we could share them, however:
  - Direct and indirect costs in sharing
    - unimportant: power, equipment depreciation, BW...
    - **Security** attacks
    - **Legal** issues/exposure
    - Exposure to **radiation**...
  - If WLAN owners rational → no one shares
  - Most private WLANs are secured (closed)

- Need **incentives**

- Payments: a standard approach
  - WLAN aggregators
  - Rely on subscriptions, pay-as-you-go schemes
  - Revenue sharing with WLAN owner
    - Focus on public venues (Boingo, iPass)
    - Focus on residential WLANs (Netshare, **FON**)

… more on FON (http://fon.com)

BOINGO WIRELESS

iPass

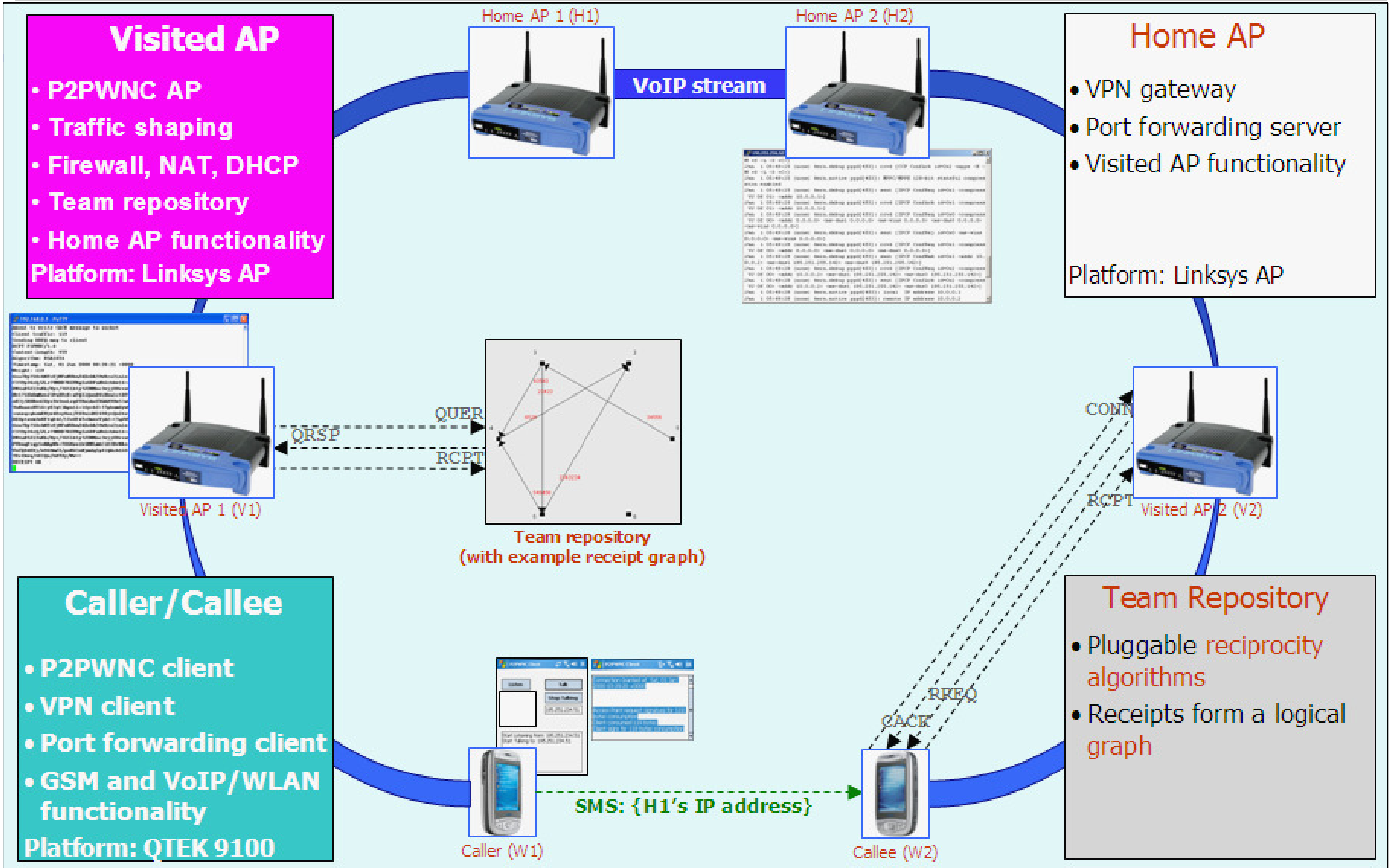
WiFi NetShare Broadband without Borders

Our approach: sharing Wi-Fi P2P-style

- P2P Wireless Network Confederation (P2PWNC)
  - A Wi-Fi sharing community
- Rely on reciprocity
  - Users set up their APs for public access
  - Get access to other peers' APs when mobile
  - Access opportunities and QoS proportional to their contribution

- No central authorities
  - Users identified by self-certified public-private key pairs
- Accounting based on the exchange of digital "receipts"
  - Receipt: proof of transaction signed by client
  - Distributed accounting: each peer stores receipts
- Implementable on common WLAN equipment
  - Linux-based AP
  - Smartphones, PDAs

Demos @ IEEE INFOCOM'06, ACM MobiSys'06



Services and Applications on top of P2PWNC

- VoIP over P2PWNC
- Multimedia conferencing
- Secure… private…
  - Using standard network security techniques (VPN tunnels…)
  - Fully distributed implementation

- (Broadband) Internet Access! – the ***Killer*** Application?

- ... “Micro-operators”

Open Issues

- P2PWNC and Wireless Community Networks
- ISP Acceptable Use Policies / Business Models

- Peripheral peers
  - Can expanded teams include them?
  - Or, factor location in receipt weight?
    - Different “prices”
- Extend cost-benefit model
- Collusion among teams, other adversarial strategies

- Mobility
  - Handovers

μ-Operators

User Provided Networks

μ-Operators

- Anybody can easily become a wireless μ-Operator
  - First time in history...
  - Legal issues...

- But... more interestingly...
  - Reliability, Availability
  - Trust
  - Security
  - Privacy (location tracking…)
    - Fully distributed implementation – no authorities
    - Cheap / renewable IDs

μ-Operators Business Model?

- ... even more interestingly: **Business issues**
- ISP Acceptable Use Policies (towards link sharing)
  - Business Models
  - BT alliance with FON
- Entry of ISPs to advanced Cellular market (4G?) with no (further) investment!(?)
- Femto-Cells: the “opposite”?
  - (mobile) operator managed (& with licensed spectrum)

Open Spectrum Access: an Alternative Spectrum Utilization Model …

- Unlicensed spectrum
  - Anyone can become an operator
    - Low entry cost
      - Residential WLAN owners, (W)ISPs, 3G operators, municipalities, etc.
    - Increased coverage (@ broader BW, lower cost)
    - Significantly increased number of operators
      - lawyer driven roaming agreements impractical
  - Increased competition
    - Fewer market hijacking phenomena...
    - Wider service offerings
      - Subject to operator interactions and not user priorities
    - Increased interference ⇒ sensing, mitigating
  - Privacy, Security, Trust…
- Open access
  - Without any form of prior contract (subscription)
  - Getting (buying? in kind?) network access in small quanta

Wireless Trends & Challenges (the dream?)

- Broadband Wireless Access
  - over unlicensed & minimally regulated spectrum
  - where competition **and** cooperation are the norm at all scales
- to a true i/Internet [a really distributed system]
  - which needs serious reconsideration/redesign
  - to address non-fully cooperative agents/networks
    - including aspects of exploiting asymmetric information
    - in an automated way (fast decisions, select from set of "contracts")
- to access or provide a wide array of services
  - including multimedia content generated (and stored) at the edges
  - & all types of secure / anonymous communications
  - & also including a wide variety of devices
    and attached networks of sensors & actuators
- where the following are important at many layers:
  - Privacy and Security, Trust (reputation), Availability (PaSTA)
- Automated Trust Management
  - becoming a key issue for interconnection and successful interoperation

Cognitive Radio Networks

Interference Sensing & Reporting

The Problem

- Proliferation of wireless networks & devices
- Increased demand for radio spectrum
  - regulation …
- Traditional approach rather inefficient
    - Difficult to find a vacant frequency
    - Competition leads to need for high investments
      - High entry barrier for new operators
      - Long payback time
      - Customers tied to a specific network
        - Often impossible to choose the best price-quality
  - Frequency bands tied to specific technologies
  - Licensed bands
    - temporal & spatial underutilization of the spectrum
  - Unlicensed bands
    - interference

The Role of Cognitive Radio

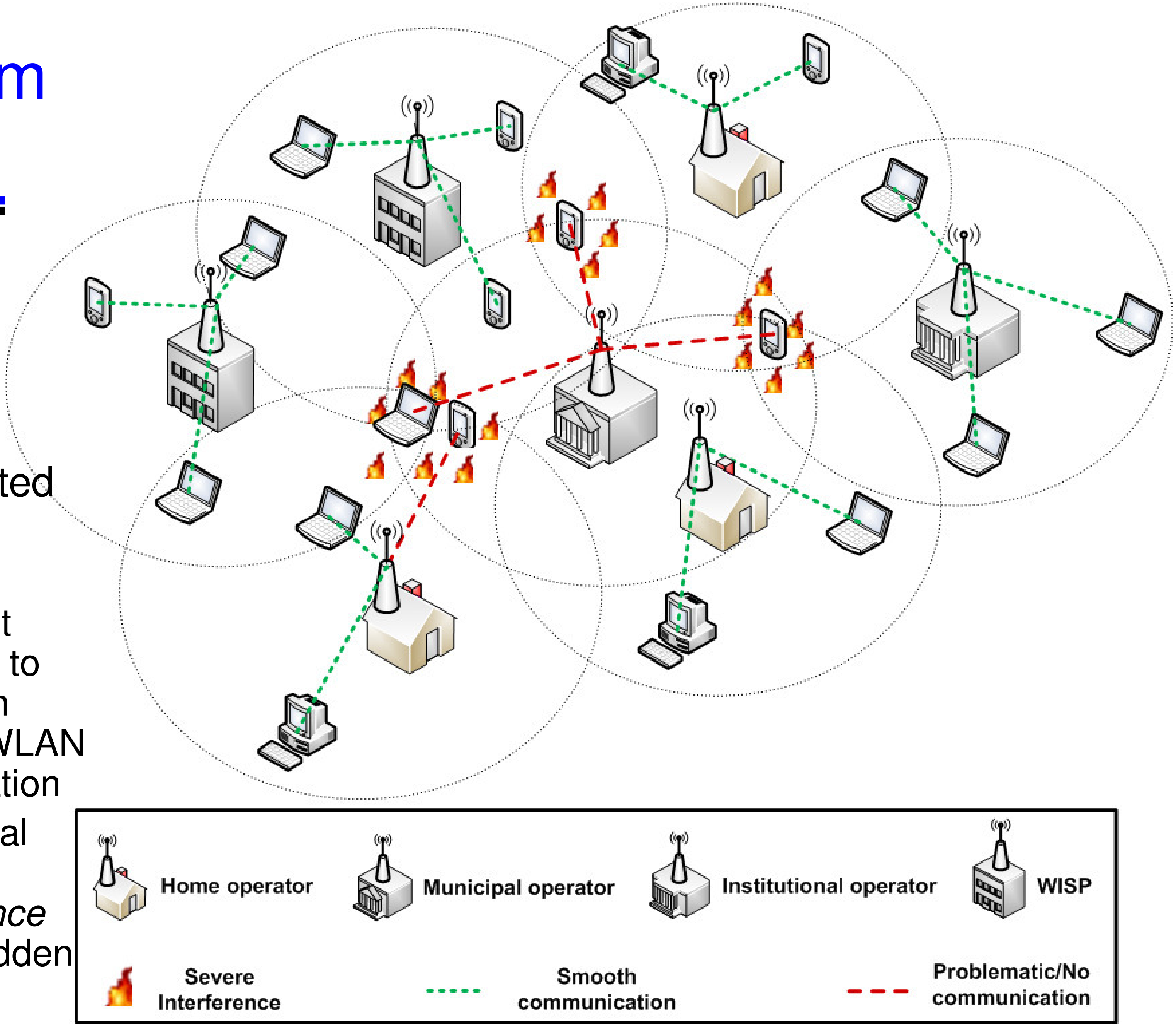
- Interact with the wireless environment
  - Sense, learn and adapt/react
- Historically mostly focused on the Primary/Secondary user model
  - Focus on spectrum underutilization
    - Filling spectrum *holes*
  - Spectrum access priorities
- However…
  - still hard/risky for secondary users/operators
    - primary user priority hinders even the minimum service guarantees
  - primary operator investments still key for growth of wireless networks & services

Dynamic Spectrum Access: Challenges and Goals

- *Spectrum sharing dimensions:* frequency (code), space and time
  - A unified framework considering all dimensions will provide the necessary flexibility (unlicensed spectrum)
- *Primary/Secondary model vs. Open Spectrum Access (OSA)*
  - enable new (μ-)operators to enter the market
- *Centralized vs. distributed (information repositories)*
  - Outer/inner feedback loop
  - Goal: a low overhead reporting system
- *Cooperative vs. non-cooperative spectrum sharing*
  - Design incentives that will lead to a high degree of cooperation between competing spectrum users
- *Game theoretic modeling of spectrum sharing*
  - Various degrees of cooperation
    - Expressed by the amount and quality of the available information
  - Translation of a game-theoretic model to a practical system

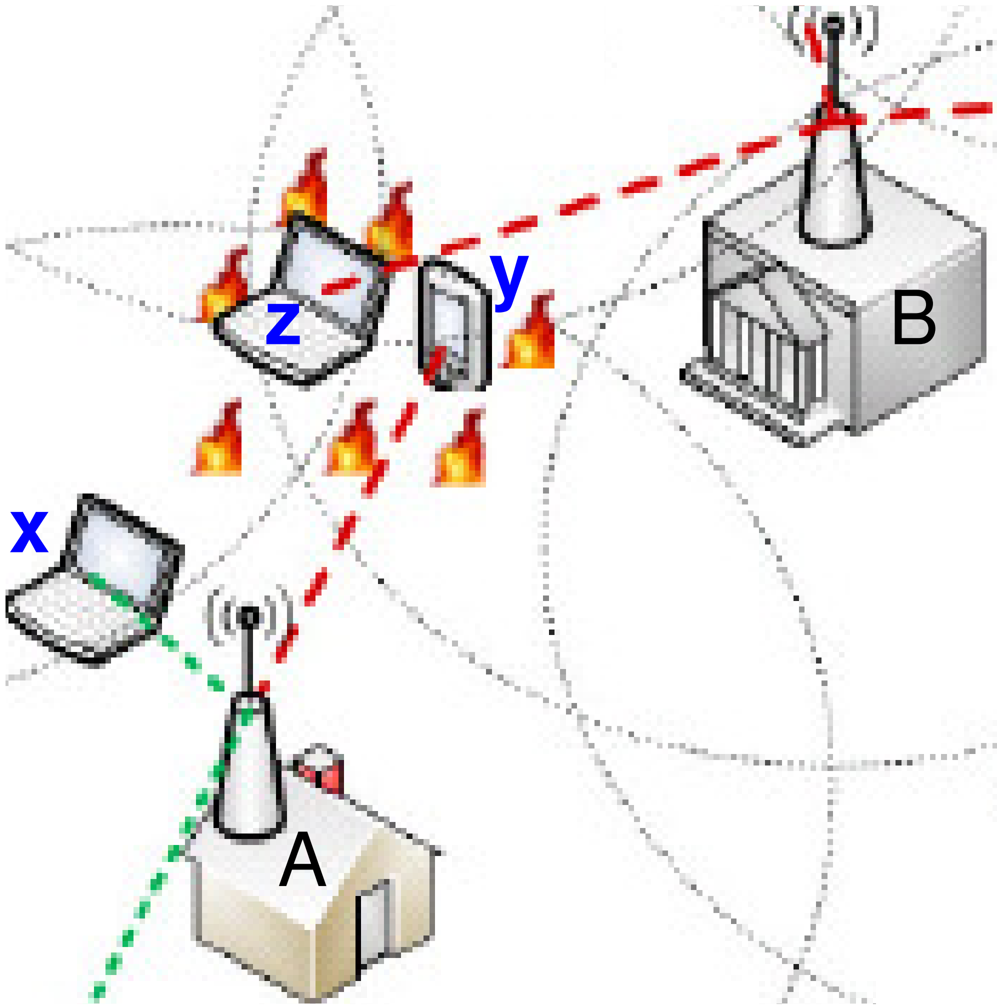
Spectrum Sharing

- Open Spectrum Access
- Client-assisted interference mitigation
  - Use client feedback to decide on optimal WLAN configuration
  - Can reveal *hidden interference* due to hidden terminals



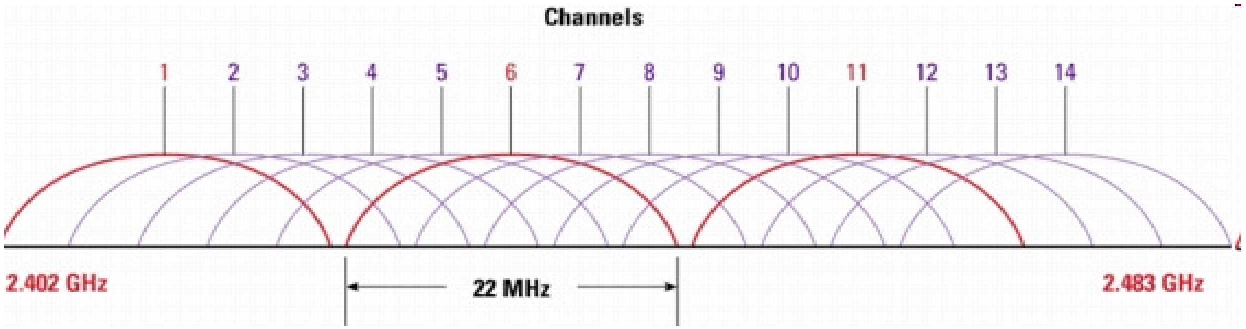
Competition and Cooperation

- Convince **A** to limit power
- Probably to **B**'s advantage to serve **A**'s client (**y**) directly (at no cost to **A**)
  - y far from A
    - low rate => long channel time
  - y closer to B
    - Can be served by B at high(er) rate => small(er) channel time



Interference

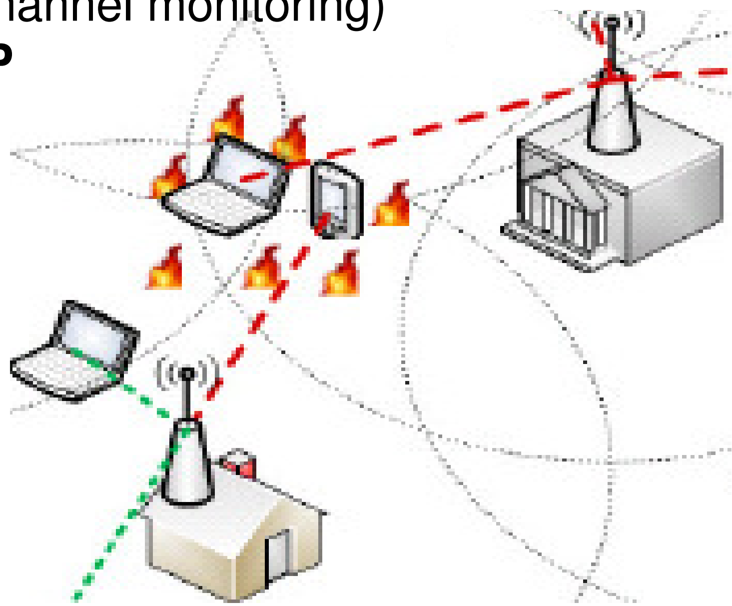
- Contributing...
  - IEEE 802.11 channels not truly orthogonal
    - 802.11b/g: 3 interference-free (non-overlapping) channels



- Interference detection
- Interference mitigation
  - channel selection,
  - **power control**, coverage,
  - directional antennas, ...

Detecting Interference / Spectrum Monitoring

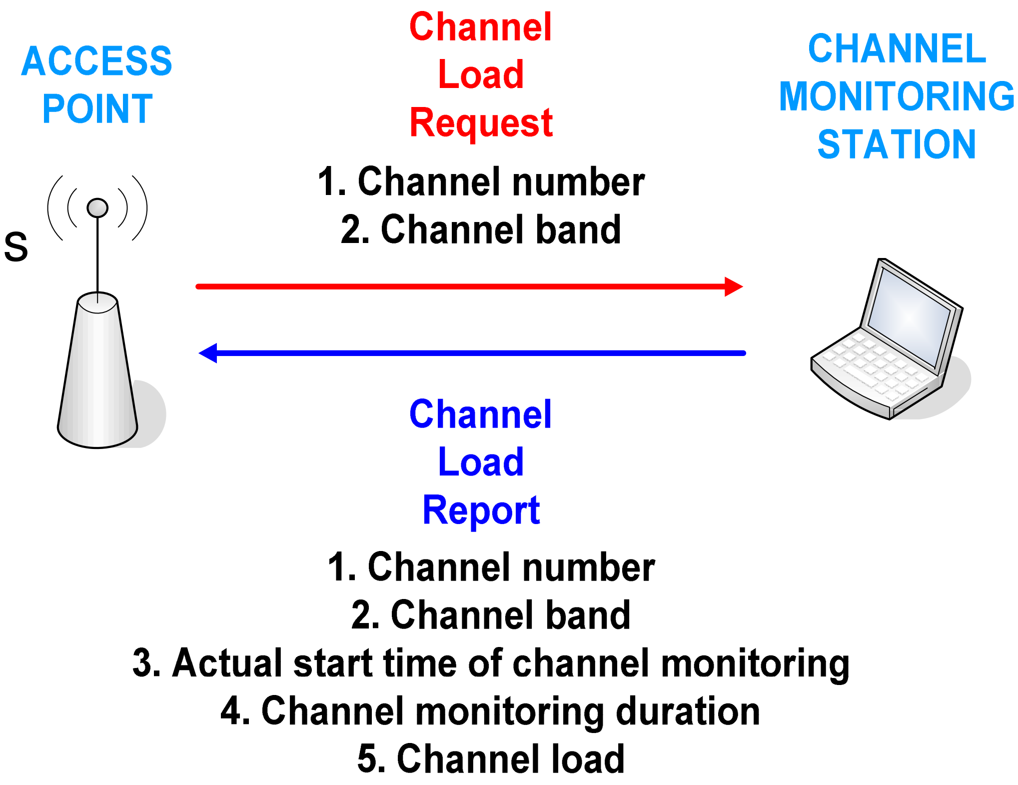
- AP-centric schemes
  - Sense spectrum usage at the AP site
  - Easier to control/manage
  - May require additional Wi-Fi interface (for channel monitoring)
  - Fail to capture **interference beyond the AP**
    - due to "hidden" terminals
    - probably the most important



- Client-based schemes
  - Clients periodically monitor channel usage
  - Report to APs (or other control entity)
  - Reveal more information
    - capture user-perceived interference
  - Trustworthy reports?
  - Monitoring overhead?
- Ad hoc sensing devices / special purpose sensors
  - Carefully placed?

IEEE 802.11k: Radio Resource Measurements

- Specifies types of ***radio resource information*** to measure and the associated request and report mechanisms
  - Provides information to discover the best available access point
  - Load Balancing
  - Improve the way traffic is distributed within a network



- **Mangold & Berlemann**: "IEEE 802.11k: Improving Confidence in Radio Resource Measurements," IEEE PIMRC 2005.
- **"Optimizing the Channel Load Reporting Process in IEEE 802.11k-enabled WLANs"**, Panaousis, Ververidis, & Polyzos, IEEE LANMAN 2008.

A Proposed Architecture

- Utilization of client-supplied information
  - Outer feedback loop
  - Spectrum usage, service offerings
  - Hidden interference problem …
  - Planning AP deployment
  - Cheap sensors deployed to supply spectrum utilization information
- Adaptive wireless infrastructure
  - Inner feedback loop
  - Interference mitigation
- Service discovery, negotiation and handovers
  - *Direct:* mobile node – AP interactions
  - *Indirect:* user reports

The Proposed Architecture: Functional Requirements

Mobile Node

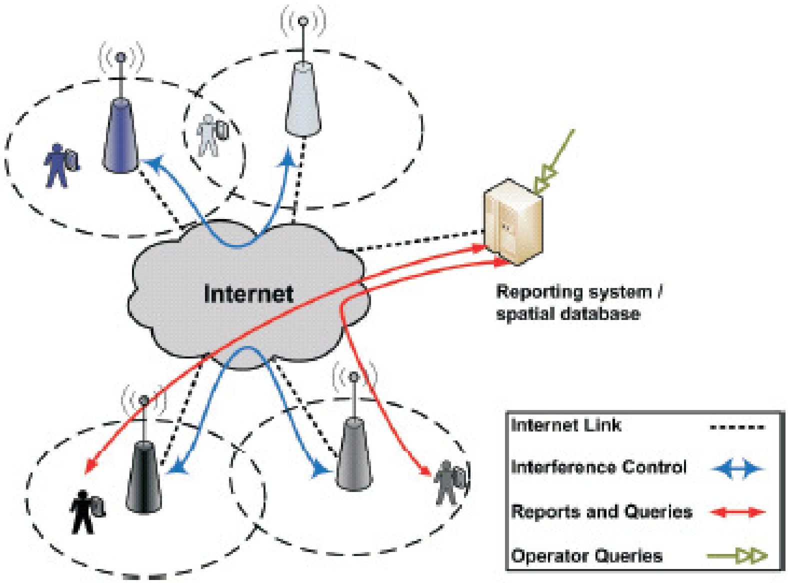
- Spectrum sensing
- Service discovery
- Reporting (especially of *white spots*)
- Spectrum agility
- Secure micro-payments
- Advanced handover capabilities (frequency, air interface, AP, operator)

Access Point

- *Announcing*
  - *Spectrum portfolio*
  - *Service capabilities*
- Secure micro-payments
- Interference feedback and reporting
- Interference control
- Handover preparation

Reporting System/Spatial Database

- Aggregate reports
- Monitoring
- Provides information on service availability and spectrum usage
  - Operators: *white* spots, interference, etc.
  - Users: coverage, services, etc.



A Plan...

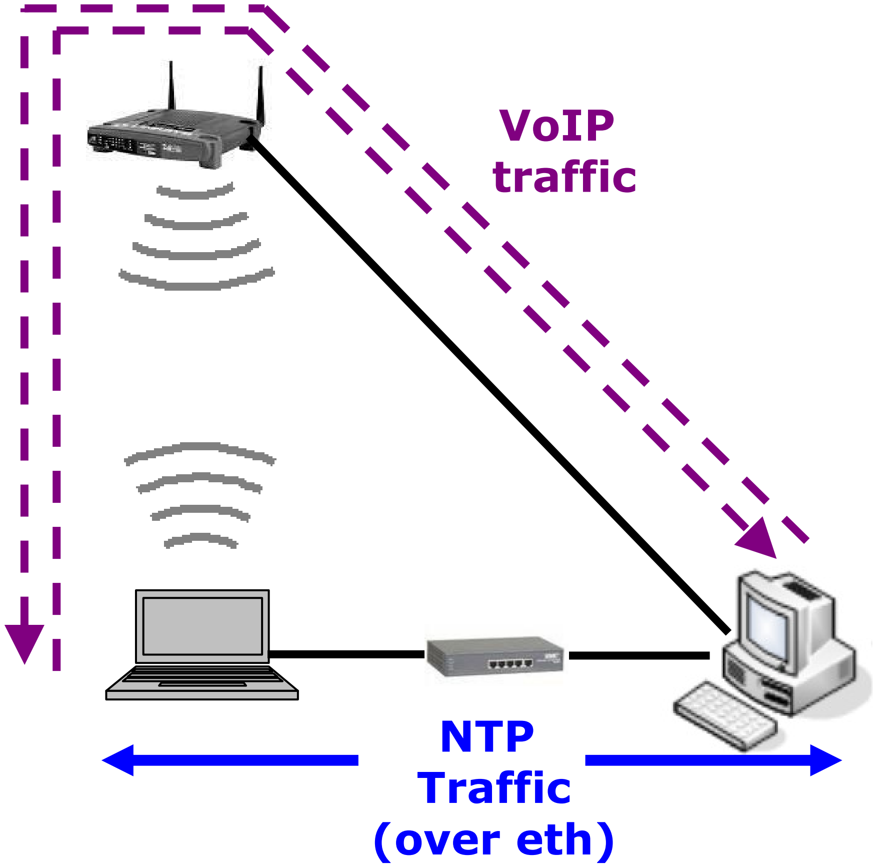
- Tackle public wireless access and interference mitigation jointly
  - P2PWNC for mobile Wi-Fi access
  - Client feedback about interference suffered
- Why should a P2PWNC client provide feedback about interference?
  - Dictate it!
  - Offer incentives
    - Offer QoS benefits in exchange
- Will it work?
  - Has a chance, if it has low overhead for the client
  - Otherwise: clients refuse to report, provide fake feedback

Performance Overhead of Spectrum Sensing

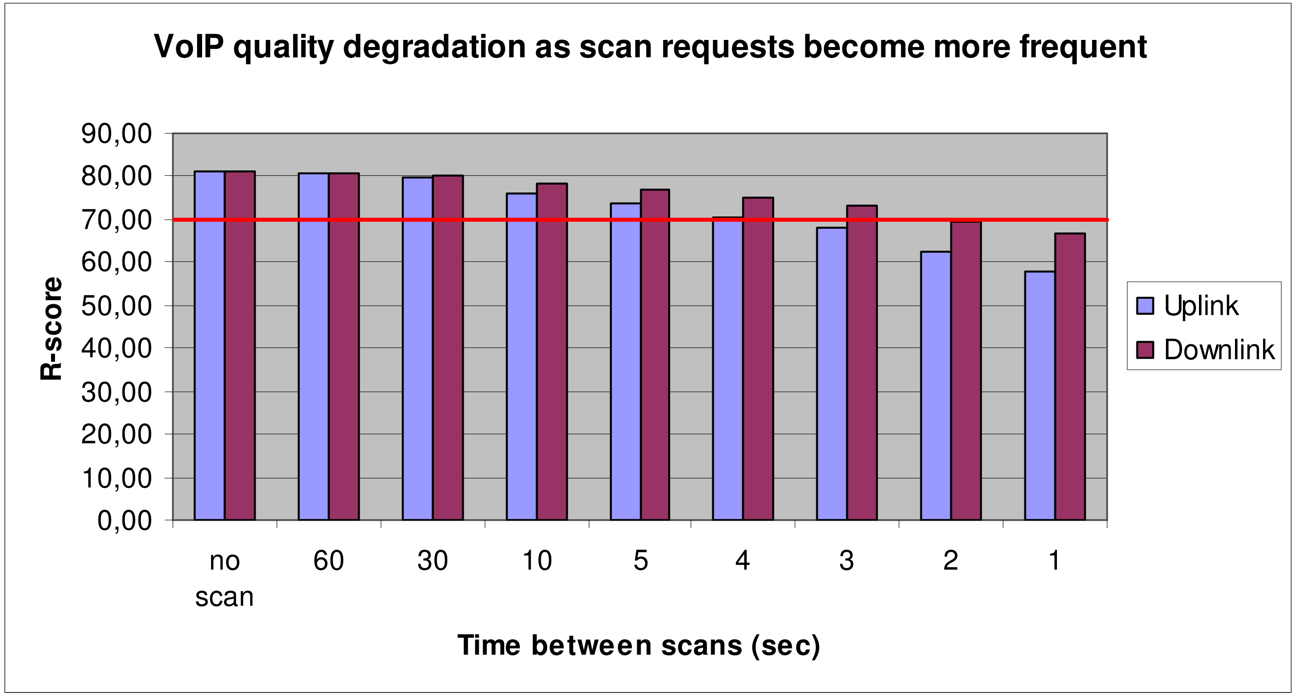
- Stations cannot receive/transmit application packets while scanning
- Active scan on 11 channels: >250msec!
- Overhead depends on report request frequency
- Disincentive for clients to contribute reports
    - Need incentives
        - Bandwidth/QoS bonus?
- But how high is this overhead?
    - …especially for delay-sensitive applications

Measuring the Overhead…

- Purpose: measure VoIP performance degradation due to periodic scanning
  - Experiment with various request frequencies
- Traffic pattern
  - Bidirectional UDP/RTP traffic, 50 packets/sec, 20bytes payload (G.729)
- VoIP quality assessment
  - E-model (R-score/Mean Opinion Score)
  - Based on network-level per-packet measurements (delay, loss, jitter)
- Testbed
  - IEEE 802.11b @ 11Mbps, no RTS/CTS
  - Linksys WRT54GS AP
  - Intel PRO Wireless 2200 card, ipw2200 Linux driver
  - Sync using NTP (over eth interfaces)



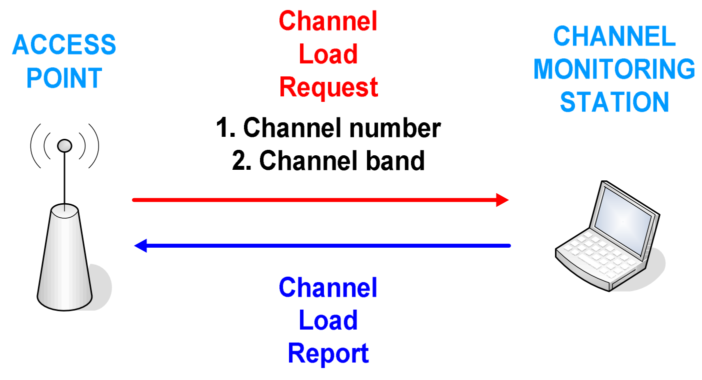
Quantification of Sensing Overhead



- Acceptable quality: R-score > 70
- Moderate scanning frequency (e.g. 2 scans/min) ➔ Minimal QoE degradation
- Negligible mean e2e delay
- Worse quality mainly due to jitter

Open Issues in Interference Detection & Reporting: the ASPECTS project

- Security and reliability
  - How to spot fake reports?
  - Use a client reputation scheme, punish/reward?
  - Use monitors/sensors
    - Where to place them?
    - How many? Who owns/deploys them?
- Model and study incentives mechanism
  - Intuitively, no strong incentive to cheat…
    - …but, still, needs to be proven



- The **ASPECTS** project: Agile SPECTrum Security
  - Euro-NF (NoE) Specific Joint Research Project
    - AUEB, Blekinge Institute of Technology (M. Fiedler), Universität Passau (H. de Meer)
- Smart monitoring/reporting
  - Optimize monitoring time, energy etc.
  - Ask each client to scan a subset of the channels/spectrum
    - Will reduce scanning time
    - Cooperative scheme / build interference maps
      - Who has the picture? Partial?

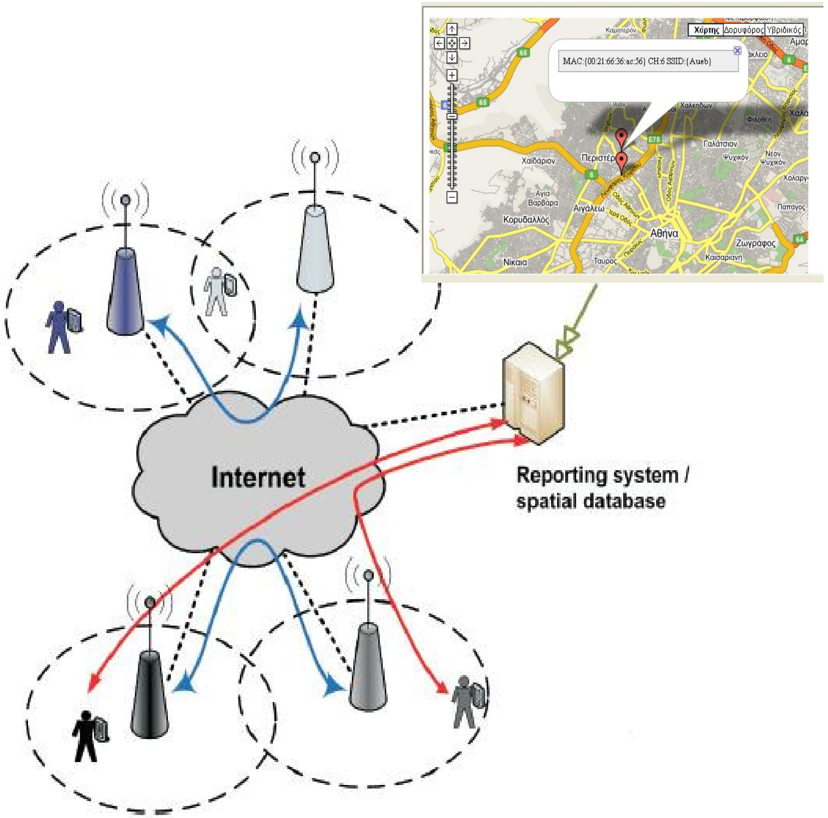
Cognitive Radio Networks

Interference Sensing & Reporting

A study of the cost of fake client reports

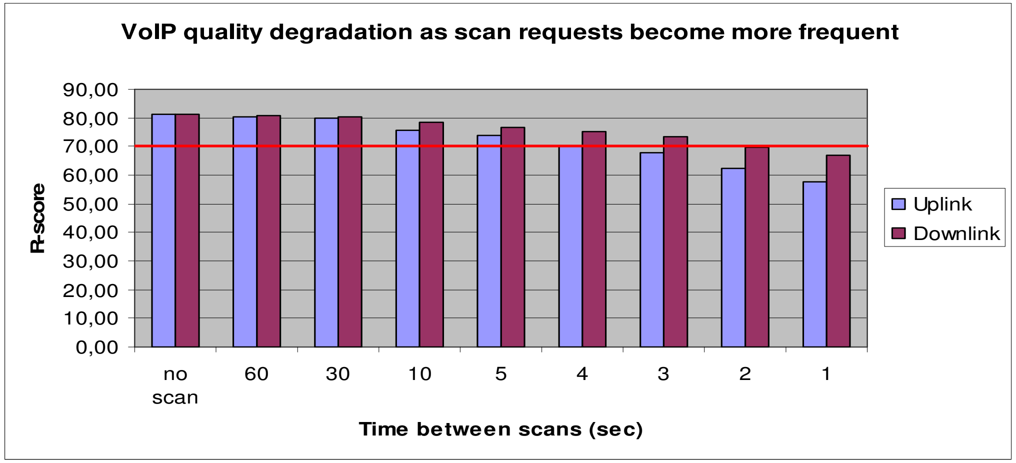
A Client-driven Architecture

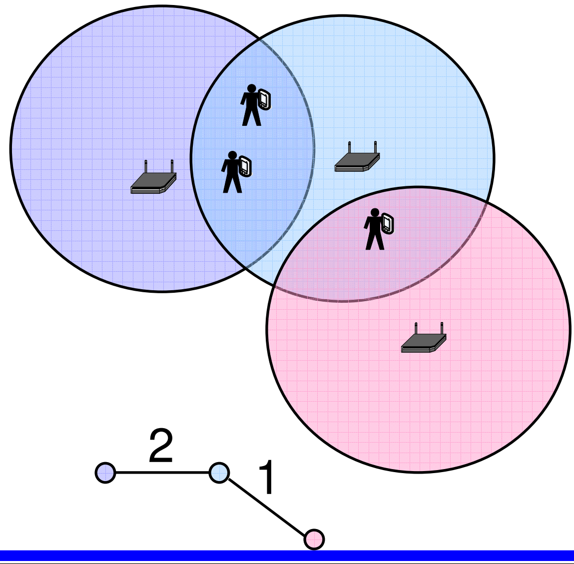
- Roaming clients scan for AP presence
- Report to AP (with location info, if available
- APs forward reports to DB
- Wireless coverage maps built
- Implemented on off-the-shelf Wi-Fi equipment
- +: detect hidden & user-perceived interference
- -: Security, robustness



Compliance, Info Reliability & Security Issues

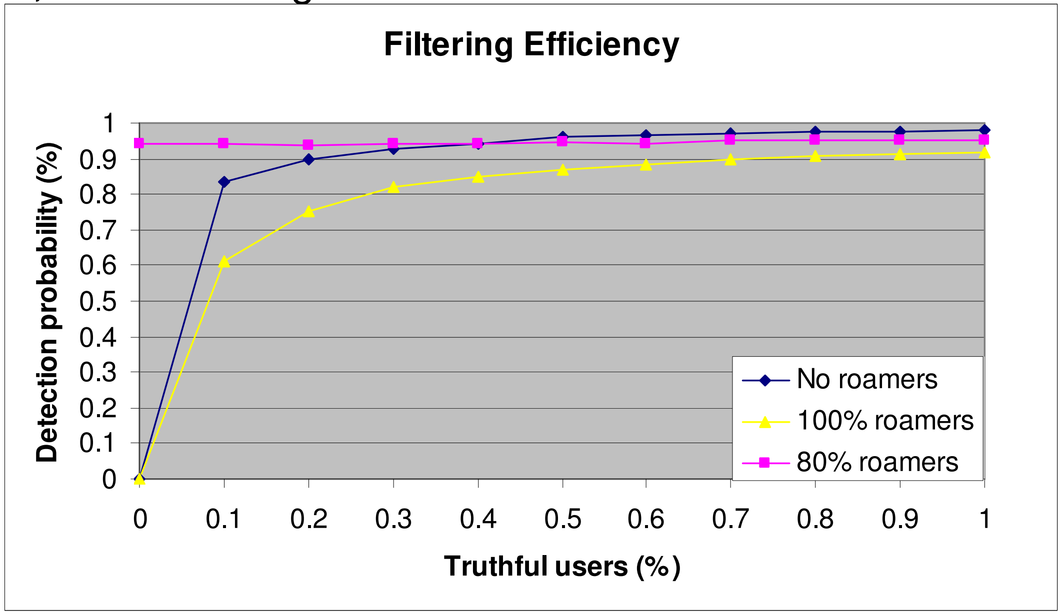
- Incentives to misbehave
  - Monitoring cost
  - Provider competition
- Countermeasures
  - Offer incentives (e.g. QoS)
  - Apply filtering schemes
- System model
  - Interference Graph
  - Edges: #reports, user-perceived interference
  - Which edges are fake??





Attacks and Countermeasures

- Scenario #1: No collusion
  - Each user submits random fake reports
  - Solution: filter unit-weight edges
- Scenario #2: Collusion
  - 2 sets of users: non-trusted roamers, trusted non-roamers
  - Roamers associated with an AP collude & report the same fake reports
  - Solution: discount roamer reports, then filter edges
- Simulations
  - Dartmouth Campus Wi-Fi (~520 APs), 6 clients/AP
  - High client density
  - Most interference instances are found, with minimal loss of info



Some Open Issues

- More sophisticated attacks
- What happens when client density is low?
  - Much info lost by pruning edges
  - Need more sophisticated filtering
- Apply reputation to evaluate reports
- Does user mobility help expose interference faster?
- Study incentives for clients not to misbehave in the first place
- What happens next?
  - Self-configuration based on collected info
  - More efficient spectrum sharing

Cognitive Radio Networks

Interference Mitigation through

Power Control

but

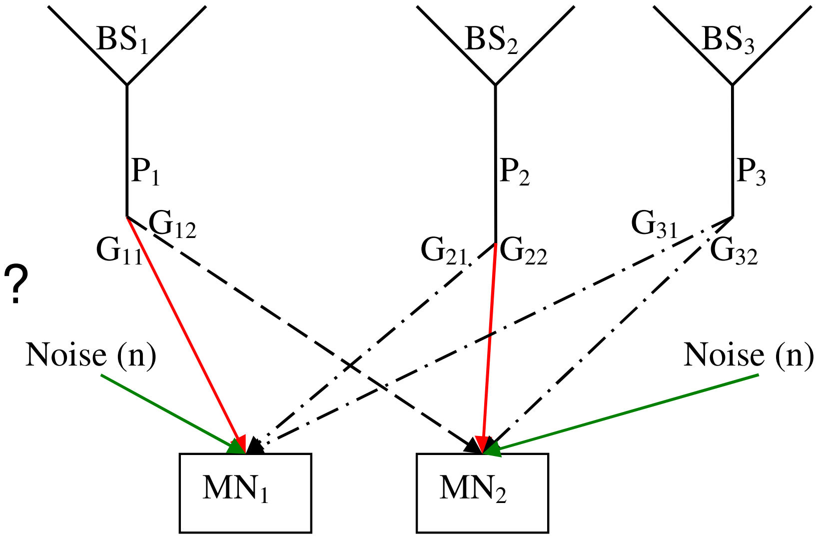
with different goals and unclear incentives

a Game theoretic approach?

Bargaining?

“Traditional” Transmitter Power Control

- Selection of transmission power to achieve a specific goal
- Simplified *Foschini-Miljanic* form: $P_i(k+1) = \gamma_i^t \frac{P_i(k)}{SINR_i(k)}$
- Given γ^t for each link
  - “genie” tells us there is a feasible power vector **P^t**
  - can we find it in a distributed way?
  - YES!
- (+) it always converges [if feasible]
- (-) generally slow convergence



$$SINR_{1\to 1} = \frac{G_{11}P_1}{G_{21}P_2 + G_{31}P_3 + n} \qquad SINR_{2\to 2} = \frac{G_{22}P_2}{G_{12}P_1 + G_{32}P_3 + n}$$

What is Missing?

- Traditional approaches are based on:
  - Entities (APs, BSs, MNs…) having a predefined (network) goal
  - Entities having no choice but/ being always willing to follow the standard (common) policy
- How to enforce (predefined) strategies and/or targets in networks with autonomous entities?
- By applying… **incentive** based power control
  - not only to find an optimal power control algorithm...
  - but also to provide the incentives to follow it!

- Incentive Based Power Control
  - in Wireless Networks of Autonomous Entities
  - with various degrees of Cooperation

Our Work in Progress: Considering Bargaining & Bargaining Theory

- Bargaining situation: 2+ players have a common interest to co-operate, but have conflicting interests over exactly how to co-operate
- Bargaining Theory as a tool, e.g.,…
  - An entity makes a "take it or leave it" offer to another so as to reduce its transmission power to: $P' = cP_{F-M}, 0 < c < 1$
  - Who offers?
    - The one with the highest quantity $\dfrac{\gamma^t - SINR(k)}{\gamma^t}$
  - To whom?
    - To the one with the lowest quantity

(+) Nearly fully distributed – no need for a link to reveal its power or its current SINR or its SINR target

Open Questions on

- Open Questions [vs. F-M scheme]:
  - Is this scheme more efficient in topologies where the SINR targets are infeasible?
  - Does this scheme converge faster to a power vector in topologies where the SINR targets are feasible?

- Extensions:
  - An entity offers money to another to allow him to increase his transmission power to a higher level than F-M scheme
  - Many entities make repeated offers to many entities
  - Some entities cheat by falsely reporting their percentage difference from its target SINR…

Our Related Work

- **"Stimulating Participation in Wireless Community Networks"**
  E.C. Efstathiou, P.A. Frangoudis, and G.C. Polyzos
  Proc. IEEE INFOCOM 2006, Barcelona, Spain, April 2006
- **"Power Control in WLANs for Optimization of Social Fairness"**
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