Cognitive Networking

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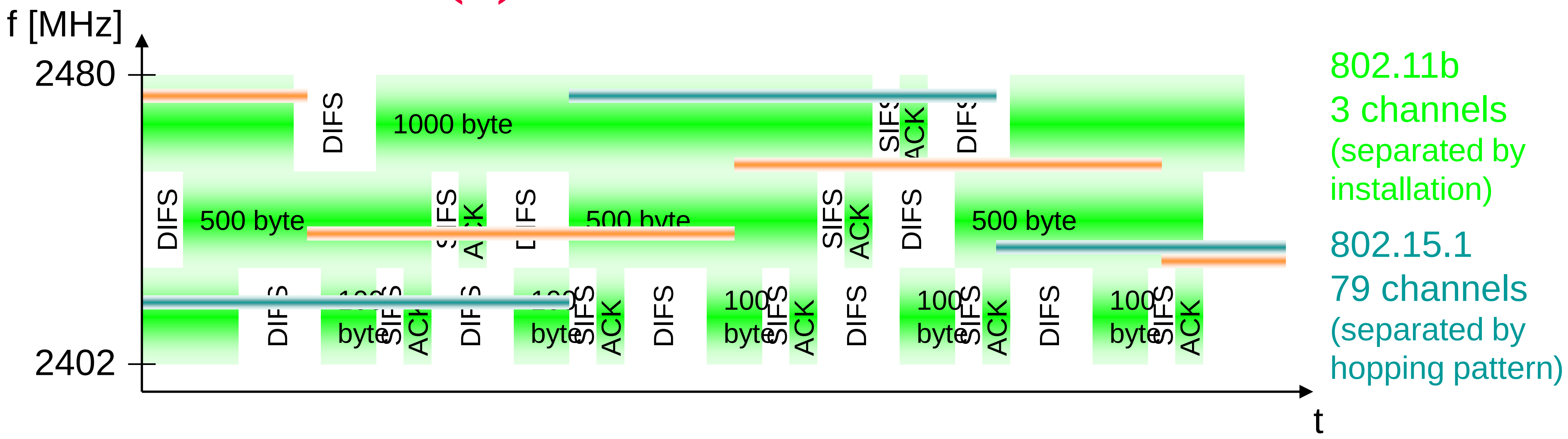
Regulatory Issues

- Wireless Spectrum scarce, shared among many different users with distinct needs
- Need either license to operate in specific frequency band or use unlicensed frequency band
- Unlicensed bands: no limit on number of users, but rules governing "behavior"
- Licenses used to be given away basically for free, but this became controversial, plus governments saw this as easy source of revenue…..
- Need for international standardization: meetings every 2 years (WARC), many international standards bodies and regulatory offices involved

Unlicensed Bands

- Industrial, Scientific, and Medical (ISM):
  - 915 MHz band (902 - 928 MHz, 26 MHz bandwidth)
    - only available in North America
    - highly crowded, expected to become even more crowded
    - many existing users are non-spread-spectrum applications
  - 2.4 GHz band (2.4 - 2.4835 GHz, 83.5 MHz bandwidth)
    - available worldwide
    - lightly loaded, but interference from microwave ovens
  - 5.8 GHz band (5.725 - 5.85 GHz, 125 MHz bandwidth)
    - only available in North America
    - lightly loaded, radar interference

ISM Band: Multiple Technologies share Spectrum: IEEE 802.11 vs.(?) IEEE 802.15/Bluetooth



- Bluetooth may act like a rogue member of the 802.11 network
  - Does not know anything about gaps, inter frame spacing etc.
- IEEE 802.15-2 discusses these problems
  - Proposal: Adaptive Frequency Hopping
    - a non-collaborative Coexistence Mechanism
- Real effects? Many different opinions, publications, tests, formulae, …
  - Results from complete breakdown to almost no effect
  - Bluetooth (FHSS) seems more robust than 802.11b (DSSS)

Licensing 3G Bands

- VERY different country rules:
  - **US**: finalise spectrum options by Q3 2001, prior to licensing 3G systems by Q4 2002. consultation process completed 30 March 2001 with reports from FCC and NTIA.
  - **Canada** auctioned PCS spectrum in January 2001 that can be used for 3G services, with 52 licences attracting bids totalling $1.48 billion.
  - Spectrum policy in USA and Canada is today not service specific. This means that any licensee can deploy 3G systems in their existing spectrum, if equipment exists for that particular spectrum.
  - **France:** 4 National licenses, beauty contest plus fixed cost. First two licences awarded to Itineris (France Telecom) and SFR (Cegetel). Conditions have yet to be set for the award of two further licences. First licences awarded 31.05.01.
  - **Germany:** 6 National licences awarded, five 2x10 + 5 MHz, one 2x10 MHz. 1st stage auction completed (17.8.00), raising DM98.8 billion. Second stage closed 18.8.00, awarding an additional 1x5Mhz unpaired to all except one.
  - **China**: ??? (I assume the government assigned them to China Unicom and China Mobicom)

Source: *http://www.umts-forum.org/brochures/3G_licensing_09_October.pdf*

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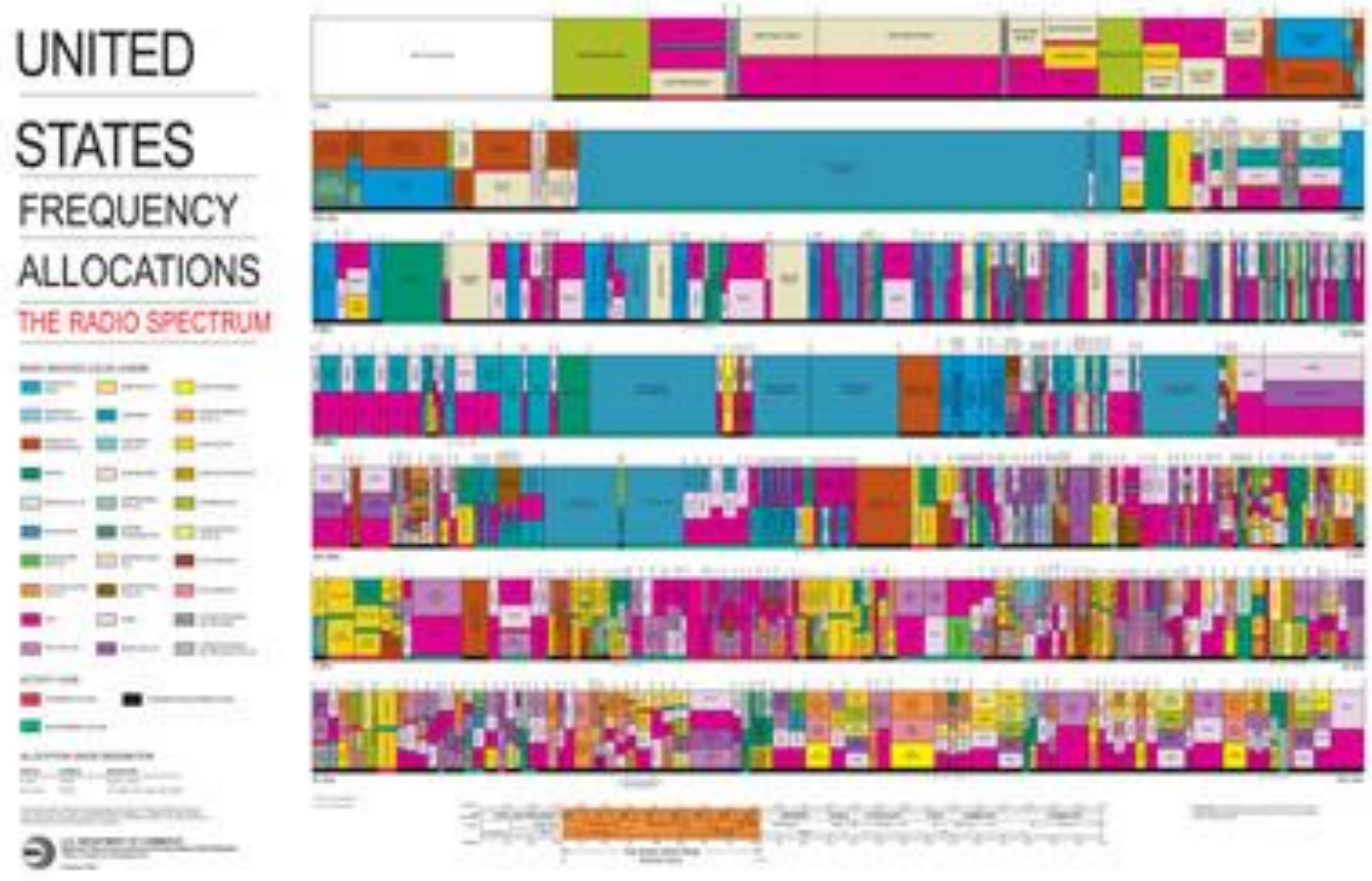
Spectrum Allocation: FCC publishes Chart for US



Spectrum Allocation State

- Not all spectrum equally valuable
  - Low end: low bandwidth
  - High end: waves attenuated by rain, leafs, fog, walls, etc., good for line-of-sight with high data rates, not good for ubiquitous coverage
- Interesting (commercially interesting) spectrum pretty much all allocated (1-5 GHz range primarily)
- Problem:
  - need for more capacity: iPhone vs. Blackberry
  - Not all spectrum that is allocated is used (or used efficiently)
- Cognitive Networking
  - Allow secondary user to user spectrum allocated to primary user who is not currently active
  - Early example: CDPD as overlay over AMPS

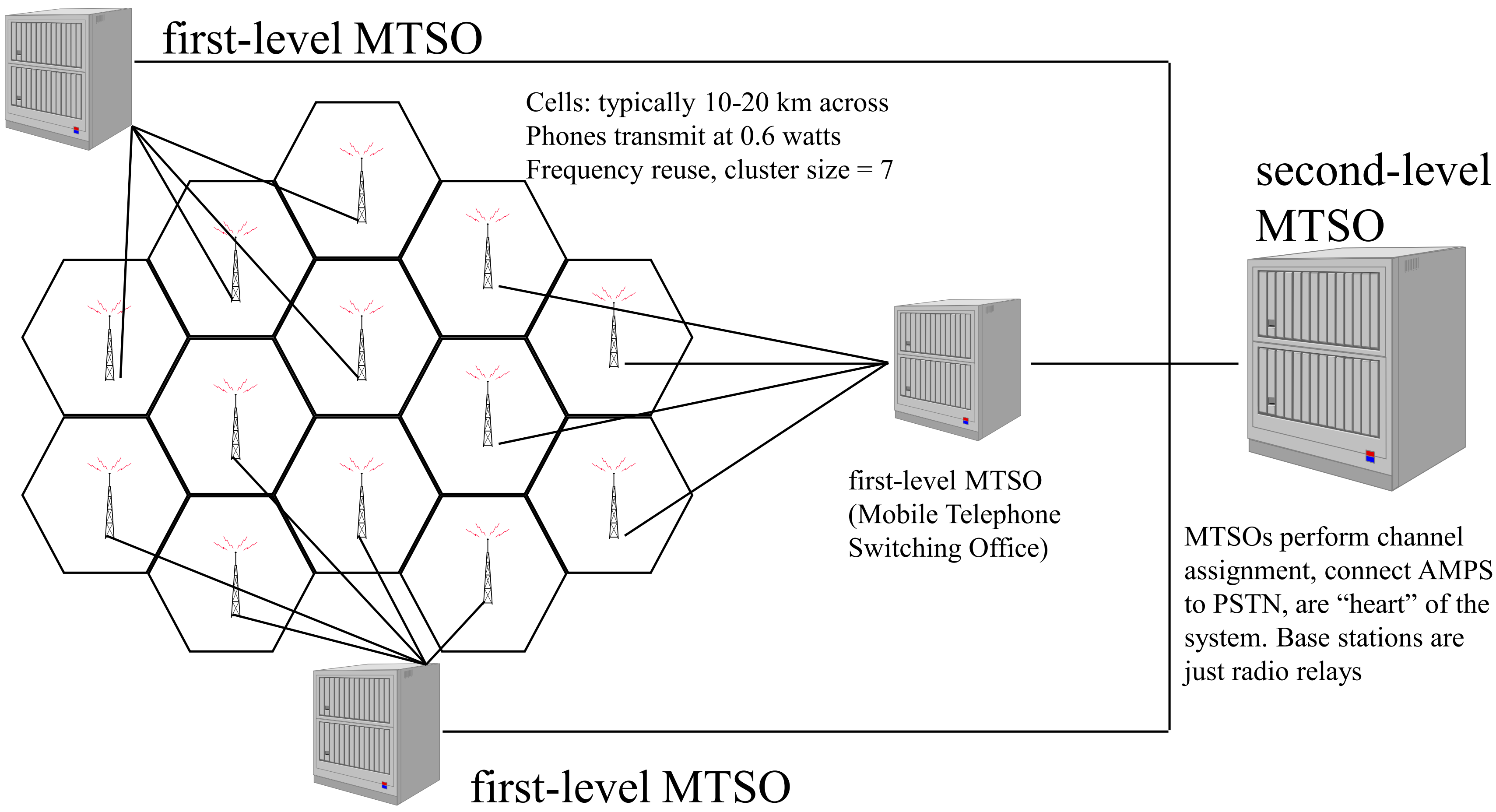
AMPS: History

- FCC allocated spectrum space in the 800 MHz spectrum and issued licenses for test systems in Chicago and Washington, D.C.
- first commercial systems available 1983, available in all major cities in US in a few years
- AMPS result of extensive research by Bell Labs in 1960s and 1970s
- 800 MHz band was compromise
  - lower frequencies occupied by FM and TV systems
  - higher frequencies were deemed too unreliable (information loss due to weather conditions, multipath fading, etc.) with existing technology

AMPS Spectrum and Allocation

- A band set up for independent carriers
- B band set up for traditional wireline carriers, such as the Regional Bell Operating Companies (RBOC)
- idea was to ensure competition in all markets, while restrict potential proliferation of companies that would complicate spectrum allocation/management
- today, many independent carriers bought by RBOCs, so it is not uncommon to have one company operating in Band A in one market and Band B in another market
- channels always come in pairs, spaced 45 MHz apart

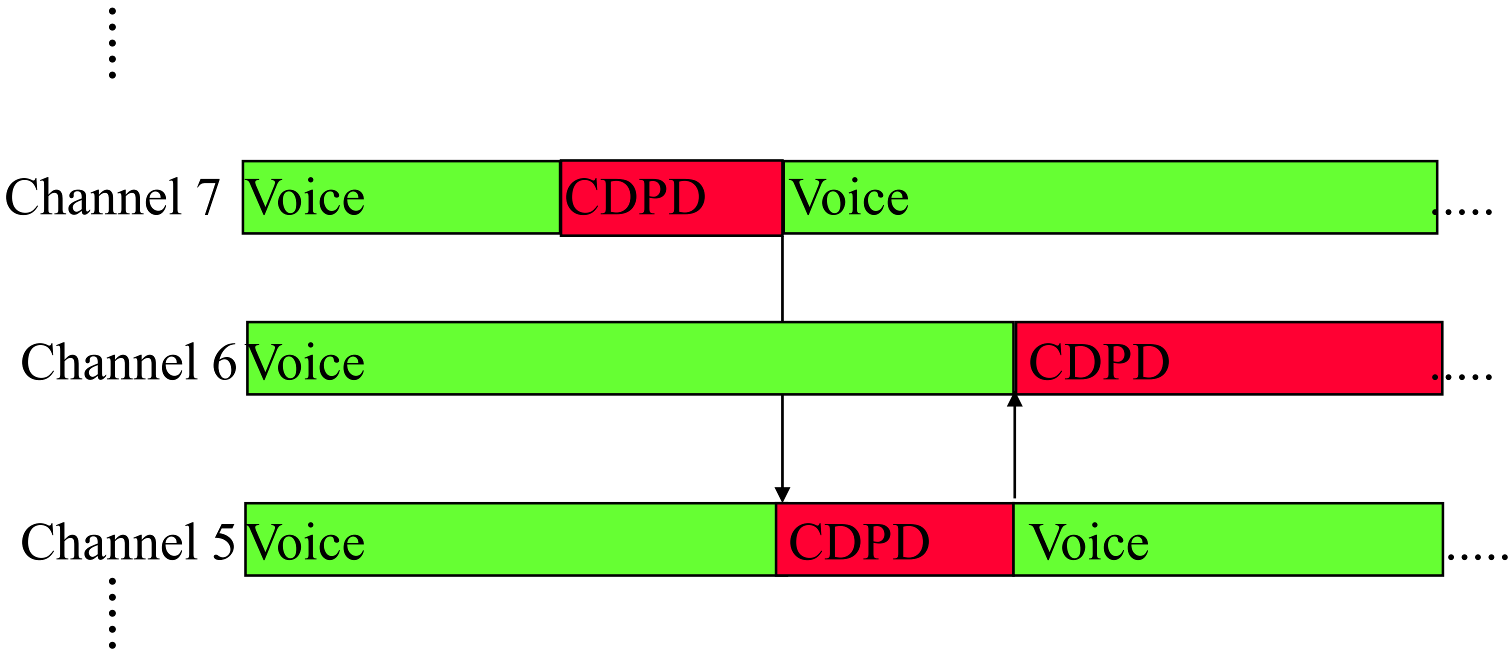
AMPS Architecture



CDPD: Cellular Digital Packet Data

- Idea: run a data packet network over AMPS channels
  - Sort of like an overlay/cognitive network (before that term was popular): opportunistically use AMPS channels that are not currently in use
- One pair of AMPS channels (one uplink, one downlink) constitute a shared data channel
- When AMPS channels about to be used by underlying AMPS system, vacate the channel pair and move to another one

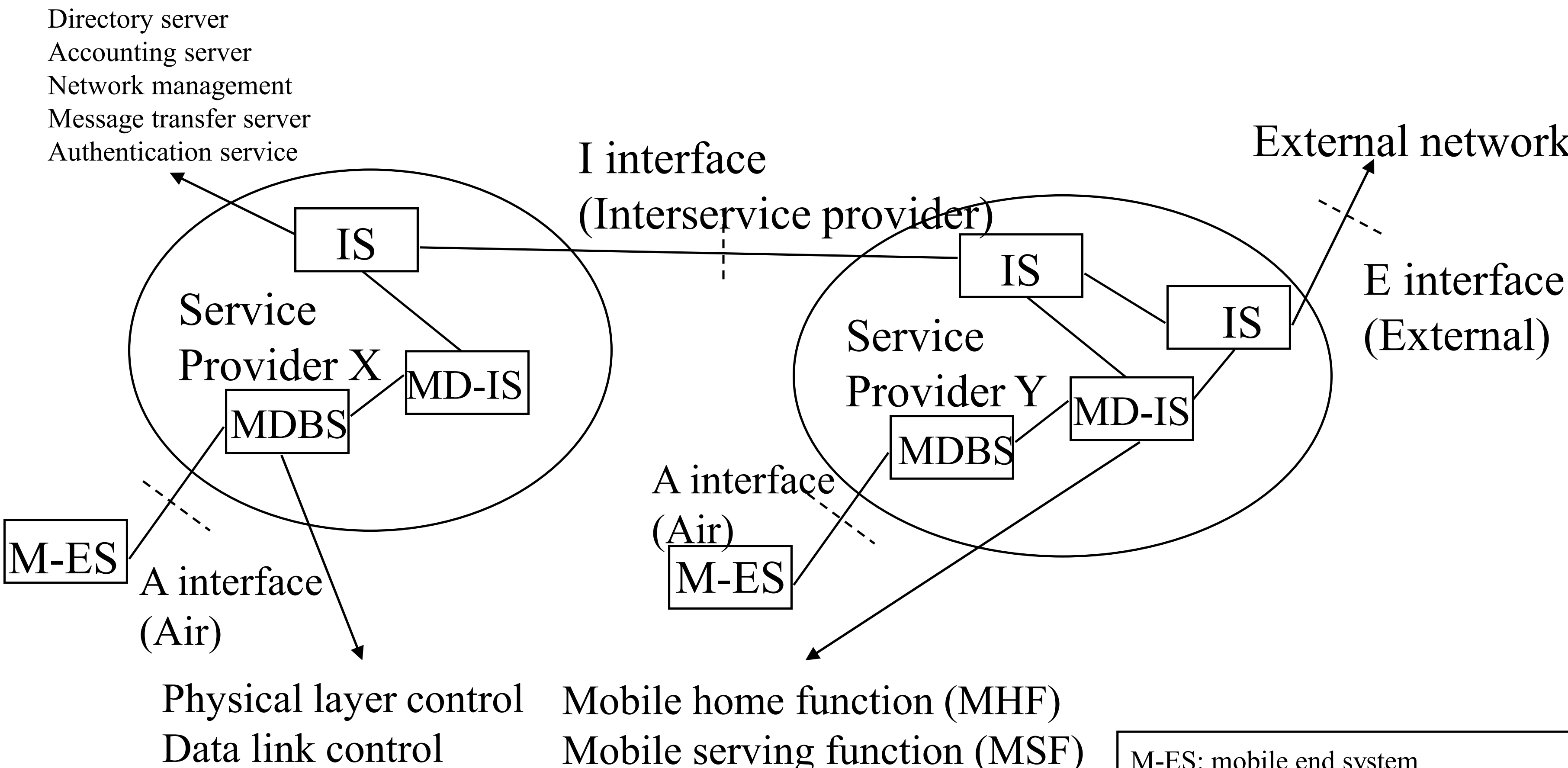
CDPD: Sharing AMPS Channels



Two scenarios:

- AMPS channel currently not in use (not assigned to a voice connection)
- AMPS channel currently assigned to a voice connection, but no talk activity (50%-60% of time)

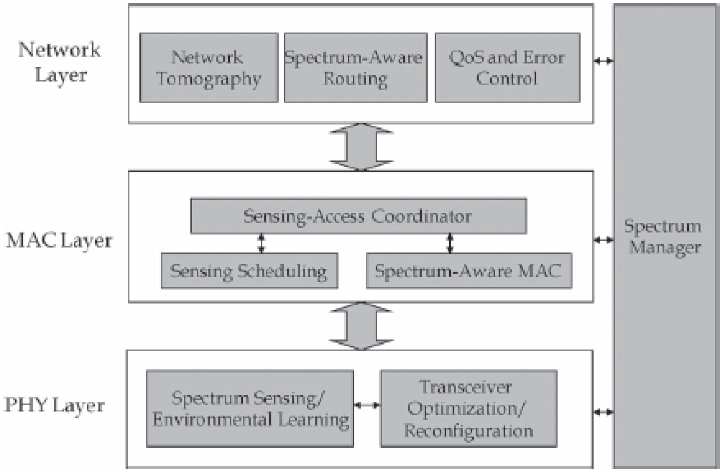
CDPD: Architecture



M-ES: mobile end system
IS: intermediate system
MD-IS: mobile data intermediate system
MDBS: mobile database station

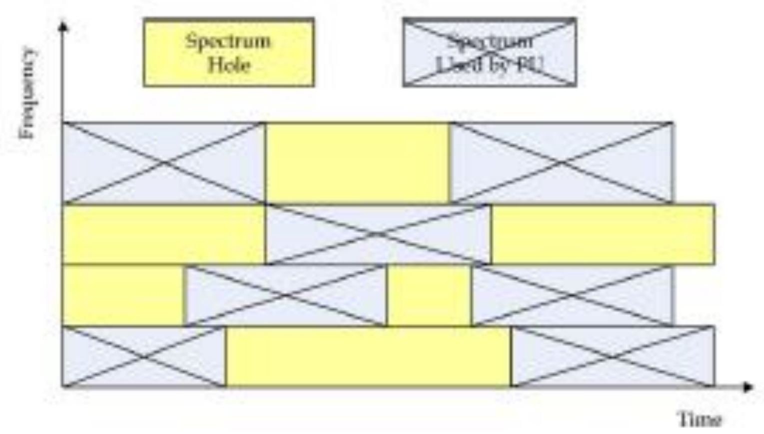
Cognitive Networks

- PU (Primary User): acquired spectrum, should be allowed access whenever desired
- SU (Secondary User): opportunistically use spectrum when “idle”
  - Lower priority than PU
  - Needs to avoid impacting the PUs
- Cognitive Radio Networking and Communications: An Overview
  - Many challenges to making this happen
    - PHY: How to sense the spectrum (is PU inactive?)
    - MAC: Schedule sensing, coordinate access to media
    - Network Layer: manage network topology and routing
  - Layers are linked by need to sense spectrum and defer access when PU is active
    - Cross-layered design



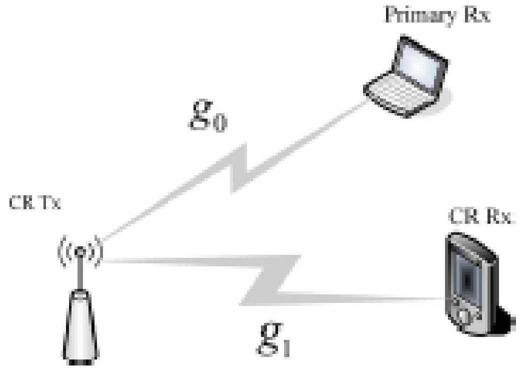
Two Basic CR Network Approaches

- Opportunistic Spectrum Access (CDPD example):
  - CR user carries out spectrum sensing to detect spectrum holes
  - Upon detecting one or multiple spectrum holes, the CR user reconfigures its transmission parameters (e.g., carrier frequency, bandwidth, and modulation scheme) to operate in the identified spectrum holes.
  - CR user needs to frequently monitor the spectrum on which it operates and quickly vacate it whenever the Pus become active.
- Also called "Spectrum Overlay" or Overlay Network



Two Basic CR Network Approaches (cont.)

- Concurrent Spectrum Access:
  - CR transmitter (Tx) refrains its transmit power such that the interference that is caused to the primary Rx is below a tolerable threshold.
  - Requires the CR Tx to predict the interference power level that is received at a particular location
- Also referred to as spectrum sharing, spectrum underlay, or Underlay Network
- Will mostly focus on Overlay Network, survey touches on both



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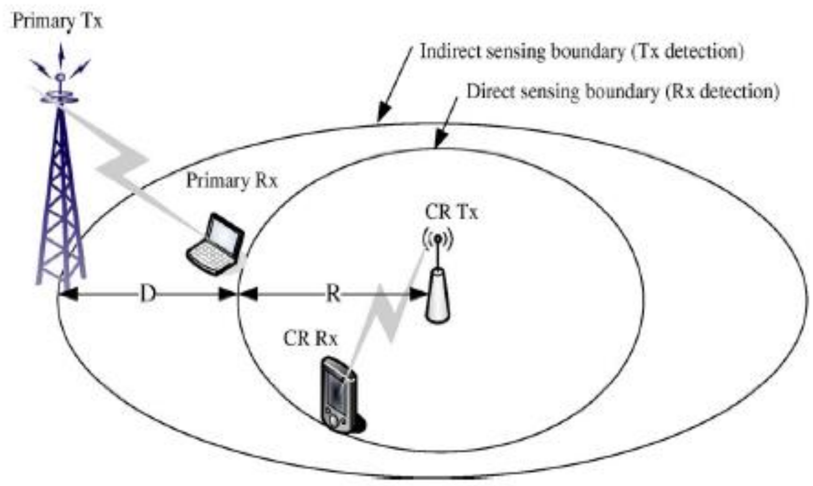
Spectrum Sensing at the PHY

- Lots about Modulation and Coding, need to understand PHY issues
- One key challenge: protect PU receivers
  - Receivers are "silent" and therefore difficult to detect
  - Transmitters are active and therefore easier to detect, but do not necessarily have to be protected
- Another issue: joint or individual detection
  - Individual: SU may be in bad spot (sheltered) to hear activity
  - Joint detection: requires message exchange/overhead



MAC Layer: Schedule Spectrum Sensing

- Where should the sensing slot be allocated within each frame?
  - Assumes TDMA
  - Make sure all SUs are inactive
- How much time should be spent for spectrum sensing in each frame?
  - Sensing takes time to be accurate
  - Sensing is overhead
- How frequent should the sensing operation be carried out?
  - Frequent enough to track incipient PU activity…

MAC Protocols

- Random Access vs. Time Slotted
- Centralized vs. Distributed
- Out-of-Band Signalling available?
- Blind (i.e., no knowledge about PU activity etc.) vs. Information-Ritch

Network Layer: Routing and Control

- Routing: can we make routing decisions based on (expected) spectrum utilization
  - Discussed later
- QoS: if any, probably statistical QoS (based on assuumptions/statistics about PU activity/spectrum availability)
- Error control:
  - Link-level schemes may be difficult (no time to send ACK back?)
  - Session-level (end-to-end) ACKs: exploit incremental redundancy, split packet across multiple coded packets. Decode at receiver once sufficient information was received

Emerging/Existing CR Standards

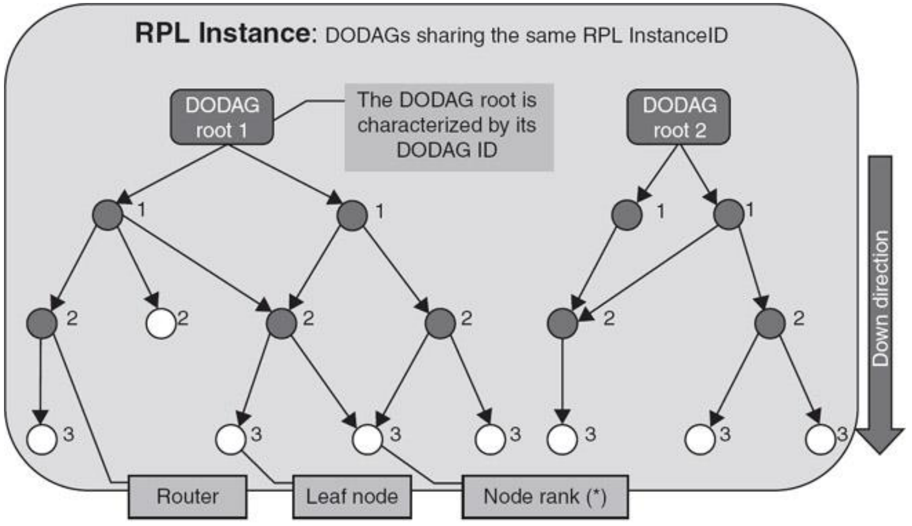
- IEEE 802.22:
  - Centralized CR system
  - Frame structure that consists of a quiet period for supporting spectrum sensing
  - Primary system: TV transmission and (wireless) microphone users
- LTE Advanced:
  - CR resource management applied to Femtocells

Example: CR Routing Protocol

- CORPL: A Routing Protocol for Cognitive Radio Enabled AMI Networks
  - AMI: Advanced Metering Infrastructure, part of the Smart Grid
  - Challenge: route data collected by smart meters back to utility and allow utility to communicate with smart meters (energy prices, emergency notifications, etc.)
    - PLC: not available when power fails, some countries regulators do not allow its use
    - Cellular networks: not optimized for IoT communication (lots of endpoint, small amounts of data)
  - Idea: build own multihop network through AMIs, use cellular bands as overlay network => cognitive network
  - Links are wireless, communication structure is tree => adapt standard routing protocol proposed by IETF, RPL

RPL: Routing Protocol for Low power and lossy networks

- RPL: create DODAGs rooted in sinks
  - Sinks periodically broadcast DOI, rebroadcast by other nodes, info used to calculate nodes' rank
- Uses rank to select parent node. Parent node has to have lower rank (avoids routing loops).
  - Focus is very much on leaf to root traffic
  - Provisions in protocol for root to leaf traffic
- One simply way to determine rank: hop count
- Other metrics are possible: root broadcasts which OF (objective function) to use/how to calculate rank.
  - Only limitation: rank increases monotonically
- Multiple DODAGs can co-exist.



(*) : the node Rankstrictly increases in the Down direction. The exact way Rank is computed depends on the DAG's Objective Function (OF), and is valid for a specific DODAG version

Specific Routing Challenges

- Don't route packets through nodes engaged in spectrum sensing
- Don't route packets through nodes that will impact PU nodes when forwarding
- On the other hand:
  - Provide high throughput for secondary users
  - Provide QoS: low latency for high-priority data

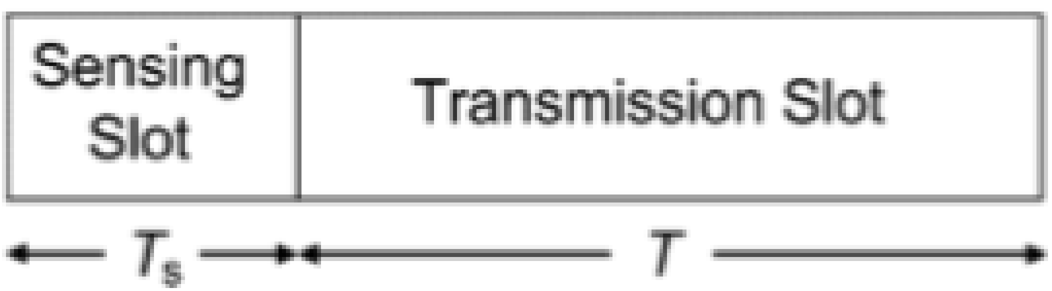
- CORPL: Cognitive RPL
  - Builds on RPL
  - Opportunistic Routing:
    - Node selects subset of forwarders and broadcasts packet
    - Forwarders collectively coordinate so that only one (ideally) forwards packet

System Model

- Static multi-hop network of AMI metering devices that can communicate wirelessly
- Single gateway/sink
- N stationary PU transmitters
  - Each with their own channel (i.e., there are N channels)
  - Each PU has known location, max coverage range, and known activity model
    - Two bursts: idle and busy
    - Duration exponentially distributed with known and fixed mean
- Spectrum Sensing: threshold-based energy detection
- SU network carries two types of traffic
  - Low priority monitoring data
  - High priority delay-sensitive information

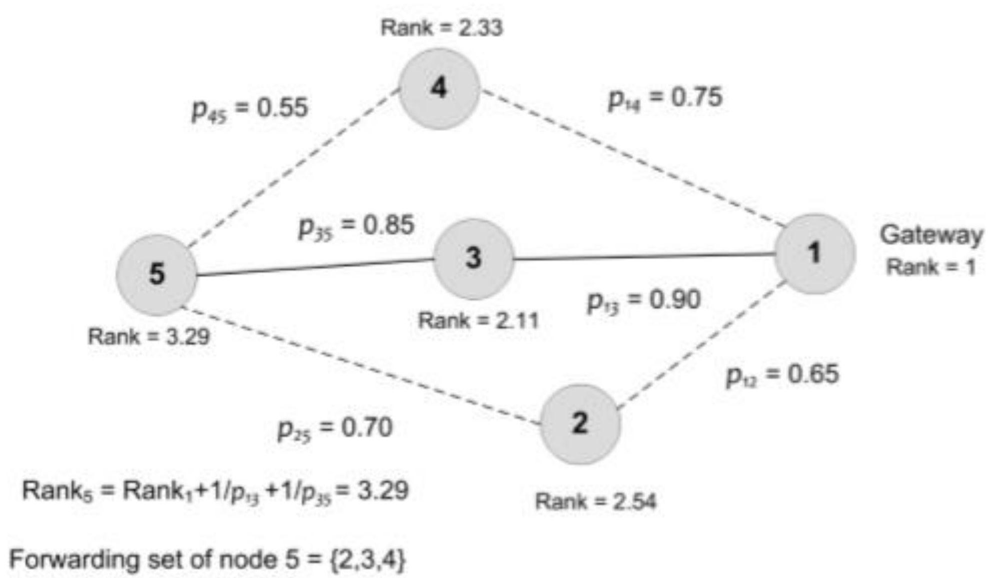
MAC

- Basic frame: sensing slot followed by transmission slot
- Optimal length of T can be determined analytically based on
  - Acceptable level of PU interference
  - Detection probability threshold used for spectrum sensing
  - Mean length of off and on bursts



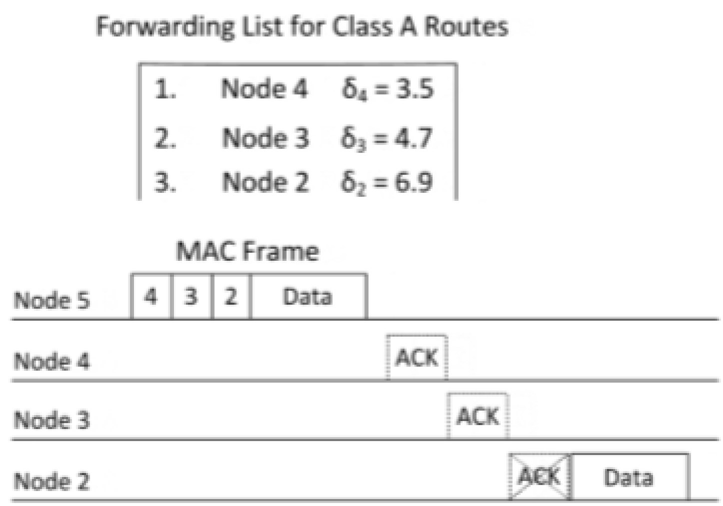
DAG Construction

- Gateway detects empty channel and starts process, broadcasting DIO
- Metric for rank computation: ETX (expected transmission count)
  - Let p_ab be probability that a packet transmitted from a is received by b
  - ETX for that link is 1/p_ab
  - Continuously update ETX as data packets are being transmitted



Forwarder List

- Each node has a default parent
- Each node selects M forwarders based on cost
  - M relatively small, as list is pre-pended to data packet
  - Cost depends on traffic class
    - Low priority traffic: give more priority to PU protection
    - High priority traffic: give more priority to meeting delay requirement



Cost Metric Components

- PU Protection
  - Measure (geographic) overlap between coverage area of PU transmitter and a node, based on their respective coverage radii and the distance between them
- Delay requirement
  - Determine fractional delay budget for next hop node

$$DB = \frac{deadline(P) - t}{d(k)},$$

- Use ETX as a measure of link quality
- Overall cost $\delta_i = \omega_1 \cdot C_i + \omega_2 \cdot E_{ki} + \omega_3 \cdot DBM_i,$ w1+w2+w3=1

- Low priority traffic: w1 >> w2, w3
- High priority traffic: w3 >> w1, w2

Opportunistic Forwarding

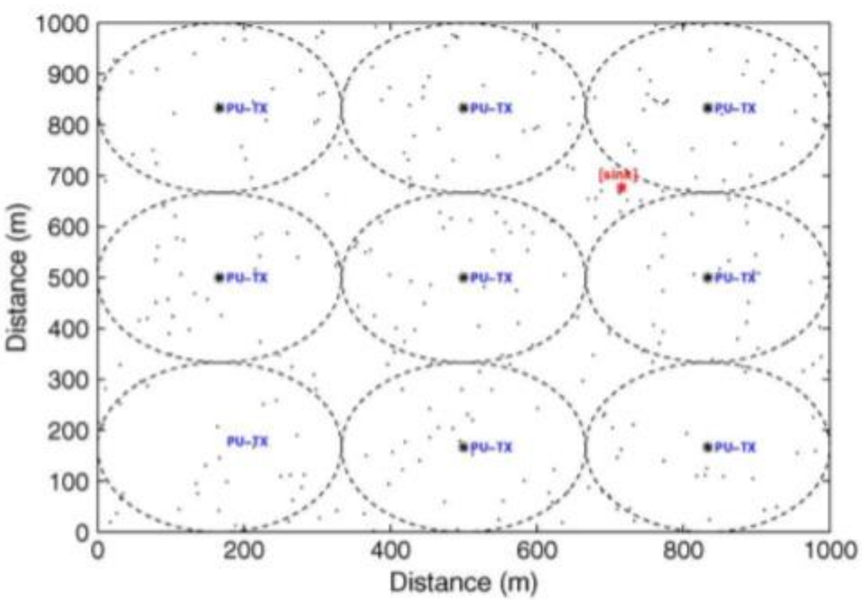
- First node in forwarder set (or default parent for best-effort traffic) forwards packet and sends ACK
- Other nodes in forwarder set listen to ACK
  - If none received within a timeout period, next node on forwarder list gets to forward data packet
  - If node mistakenly misses ACK, two data packets get forwarded

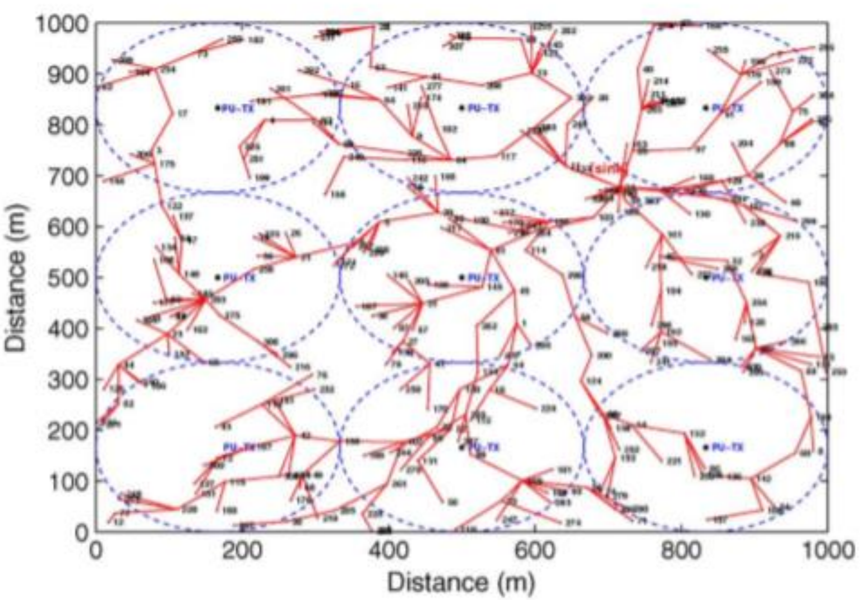
Performance Improvements

- Distribute spectrum sensing schedule with DIO message
  - Will not forward delay-sensitive traffic to nodes that are busy with spectrum sensing
- Adapt sensing time based on PU activity
  - Start out with max sensing time
  - If PU activity is low, decrease sensing time
  - If this leads to missed detection, increase sensing time again (unspecified how that is determined though)

Performance Evaluation

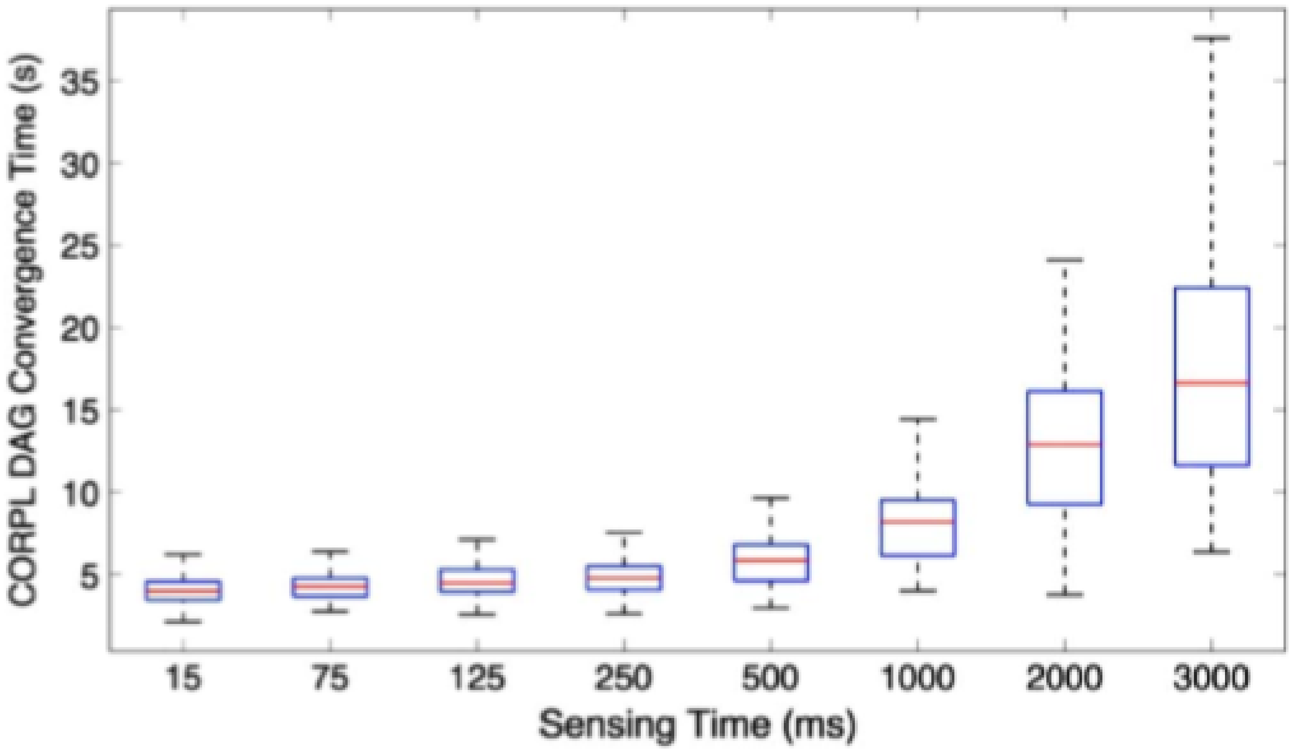
- Implemented protocol in MATLAB
- Rayleigh fading channel, forwarder set limited to 5, PU activity 40%
- Evaluation focuses on upstream traffic (from metering devices to gateway) only





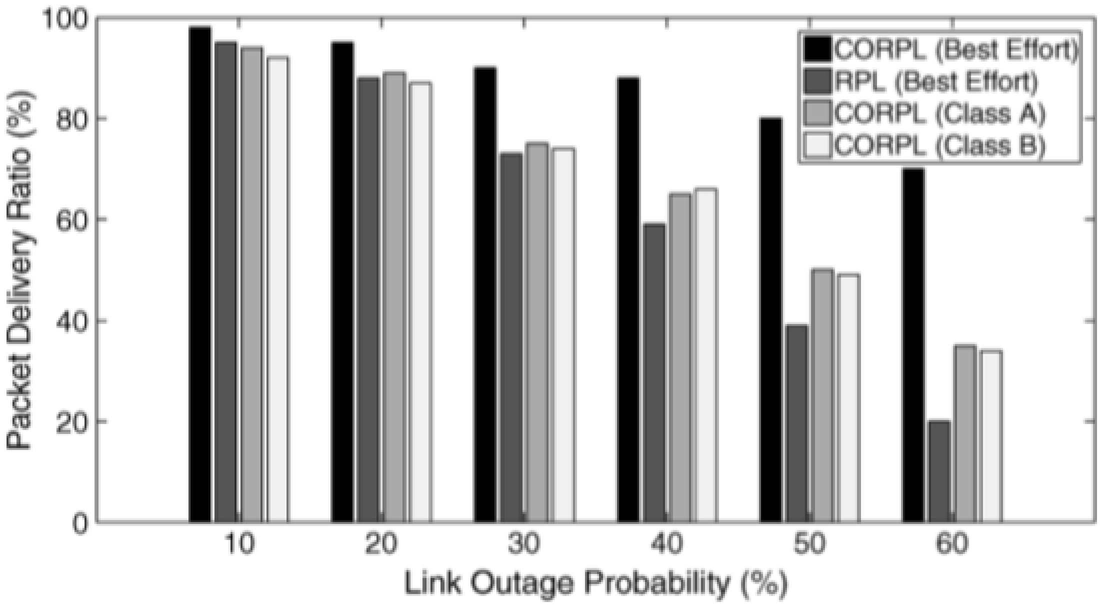
Spectrum Sensing vs. DAG Convergence

- Network is static, so eventually a DAG is built
- The longer the sensing time, the longer it takes to build/converge on that DAG



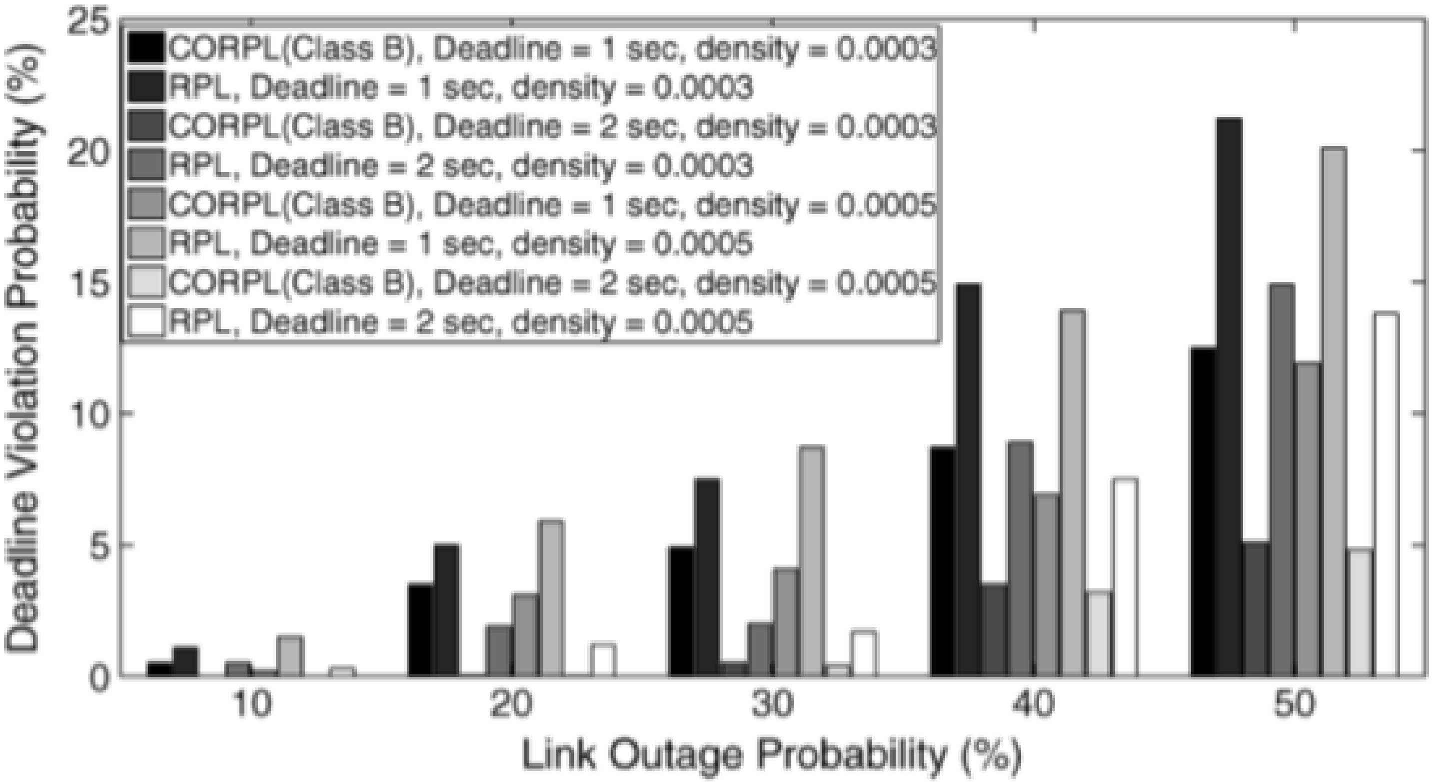
PDR Performance

- RPL vs. three different traffic classes in CORPL:
  - Best effort (uses default parent)
  - Low-priority traffic
  - High-priority traffic
- CORPL almost always better than "regular" RPL, particularly when link outage probability increases
  - Key reason: opportunistic forwarding



Latency Performance: Missed Delivery Deadlines

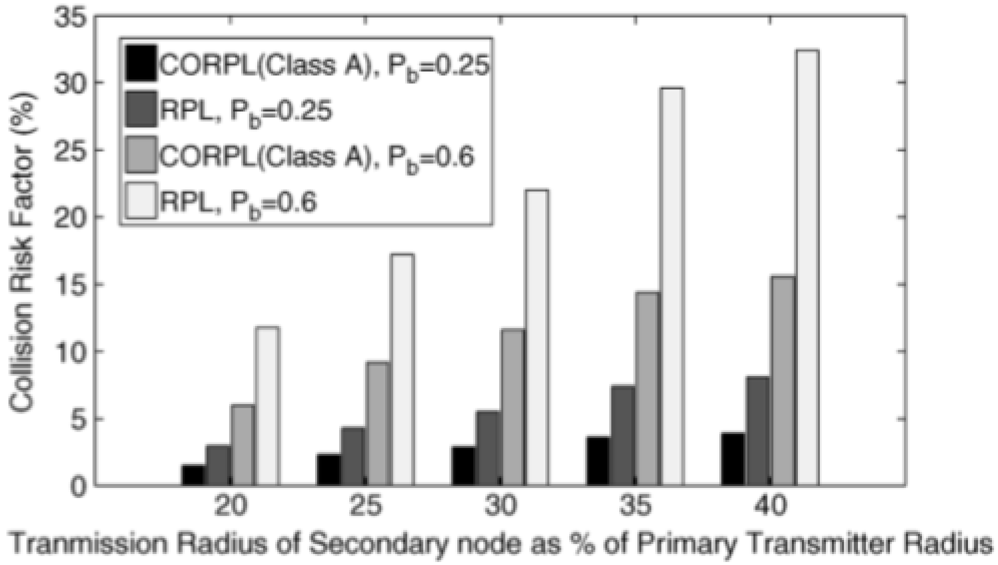
- Higher link outage probability: more packets miss delivery deadline
- Higher density: fewer packets miss deadline, as shorter hop paths exist
- CORPL better than RPL in all scenarios



Performance Evaluation: What is Missing?

Cognitive Networks: No Impact on PU!

- CRF: Collision Risk Factor, measures the ratio of colliding transmissions (normalized by the number of SU transmissions) at the PU receivers
- Depends on the spatial location of PU receivers, the PU transmitter activity level, and the SU transmission range
- For low-priority traffic (high weight on avoiding such interference), CORPL outperforms RPL



Conclusion on Paper

- Paper claim:
  - CORPL utilizes an opportunistic forwarding approach that not only ensures protection to PUs but also fulfils the utility requirements of the secondary network. Results show that CORPL improves the reliability of the network while reducing harmful interference to PUs by up to 50% as well as reducing the deadline violation probability for delay sensitive traffic. Hence, CORPL provides a viable solution for practical cognitive AMI networks.

- Would you agree?

CRN Challenges

- Common control channel: do we need one
  - Protocol designs are certainly simplified if we have one
  - But unless spectrum is regulated accordingly, we may not have one
- Joint spectrum sensing and access
  - Usually designed separately
  - Better performance could be achieved by joint design
- Economic models
  - How to encourage PU to support SU existence (probably through financial or regulatory incentives)
  - Is there enough "capacity" in SU network to provide interesting services?
- CRN and CR implementation architectures: how to make cross-layering work