Wireless Technology for Autonomic Networks

July 4, 2011

PhD School on Information Engineering

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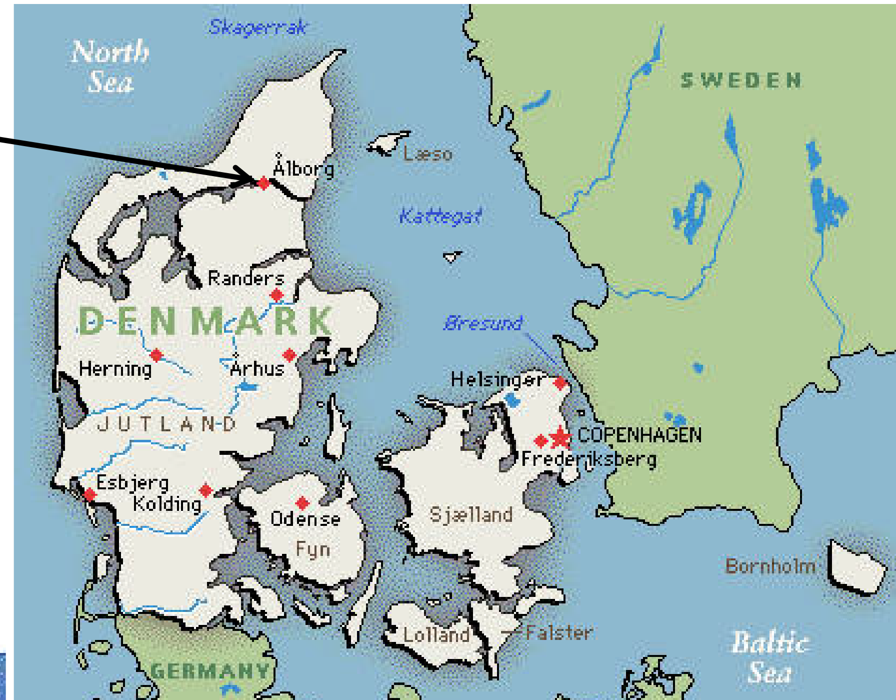
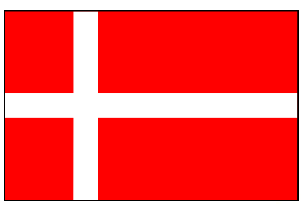
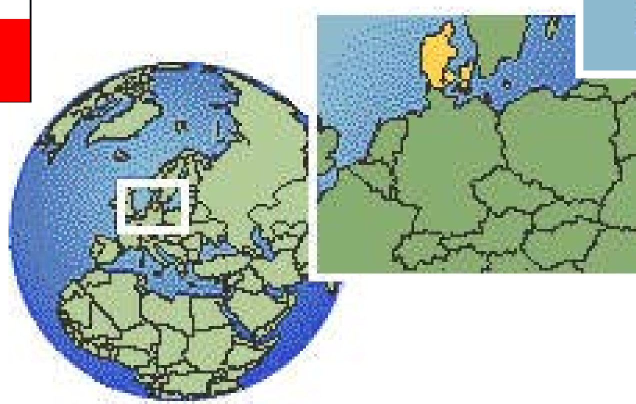
Denmark

Facts

- Aalborg
  - Population: 200 000
  - Aalborg University and Center for TeleInfrastruktur





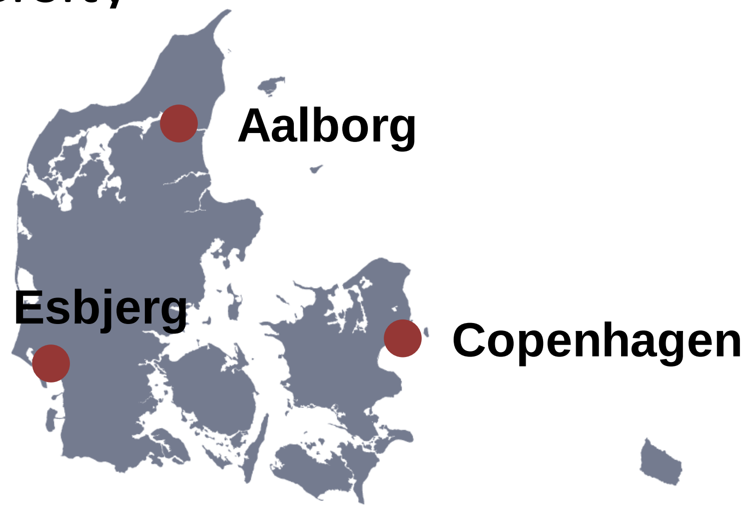


Area:	43 094 km^2
Population:	5.6 millions

Aalborg University

On the Forefront of Innovation

- Aalborg University is a young university
  - Inaugurated in 1974
- A Network University
- Four faculties



- 15.000 students
  (10% international)
- 1.500 researchers
  (30% international)
- 700 techn.-adm. personnel
- Total budget 2,2 bn. dkk (415 mio $)

[1]Danish magazine - The Engineer (Ingeniøren)and IDA (the Danish union for engineers)

Aalborg University

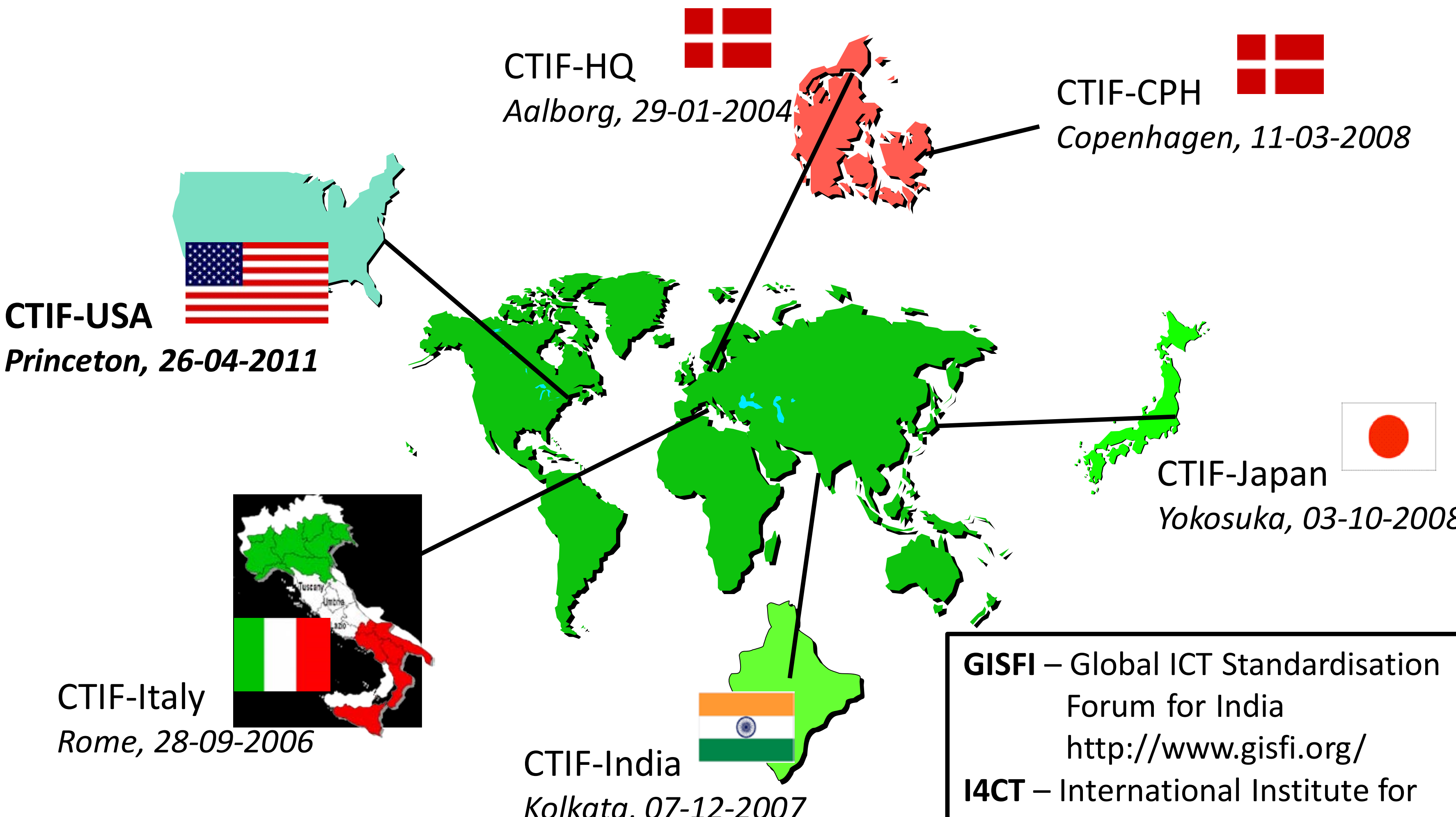
On the Forefront of Innovation

- *Wireless Communications* is a major research area at Aalborg University
  - Covered under the umbrella of *Center for TeleInFrastruktur (CTIF)*
  - CTIF is one of the world's leading research centers in the field of wireless communications
- Other significant areas are: Health science and green energy

[1]Danish magazine - The Engineer (Ingeniøren)and IDA (the Danish union for engineers)

CTIF is a global ICT-based inter- and cross disciplinary research center with focus on scientific innovation and academic education:

Divisions



GISFI – Global ICT Standardisation Forum for India http://www.gisfi.org/

I4CT – International Institute for Innovation in ICT

CTIF-Global

Networks

CTIF-Education

CTIF

Expertise

- CTIF has a strong experience in radio access networks, wireless sensor networks, wireless personal networks, Internet of Things, security, self-organising networks and testbeds. Our latest research area is in the area of wireless robotics. The concept of wireless robotics relies strongly on CRNs and autonomous self-organising networks.

Abstract

Traditional telecommunication systems were designed for a single technology, while the modern communication infrastructure builds on a suite of technologies, devices, equipment, facilities, networks and applications for support of communication at a distance, often without human intervention. Each communication element (e.g., device, service, application) uses a mobile radio component for communicating data by way of some specific technology. Communication scenarios in the context of modern telecommunication systems are defined by the data context and can occur randomly among mobile components based on different technologies (i.e., heterogeneous), leading to an unpredictable and complex communication process and dynamic network topology. Reliable end-to-end transfer of data to application, which provides the particular network functionality and interface to the user, depends on algorithms and protocols for medium access control, routing, and mobility. Currently, these are organized in layers in architecture known as protocol stack and need the cooperation of a set of complimentary layered capabilities. The layered design is a key limitation as it assigns each protocol layer a specific purpose and task to support the data transfer, and is executed by means of targeted design protocols associated with it.

What you will learn

- What are autonomic wireless networks?
- What types of technologies are needed to support autonomic wireless communications?
- How should the design of autonomic wireless networks be approached?

Outline

Part 1: General Concepts and Motivation

- Introduction to autonomic wireless networks
- Wireless Technologies enabling autonomic communications
- Wireless network protocols for autonomic communicaitons
- Hardware design for autonomic wireless communications

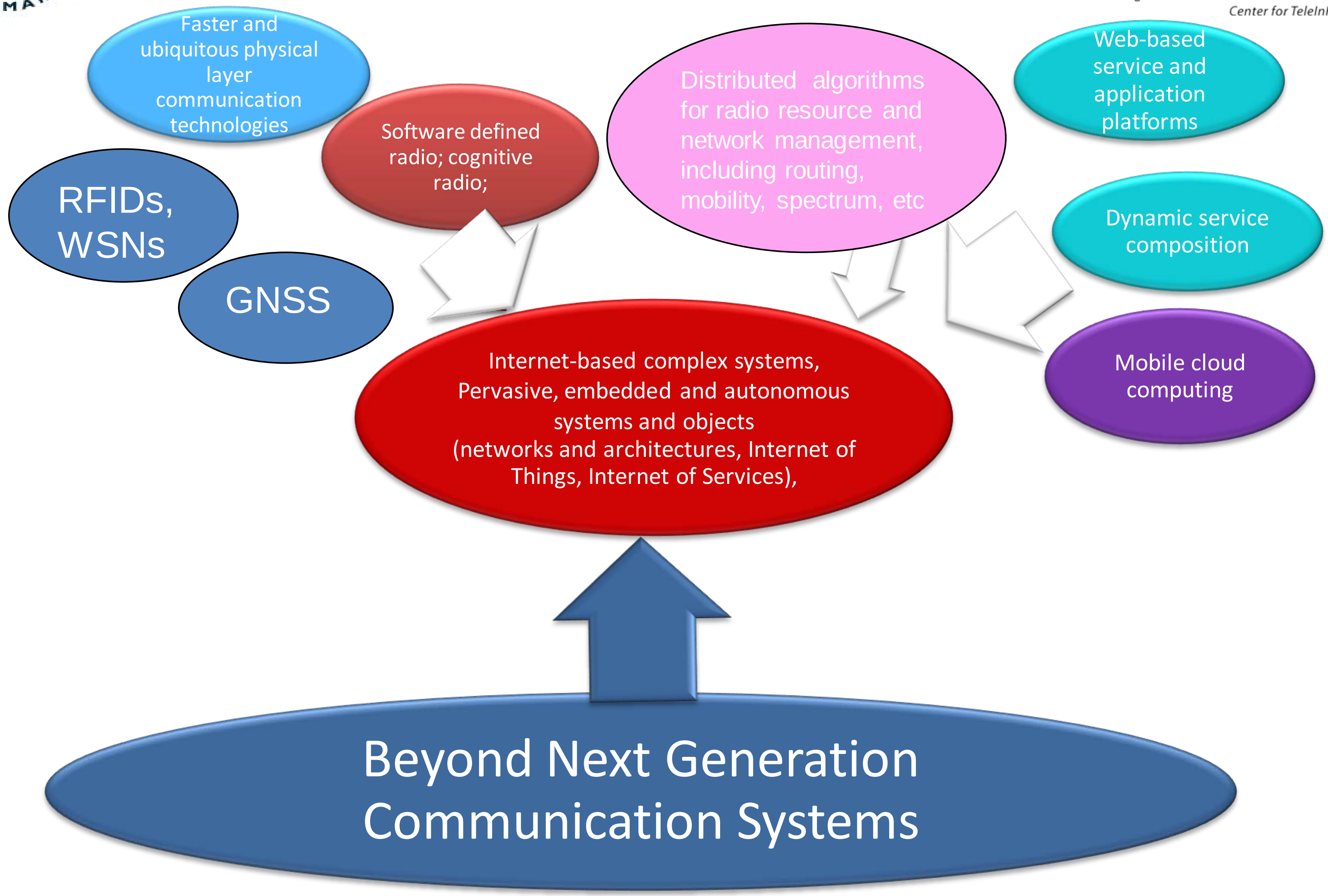
Outline

Part 2: Specific Technologies and Challenges

- Spectrum access and sharing
- Cognitive Radio Networks:
  - Protocol Architectures for Cognitive Networks
  - Routing;
  - Security
  - CRN and the Internet
- Self-Organization

Beyond Next Generation Communication Systems

A Few Concepts

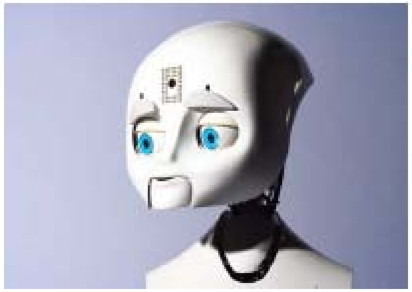


Introduction

AWC Systems

- Personal mobile devices gain a new dimension: not merely mobile phones but capable of :
  - Sense and communicate over radio
  - Plan and communicate over radio
  - Act and communicate over radio

A glimpse of tomorrow



Autonomic Wireless Communication (AWC) Systems

Reference Scenario

- Each element of the AWC system has a ***mobile radio component*** allowing it to:
  - Sense and communicate over radio
  - Plan and communicate over radio
  - Act and communicate over radio

- Possible communication scenarios are defined by ***data and situation context***

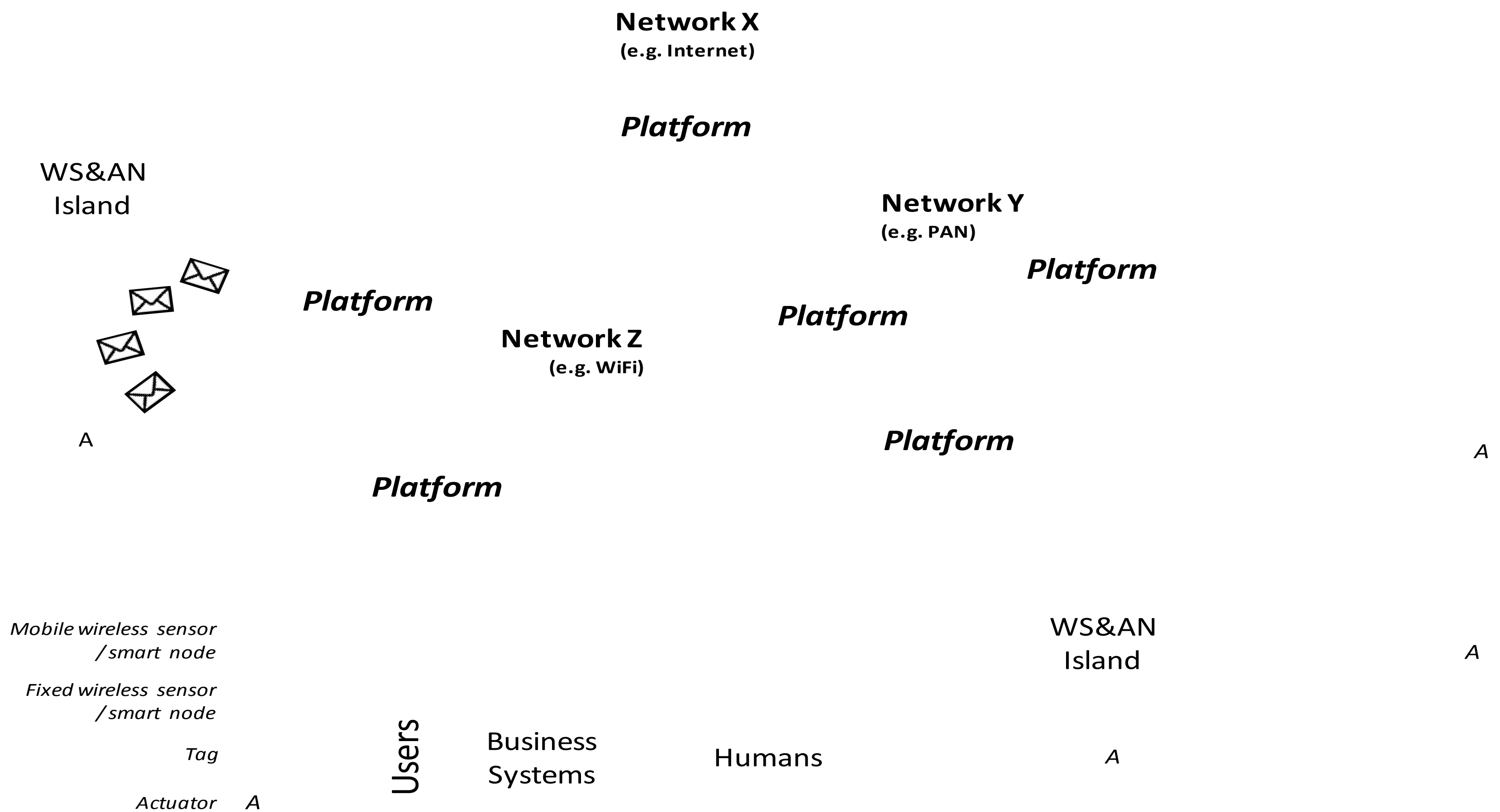
- ***Randomness of events changes scalability and stability***

  - *<u>requires fundamental changes both in network and individual nodes</u>*

  - *<u>Move away from traditional architectures towards concepts that allow for increased degrees of network and environmental awareness.</u>*

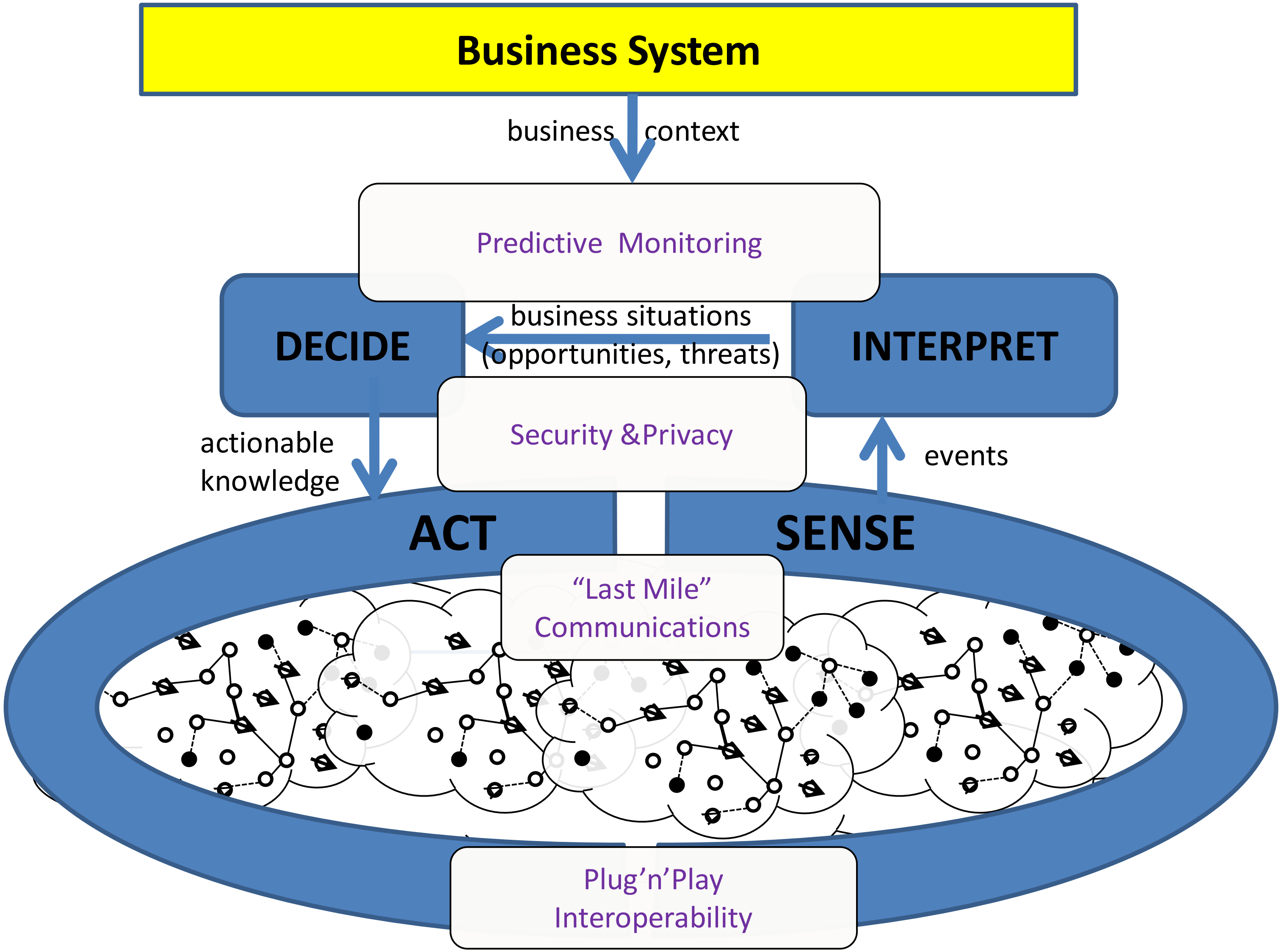
Introdcution

From dedicated deployments to scalable energy-efficient heterogeneous autonomous networks



Introduction

The cognitive cycle is a basic funcitonality of the Beyond Next Generation Architecture



Introduction

Summary

- The number of wireless devices and mobile network traffic is growing rapidly
- The fundamental stability and scalability assumptions of today's networking will no longer hold. Future networks will need to be highly scalable and agile in terms of the number and type of networked devices, as well as to provide greater flexibility to spectrum scarcity, energy limitations, bandwidth and cost objectives.
- Adaptation and reconfiguration should vary at different levels of the network to satify varying characteristics creating more advanced architectural concepts

Wireless Technologies for AWC

Current architectural solutions

- Defficiencies
  - Centralised design does not allow for flexible topology reconfiguration and efficient spectrum resource utilisation.
  - Monolithic radio access and protocol architectures
  - Any evolving /optimising solution leads to higher costs and management complexity
  - Rigidness of spectrum regulation and usage: frequency bands are pre-allocated withou a consideration of the spectrum utilisation degree'

Communication Challenges

- Communication between groups of scattered communication elements that are reachable via the available communication mediums; from direct link to multi-homed connectivity to various infrastructure segments and operators

- Spontaneous communication with neighboring objects using different wireless technologies

- Continuous monitoring of resources (software or hardware component)
- Autonomous re-configuration to keep parameters within a desired range

Seamless provision of necessary services:

Wireless Technologies for AWC

New architectural solutions

- The AWC architecture should be:
  - scalable and agile in terms of the number and type of networked devices, and should provide great flexibility to spectrum scarcity, energy limitations, bandwidth, and cost objectives
  - Adaptation and reconfiguration scales will be required to vary considerably at various levels of the network architecture, in order to provide diverse and on-demand service requirements with widely varying characteristics

Enabling Technologies for AWC

Ad hoc and Cognitive Radio (CR) Networking

- Decentralised technologies with potential
  - Although ad hoc networks are limited by the design principle of sharing limited radio channels by all communication peers
  - CRs are intelligent-enviromentally aware devices able to adapt their physical characteristics and capable to be tuned for utilising the available spectrum in multiple frequency bands

CRs allow for reconfiguration of ad hoc networks by optimally exploiting trade offs between the node trasnmission range (e.g., connectivity) and netwrok capacity

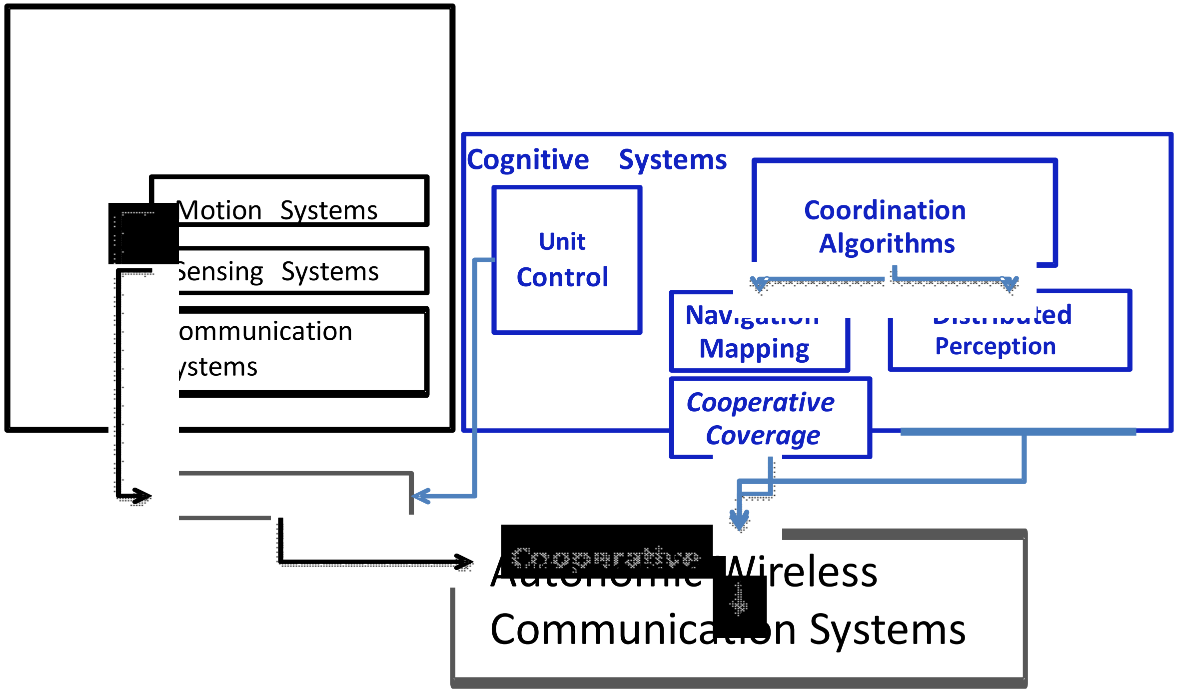
Design and Architectural Considerations

- How to design an architecture that will support autonomic behavior?
- How to represent the information necessary to an autonomic object in a wireless scenario to achieve an autonomic behavior?
- How wireless autonomic object communicate together, and organize among themselves in a possibly large context?

New Protocol Architecture for CRN

- Novel approach to protocols: holistic protocol stack
- Routing, mobility, communication should be revisited:
  - Satisfy multiple, diverse and conflicting traffic flows requirements- *requires novel routing techniques*
  - Maintain end-to-end path quality subject to available spectrum and link *performance-requires proactive QoS techniques*
  - Coordinated channel usage and better spectrum exploitation: *novel resource allocation techniques*

Architecture and Elements



Technological Vision

Challenges:

How can we enable autonomics and cooperation?

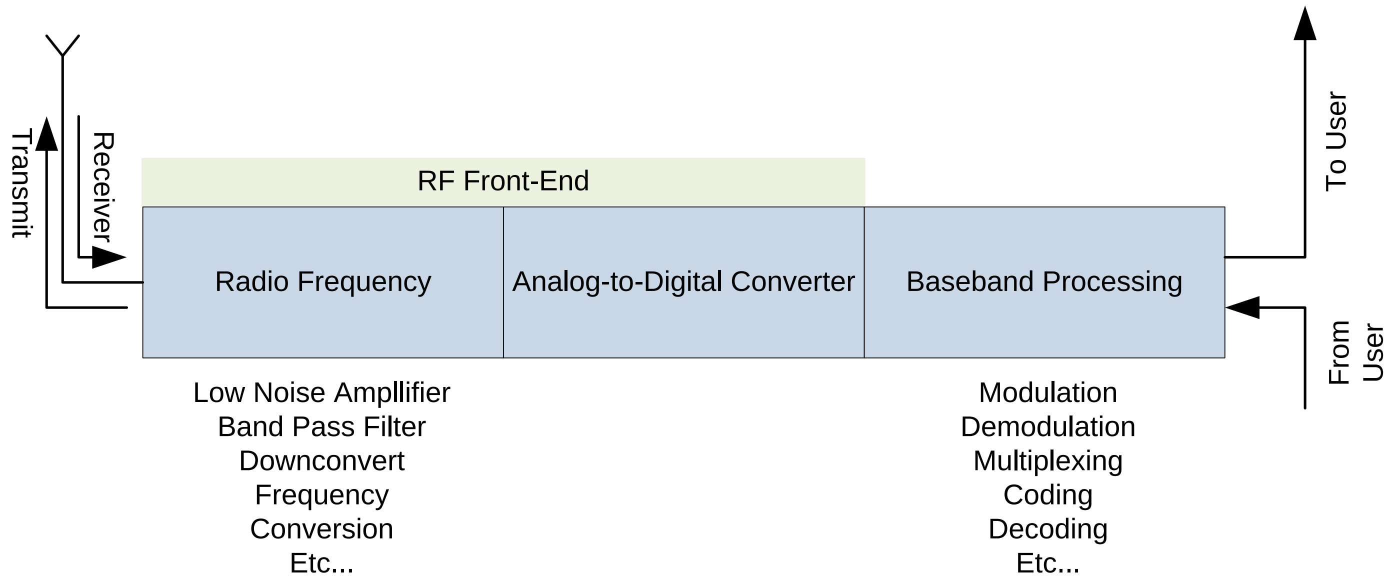
- Communication
- Networking
- Security
- Synergy beween and cognitive systems

AWC Enabling Technologies

COGNITIVE RADIO AND SOFTWARE DEFINED RADIO

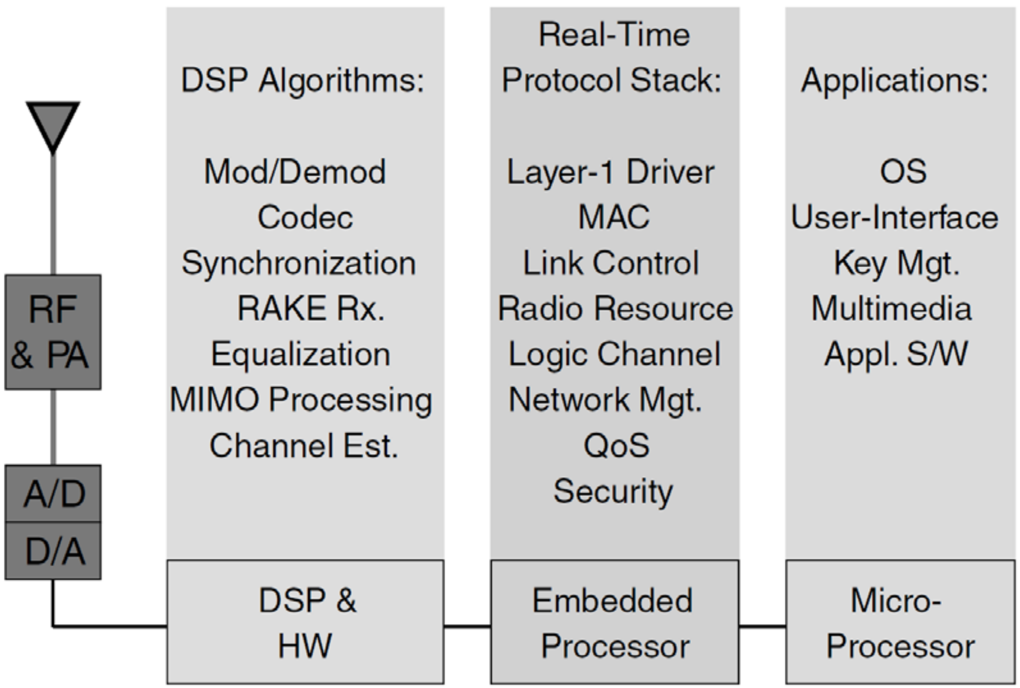
Software Defined Radio

Traditional Radio



RF Front-End and Baseband Processing is implemented in hardware.

Software Defined Radio



Example of SDR Architecture illustration in:
KC Chen *and R. Prasad., "Cognitive Radio Networks"*, Wiley 2009

For more details check:
Chapter 2 - KC Chen *et al., "Cognitive Radio Networks"*, Wiley 2009

RF Front-End is implemented in hardware
Baseband and subsequent are implemented in FPGA controlled by software

Software Defined Radio == Signal Processing of Radio in Software

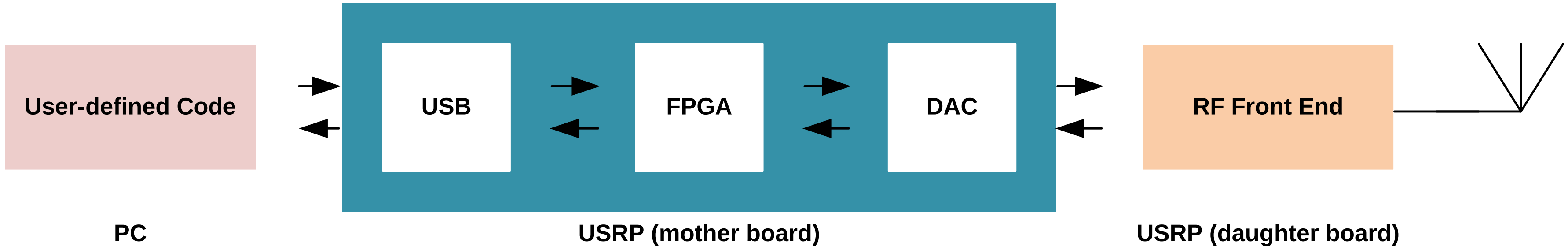
Software Defined Radio

USRP - SDR Solutions

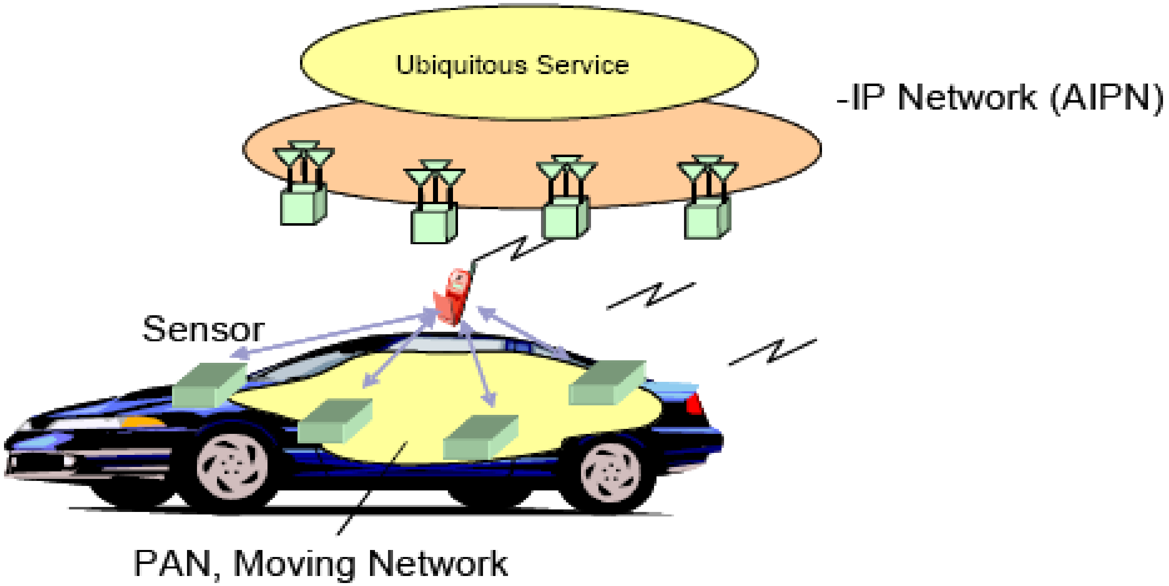
USRP 2 (*Built by Ettus Research*)
You can ask for a Demo in the CTiF Lab!!!

Powered by GNU Radio
http://gnuradio.org/

Hardware Architecture



Example: Moving Network



SDR for the provision of ubiquitous services

SDR Current Implementations

Network on Chip

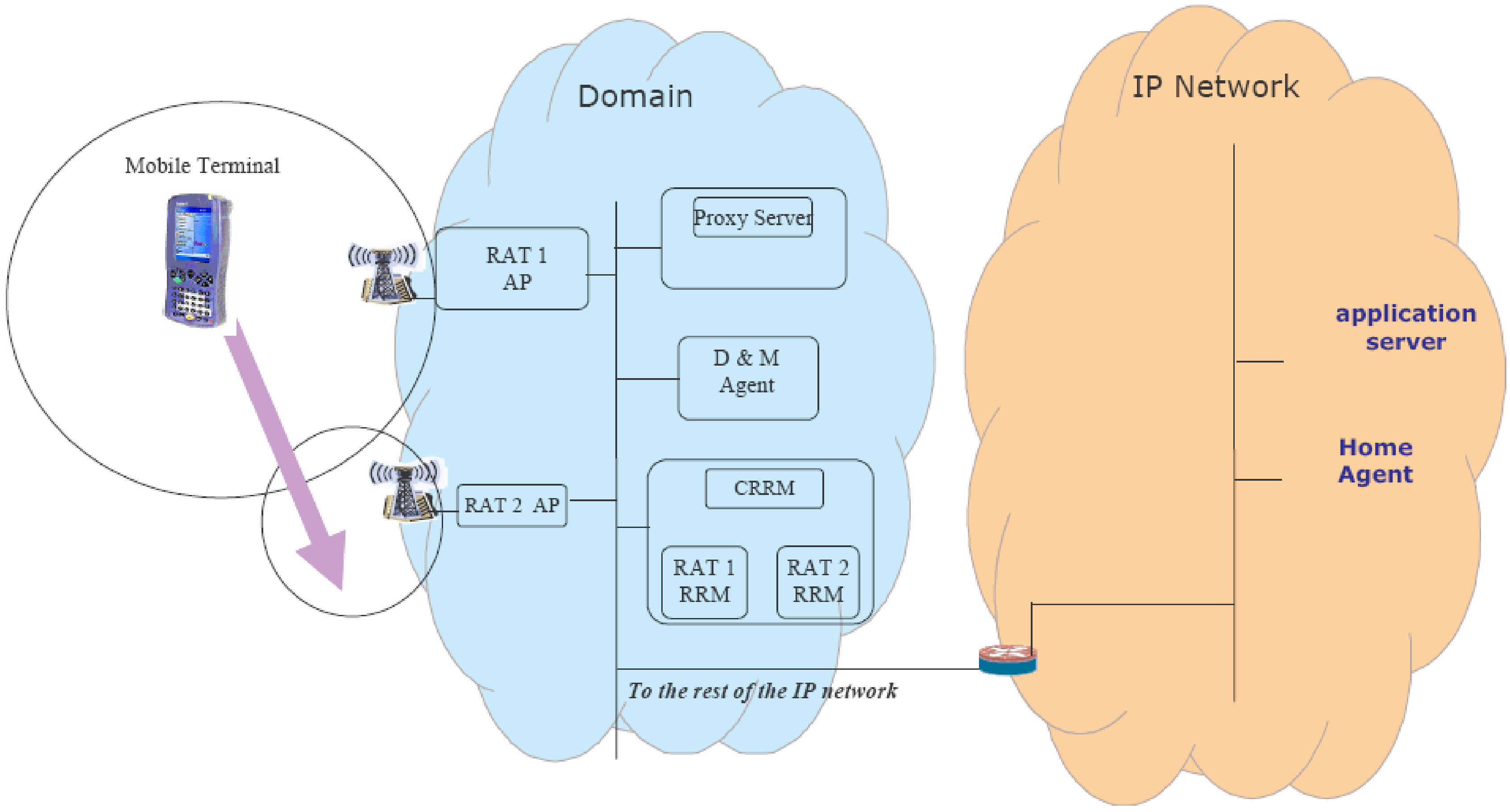
- The MAGALI NoC technology is able to handle the complete reconfiguration of the system between two transmission standards.
- It is not the case of the BS emulator, which is implemented on an FPGA prototyping platform with few hardware resources left, i.e. without the possibility to support two different systems.

Constraints

- The re-configuration is carried out with a modification of both the network routing and nodes functionality
- Time constraint is essential as reconfiguration happens at very low levels and any delay will add to the higher layer delays and exchanged information
- Example (NoC): the reconfiguration time must not exceed 10 % of the total frame time (1 ms), which means 100 µs maximum for the reconfiguration time.

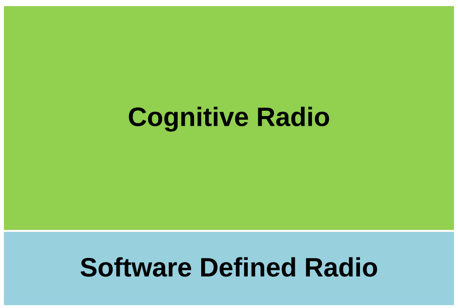
SDR

Application of SDR for seamless services



Software Defined Radio

- Cognitive Radio and SDR



Cognitive Radio is built on top of the Software Defined Radio

Cognitive radios are software-defined radios capable of sensing their environment and making decisions instantaneously, without any user intervention. Rapid change of modulation schemes and communications protocols provides an enhanced performance in a sensed environment.

By Ramjee Prasad

Cognitive Radio

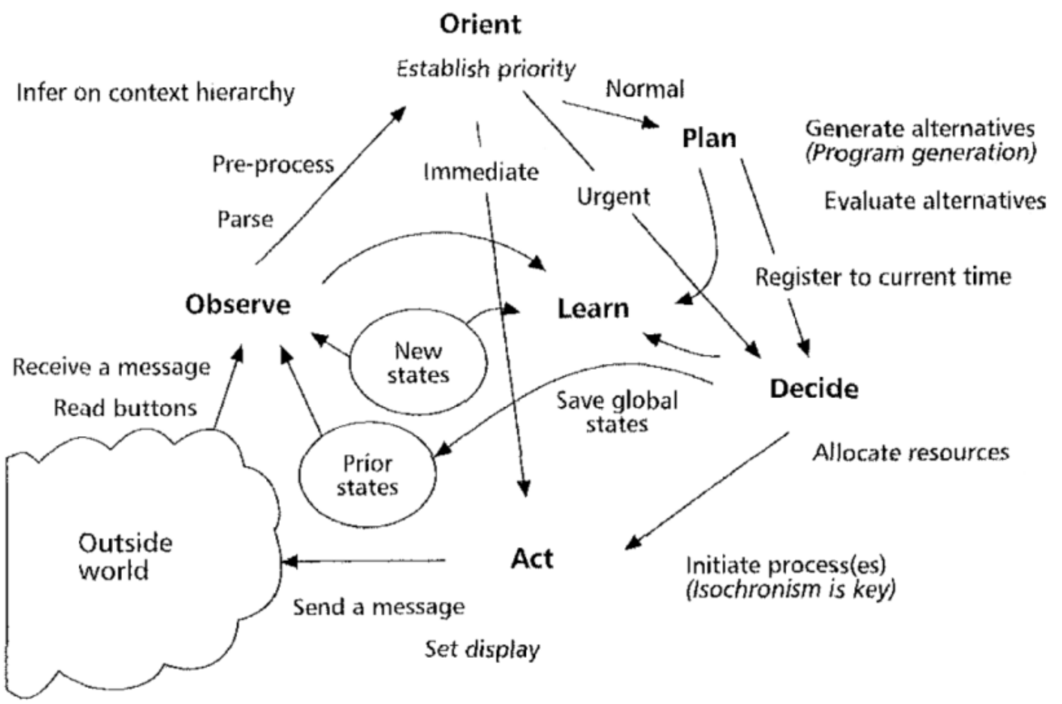
Definitions

Center for TeleInFrastruktur

- **Mitola : "**Cognitive radio signifies a radio that employs model based reasoning to achieve a specified level of competence in radio related domains ".
- **FCC** - A cognitive radio (CR) is a radio that can change its transmitter parameters based on interaction with the environment in which it operates.
- **Kolodzy** - A cognitive radio has the flexibility and the adaptability to change its operating conditions to its environment (either real or perceived)
- **Early SDRF Draft** - The term Cognitive Radio refers to a radio that has, in some sense, (1) awareness of changes in its environment and (2) in response to these changes adapts its operating characteristics in some way to improve its performance or to minimize a loss in performance.

Cognitive Radio

What is a Cognitive Radio Cycle?



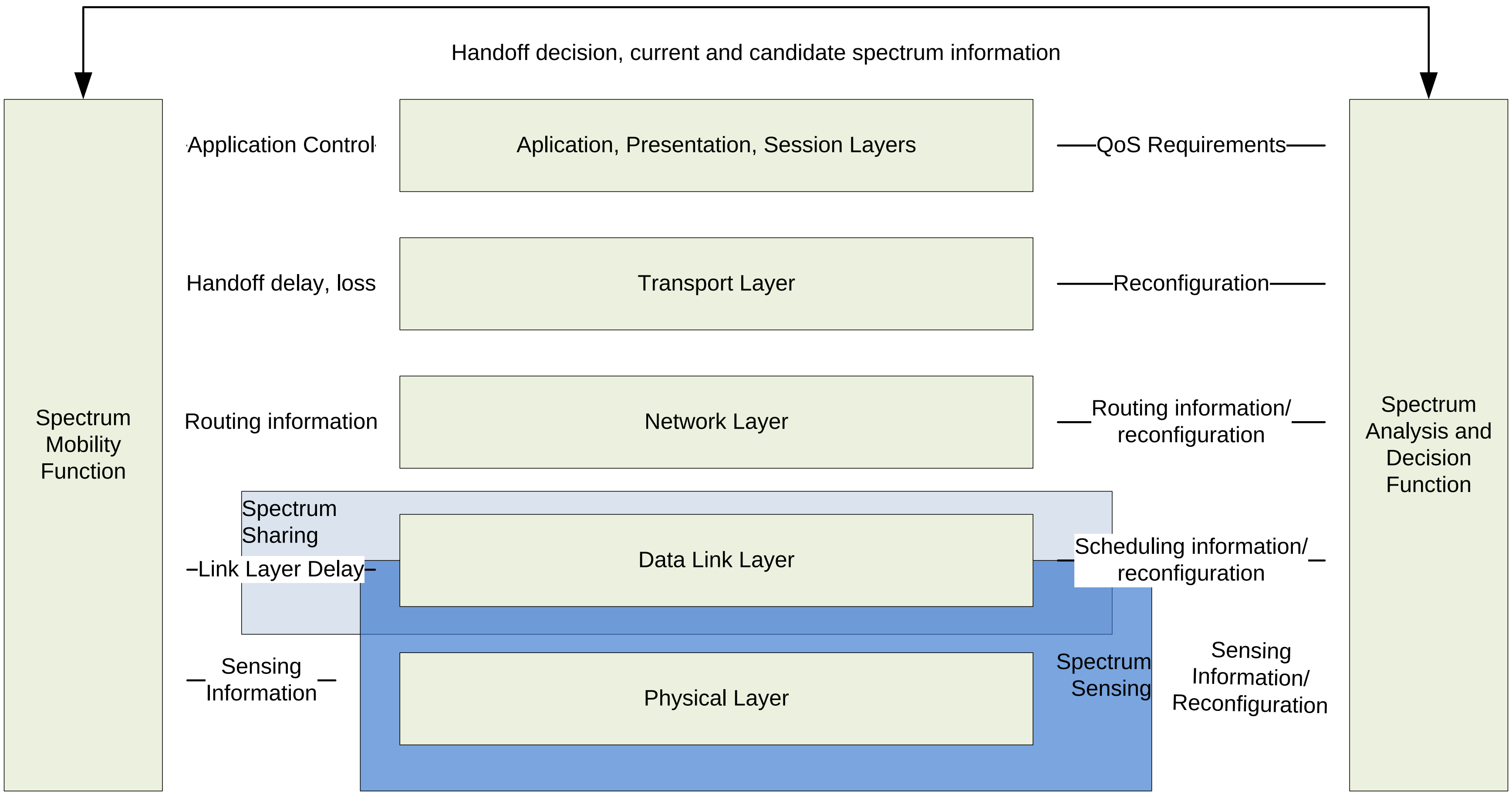
Cognitive cycle in**:**
J. Mitola. "Cognitive radio: Making software radios more personal". IEEE Personal Communications, 1999.

An enhancement over the traditional **software radio** concept wherein the radio is **aware of its environment** and its **capabilities**, and is able to **independently alter its physical layer behavior**, and is capable of following **complex adaptation strategies**.

Cognitive Cycle illustration in**:**
S. Haykin,, *"Cognitive radio: brain-empowered wireless communications"*, JSAC, February 2005)

Cognitive Radio

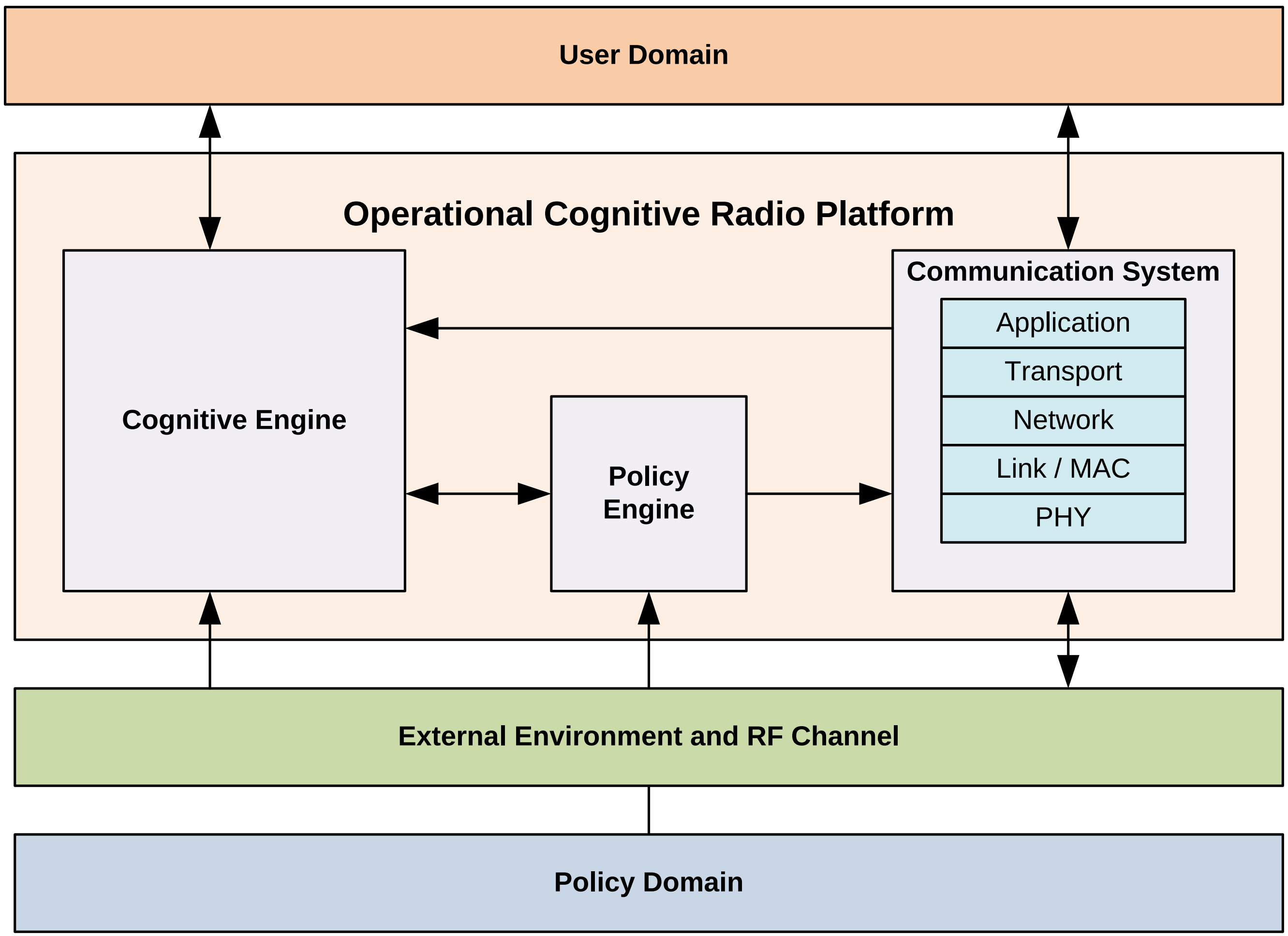
OSI CR Architecture



OSI model updated with the Cognitive Radio functionalities illustration in**:**
Ian F. Akyildiz *et al.*, *"*NeXt generation/dynamic spectrum access/cognitive radio wireless networks: A survey", Computer Networks 2006

Cognitive Radio

General View CR Architecture



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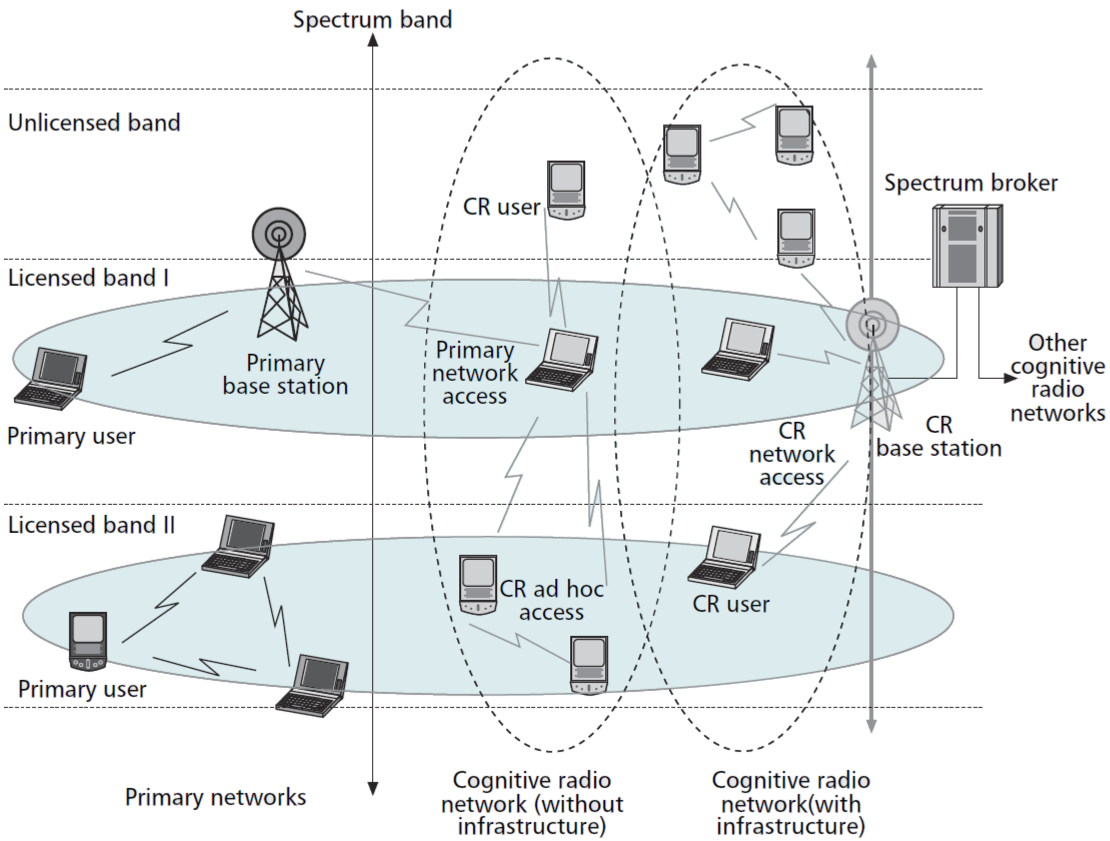
Cognitive Radio

General View CR Architecture



Elements of Cognitive Radio Networks illustration in:
Ian F. Akyildiz *et al.*, "A Survey on Spectrum Management in Cognitive Radio Networks", IEEE Communications Magazine April 2008

Basic Elements of the Network:

- Primary Network
  - Primary user
  - Primary BS
- CR enabled Network
  - CREN user
  - CREN BS
  - Spectrum broker

Cognitive Radio

General View CR Architecture

Primary Network:

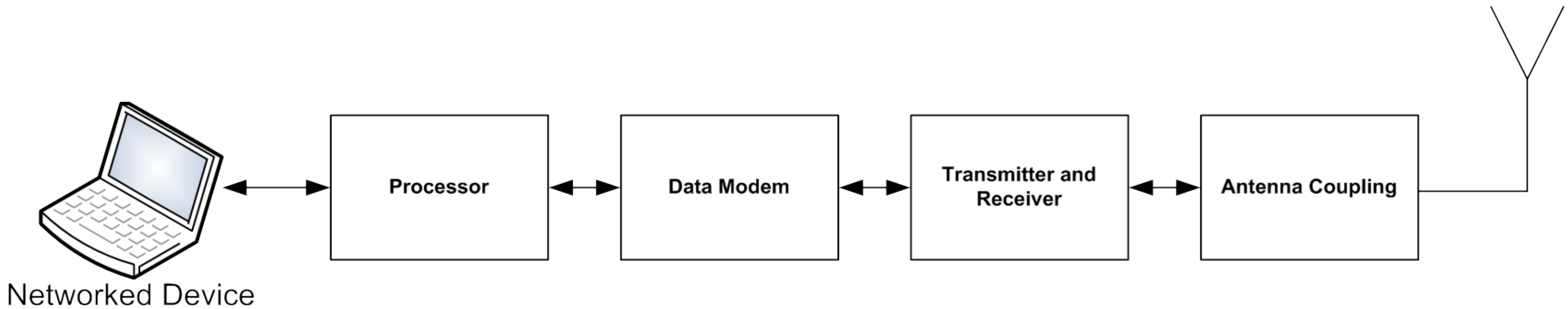
- An existing network infrastructure and has exclusive right to a certain spectrum band
  - Primary User: Has a license to operate in a certain spectrum band.
  - Primary Base Station: Is a infrastructure network component and has a spectrum license.

Cognitive Radio Enabled Network (CREN) :

- Do not have a license to operate in a certain band. The spectrum access is allowed in an opportunistic manner.
  - CREN User: Has no spectrum license .
  - CREN Base Station: Is a infrastructure with CREN capabilities.
  - Spectrum broker: Is a central network entity that plays a role in sharing the spectrum resources among different CREN.

Cognitive Radio

Block Diagram of a Traditional Radio



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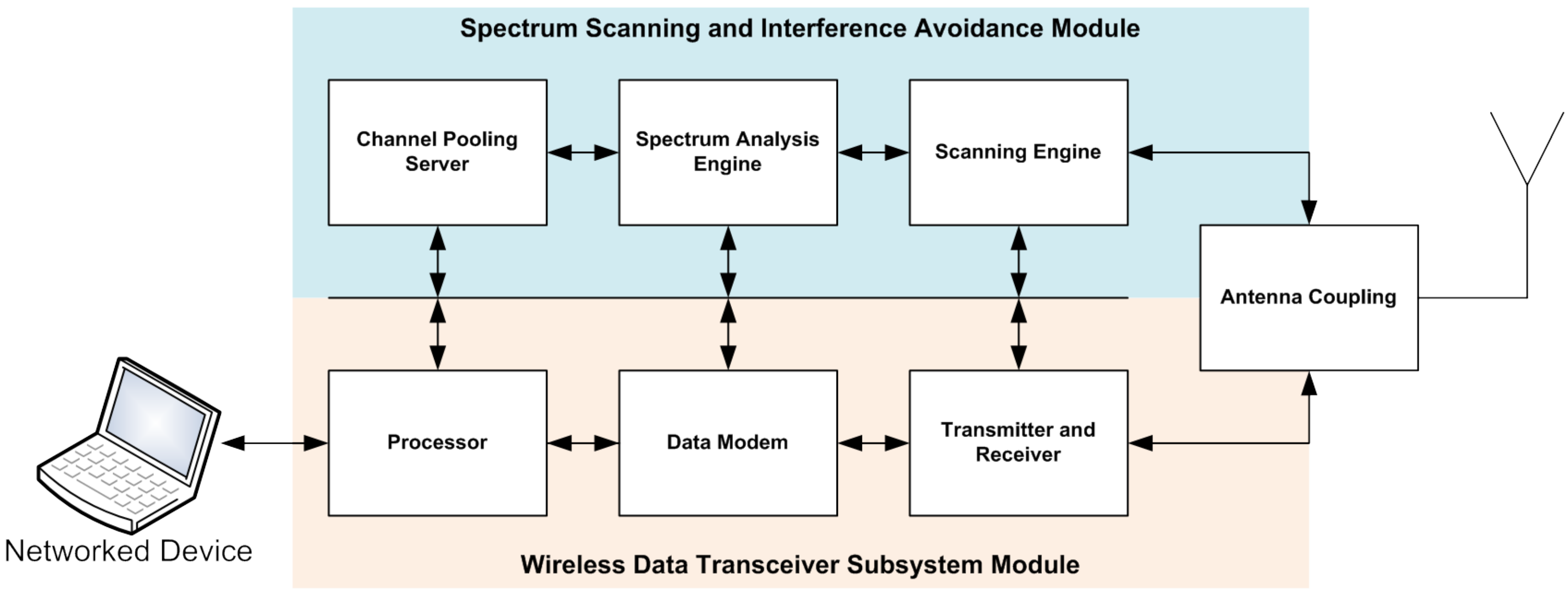
Cognitive Radio

Block Diagram of a Cognitive Radio



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Cognitive Radio

Cognitive Radio Functions

Sensing Radio

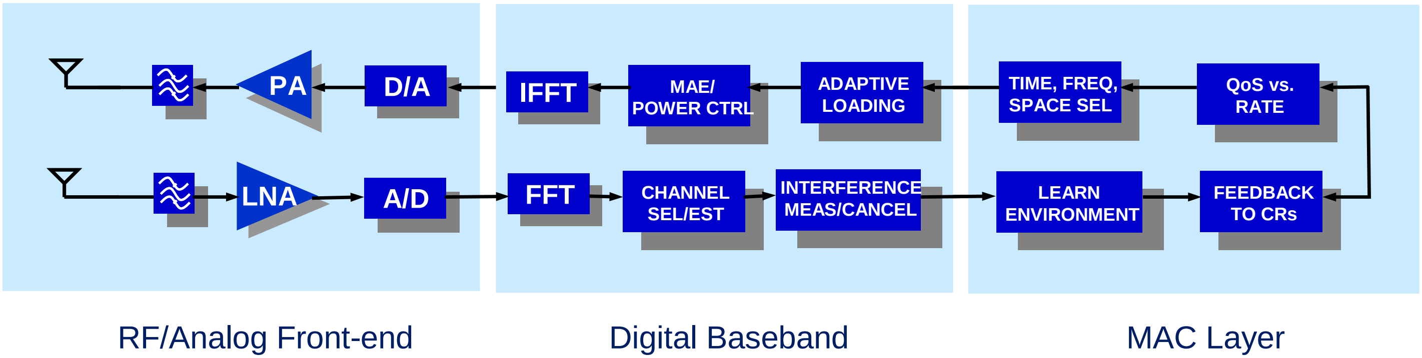
- Wideband Antenna, PA and LNA
- High speed A/D & D/A, moderate resolution
- Simultaneous Tx & Rx
- Scalable for MIMO

Physical Layer

- OFDM transmission
- Spectrum monitoring
- Dynamic frequency selection, modulation, power control
- Analog impairments compensation

MAC Layer

- Optimize transmission parameters
- Adapt rates through feedback
- Negotiate or opportunistically use resources



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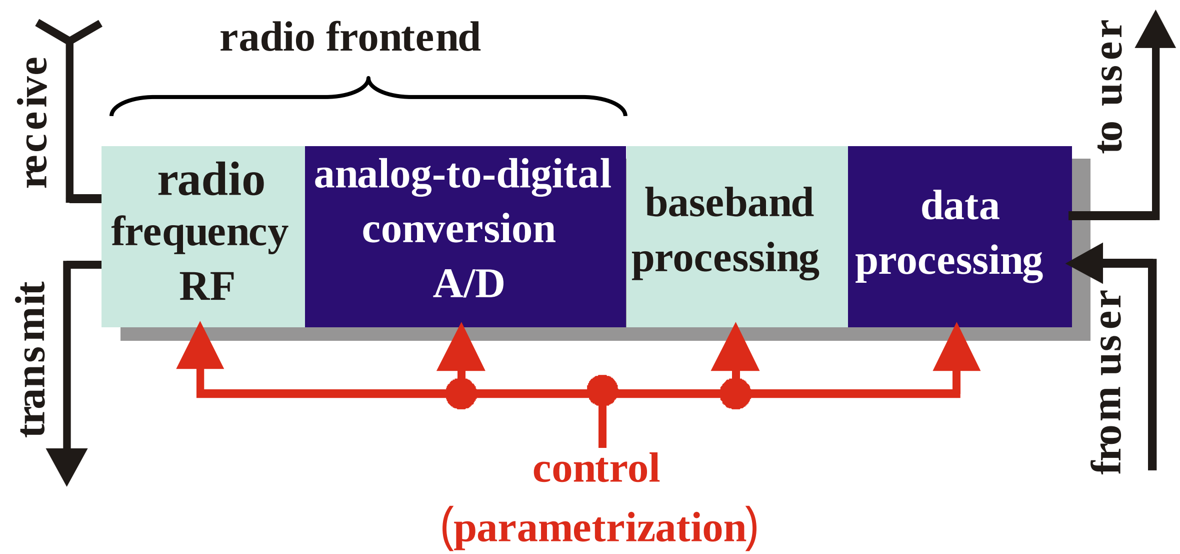
Cognitive Radio

Physical Architecture of the Cognitive Radio



Cognitive radio transceiver

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Cognitive Radio

Application Scenarios

Licensed network

Cellular, PCS band

Improved spectrum efficiency

Improved capacity

3rd access in licensed networks

TV bands (400-800 MHz)

Non-voluntary third party access

Licensee sets a protection threshold

Secondary markets

Public safety band

Voluntary agreements between licensees and third party

Limited QoS

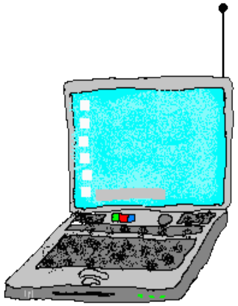
Unlicensed network

ISM, UNII, Ad-hoc

Automatic frequency coordination

Interoperability

Co-existence



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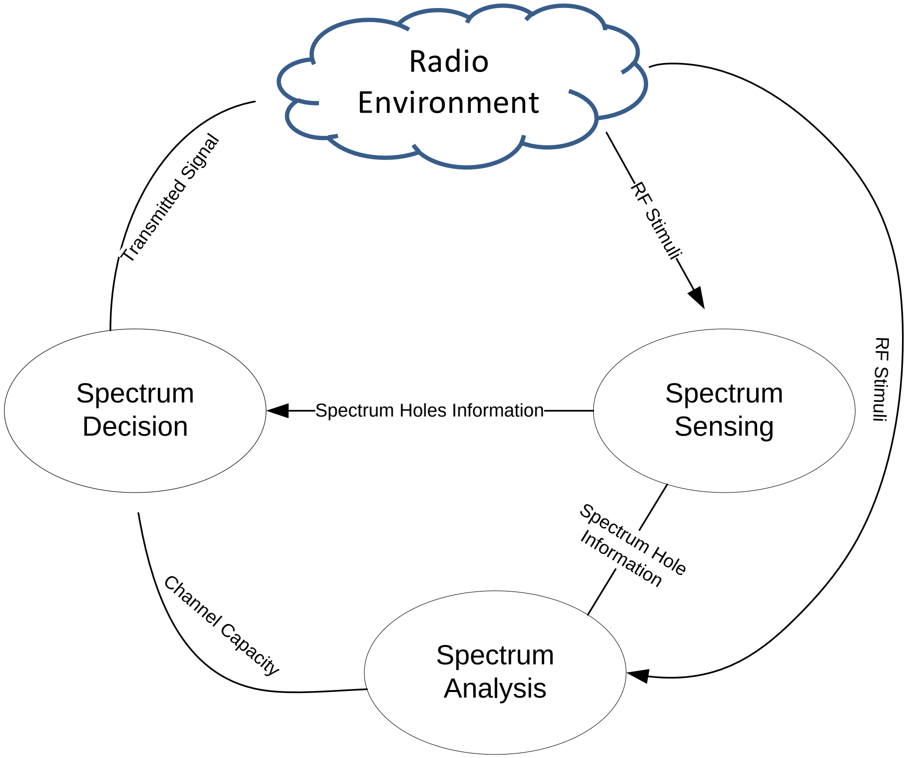
Cognitive Radio

Role in the Spectrum Use



Spectrum Sensing:

Monitoring, Capturing information and detecting free bands

Spectrum Analysis:

Estimate the characteristics of free band and the possible interference

Spectrum Decision:

Choose a band depending on the spectrum characteristics and user requirements

By Ramjee Prasad

Cognitive Radio

Motivation

- A CR is an autonomous unit in a communications environment.
- In order to use the spectral resource most efficiently, it has to:
  - be aware of its location;
  - be interference sensitive;
  - comply with some communications etiquette;
  - be fair against other users;
  - keep its owner informed.
- Cognitive radio provides a framework for a device to evaluate tradeoffs in the creation of dynamically-created links.

Cognitive Radio

Properties & Requirements of Cognitive Radio

- Cognitive radio properties
  - RF technology that "listens" to potentially huge spectrum
  - Knowledge of primary users' spectrum usage as a function of location and time
  - Rules of sharing the available resources (time, frequency, space)
  - Embedded intelligence to determine optimal transmission (bandwidth, latency, QoS) based on primary users' behavior

- Cognitive radio requirements
  - co-exist with legacy wireless systems
  - use their spectrum resources
  - do not interfere with them

Cognitive Radio

Applications of a CR enabled network

Leased network

Cognitive mesh network

Emergency network

Military network

Cognitive Radio

Advantages of Cognitive Radio

- For users
  - Select best wireless access method (i.e. function of location and time)
  - Location awareness will support concierge services
  - Sophisticated services with held of database servers

- For network
  - Enhance the stability and robustness of the network e.g. through traffic control
  - Select the most appropriate network for service requests of the user

- For network operator
  - Benefit from convergence of wireless services through multiple access networks with seamless and economical transition across the various networks

Cognitive Radio

Advantages of Cognitive Radio

- For regulatory organizations
  - Policy engine rule: ability to adapt the design depending on the requirements and restrictions of the geographic region
  - Addition of rules to ensure security for instance during software download

- For spectrum owner and users
  - Measurements help to minimize interference and support more users
  - More information on interference properties, multipath properties, signal strength etc.
  - Dynamic spectrum access

Cognitive Radio

Key Components

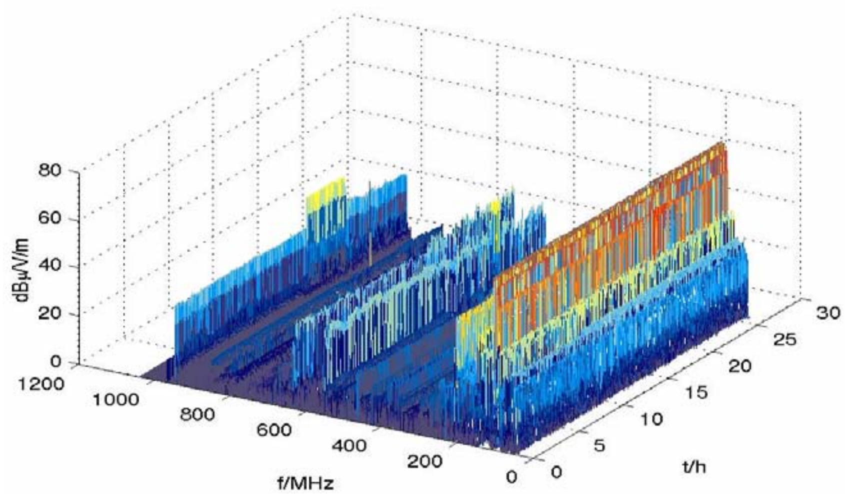
- Many different definitions with common components.

- A Cognitive Radio can autonomously:
  - Observe the radio environment;
  - Observe users’ needs and network policies;
  - Adapt transmission and reception parameters to exploit spectrum opportunities;
  - Learn from experience.

Cognitive Radio

Why the CR Hype?

- Some measurements indicate underused spectrum;
- Increasing number of devices want access to the spectrum;



- Some regulators see the possibility to reduce regulatory complexity and increase spectrum flexibility and utilisation;
- New hot research topic attracting academic interest

Cognitive Radio

So...what are the Challenges?

- Regulations:
  - Actual availability of secondary spectrum;
  - Ensuring compliance with radio regulations;
  - Spectrum utilization efficiency.

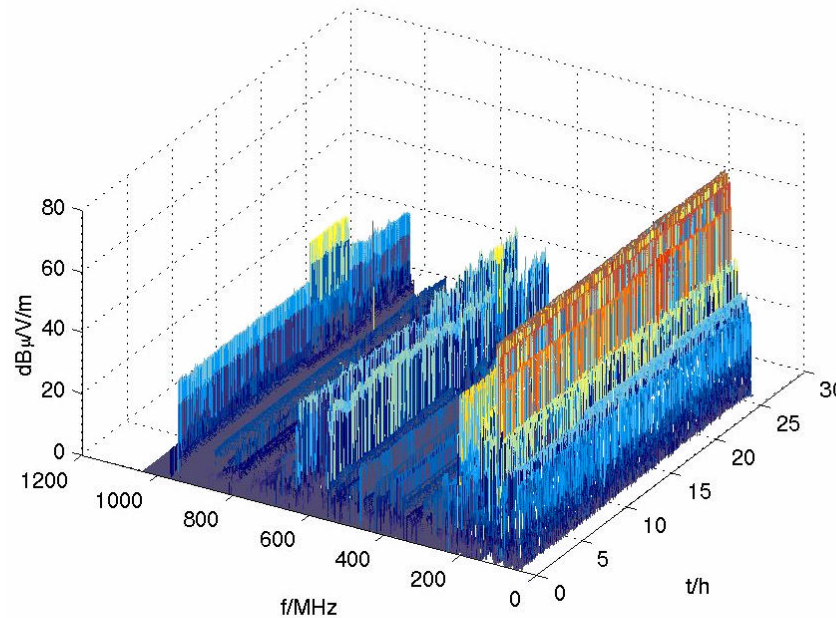
- Devices:
  - Flexibility requires SDR or similar.

- System Aspects:
  - Observation of radio environment;
  - Efficient distribution of radio information (e.g. Cognitve Pilot Channel).

Cognitive Radio

Availability of Secondary Spectrum

- Actual availability of secondary spectrum is unknown
  – Broadcasting bands!
  – Radar and Military bands?
  – ... ?



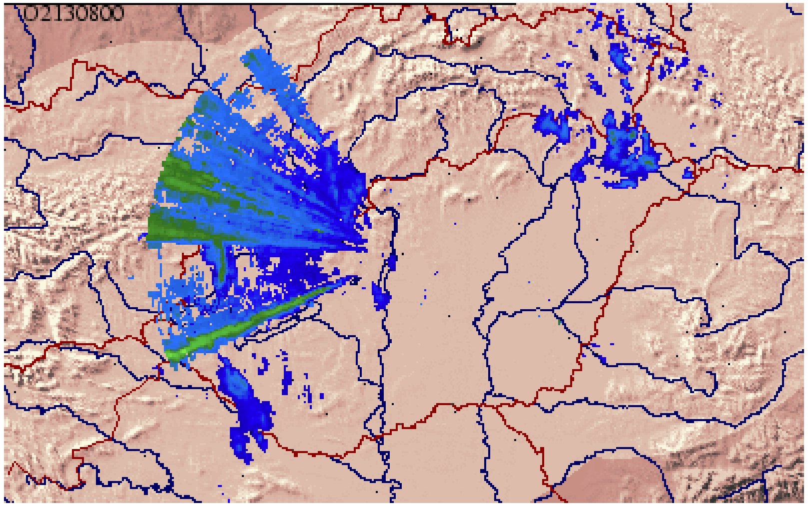
- What combinations of primary and secondary are preferable?

- Capacity AND Coverage needed for secondary systems!

Cognitive Radio

Compliance with regulations

- Guaranteeing primary user protection from secondary users: difficulties observed in 5 GHz and UHF trials.
- Complex testing of radio devices.
- Fair split of resources between secondary users?



RLAN interference to Budapest meteorological radar

Cognitive Radio

Spectrum Utilization Efficiency

- Efficiency:
  - The number of users that can be supported for a given amount of spectrum in a specific geographic area.
- Utilization:
  - How much of the spectrum is used;
  - A lot of used spectrum does not necessarily mean high spectrum efficiency.
- Observations:
  - CR results in lower efficiency;
  - CR may result in higher utilisation.
- The net increase/decrease by using CR is uncertain.

Cognitive Radio

Radio Hardware

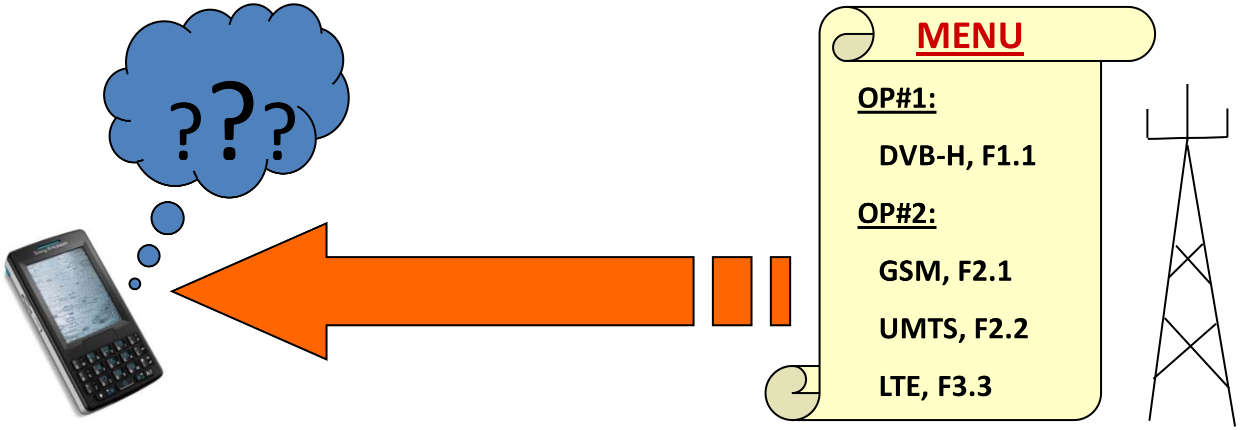
- Flexibility requires SDR or similar;
- Will increase cost for equipment;
- Energy consumption may increase due to generality requirements;
- Some objectives are difficult due to laws of physics, e.g. wide frequency range.

Acknowledgment:
Dr. Muhammad Imadur Rahman,
Ericsson Research

Cognitive Radio

Efficient Distribution of Radio Information

- Dedicated channel (CPC) sometimes claimed to be necessary for initial access discovery; in reality this is a rare event.
- Similar control channel already available in today's systems
- Difficult to implement global/regional control channel in reality. Who will be responsible?



Summary

- CR has become a buzzword, but is not clearly defined.;
- No quantification of available spectrum for CR usage, efficiency of CR or impact on primary systems;
- Practical experience indicates measurement difficulties;
- Research, standardization and spectrum regulation activities far from concluded;
- CR will result in more expensive radio hardware.

Acknowledgment:
Dr. Muhammad Imadur Rahman,
Ericsson Research

Summary

AWC

- Autonomic communications seek to improve the ability of network and services to cope with unpredicted
- change, including changes in topology, load, task, the physical and logical characteristics
- of the networks that can be accessed, and so forth. Broad-ranging autonomic solutions require
- designers to account for a range of end-to-end issues affecting programming models, network and
- contextual modeling and reasoning, decentralised algorithms, trust acquisition and maintenance—
- issues whose solutionsmay drawon approaches and results from a surprisingly broad range of disciplines.

Wireless Technology for Autonomic Networks-Part 2

July 4, 2011

PhD School on Information Engineering

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Outline

Part 2: Specific Technologies and Challenges

- **Spectrum access and sharing**
- Cognitive Radio Networks:
  - Protocol Architectures for Cognitive Networks
  - Routing;
  - Security
  - CRN and the Internet
- Self-organization

SPECTRUM ACCESS AND SHARING

Spectrum Sensing and Medium Access Control

Spectrum Hole

Definition

- What is meant by "Spectrum Hole"?
  - Spectrum that is unused at a certain location and/or at a certain time interval.

- In the context of UHF bands:
  - Unused TV channels;
  - Large re-use distance due to high power high tower concept (traditional broadcasting).

Areas in which one particular TV channel is used (illustrative)

UHF White Spaces are a result of how Broadcasters build their networks!

Spectrum Hole

Regulator Ruling Example

- FCC allows unlicensed radio transmitters (called TV Band Devices, TVBD) to operate in the broadcast TV spectrum at locations where that spectrum is not being used by licensed services
- Many safeguards to prevent harmful interference to licensed services (Broadcasting, Wireless microphones)
- Rules became effective from Feb 18, 2009
- Review of the rules after 2 years

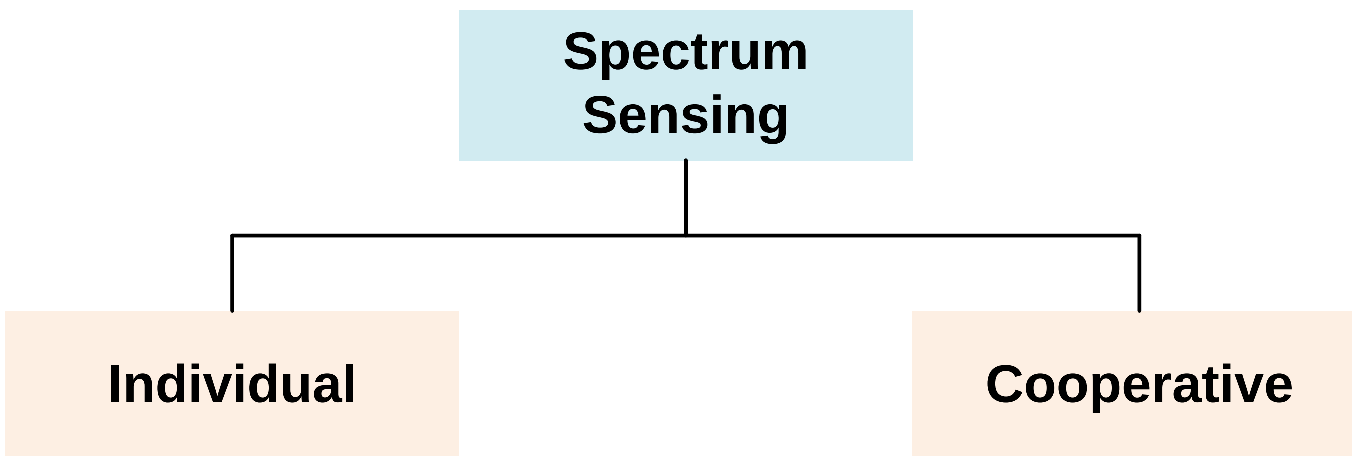
Spectrum Hole

Classification

- Black Spaces
  - Unusable, always occupied
- Grey Spaces
  - High Power RF Interferers, may be usable
- White Spaces
  - Low Power RF Interferers, usable
- “Cave Spaces”
  - Free of RF Interferers, Noise Only (Anechoic Chamber)

Spectrum Sensing

Spectrum Sensing Architecture



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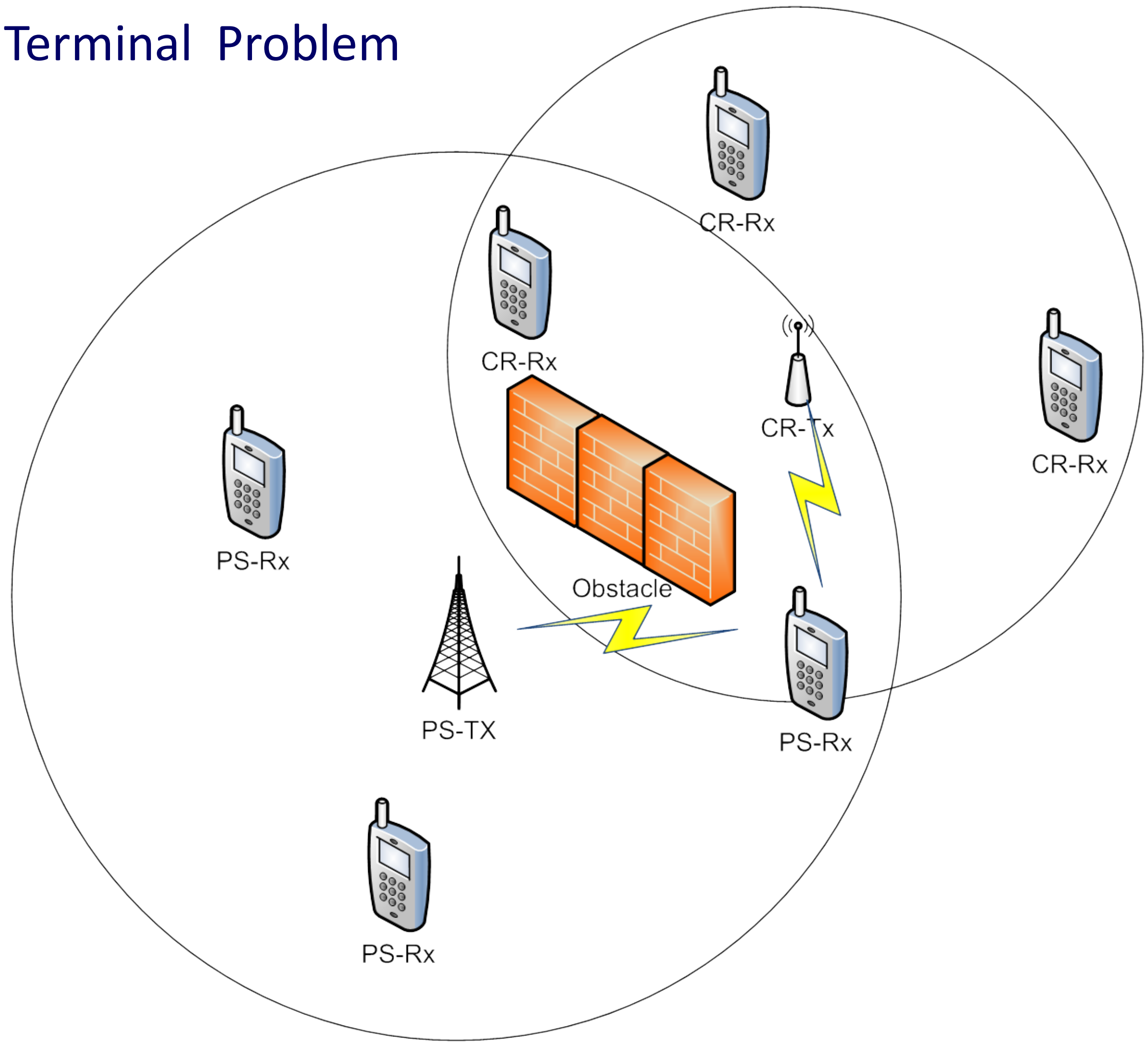
Cooperative Spectrum Sensing

Motivation

Hidden Terminal Problem

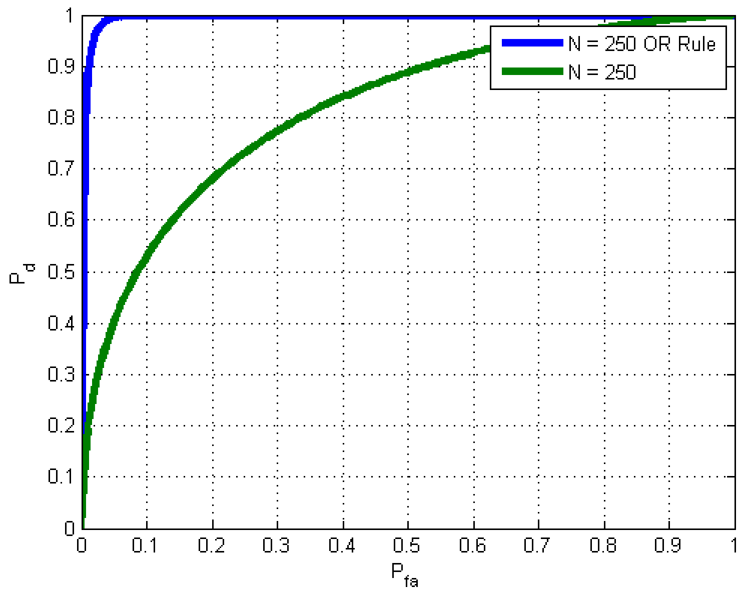


Cooperative Spectrum Sensing

Motivation

- Through cooperative sensing it is possible:
  - Mitigate the hidden node problem;
  - Robustness against Fast Fading when nodes are separated by at least λ/2.

- Cooperation between Energy detectors:
  - N = {250,500}
  - SNR = -21 dB
  - #Cooperating Nodes = 10

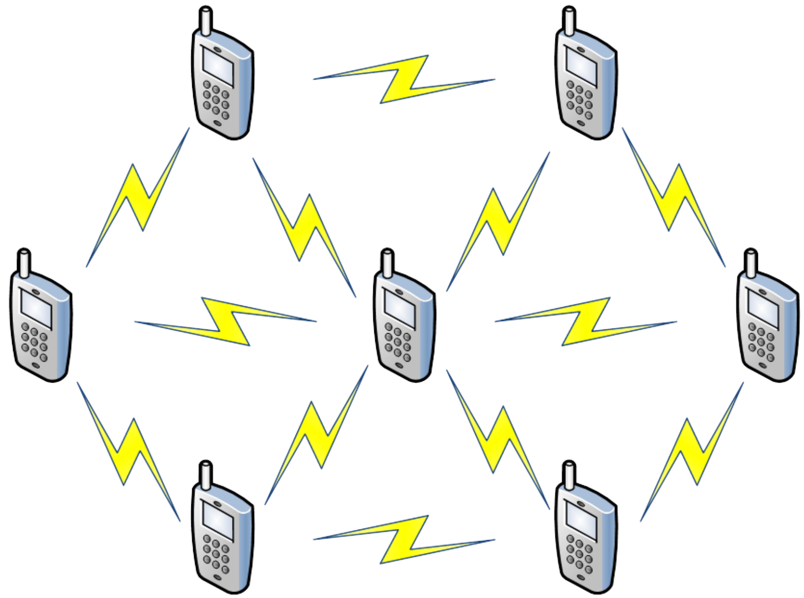


Cooperative Spectrum Sensing

Scenario Description

An Ad-hoc Scenario:

- *A Ad-hoc network, where the nodes are organized in clusters;*
- *Nodes are capable of transmitting and sensing any narrow band channel of a targeted wide range of spectrum.*



Cooperative Spectrum Sensing

Scenario Description

- *The network nodes are already organized in clusters;*
- *Targeted spectrum is divided in channels of equal bandwidth;*
- *Each node can only sense one channel in each sensing session;*
- *Only the inner cluster interactions are considered;*
- *Each cluster as a Common Control Channel always available.*
  - *Common Control Channel*

Control Frame

Control Exchanges	Sensing Exchanges

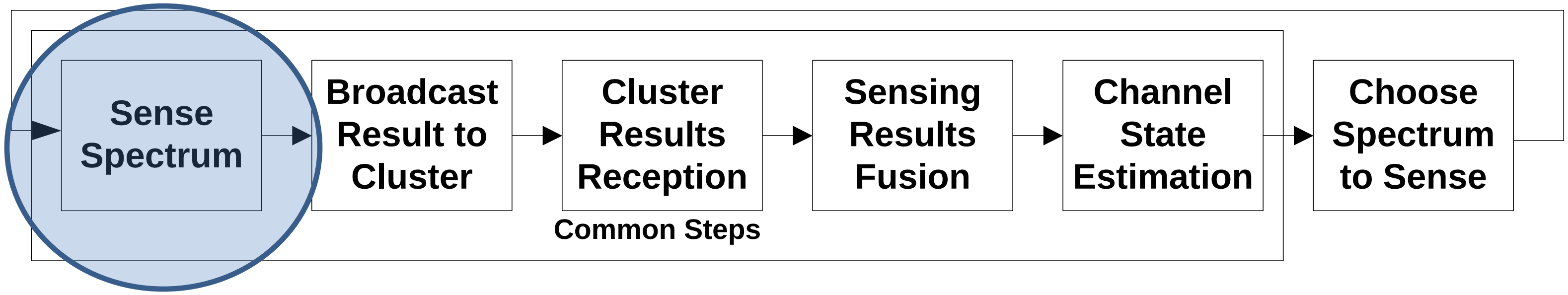
- *The sensing is performed using the Dedicated Data Channel.*
  - *Dedicated Data Channel*

Data Frame

Sensing	Data

Cooperative Spectrum Sensing

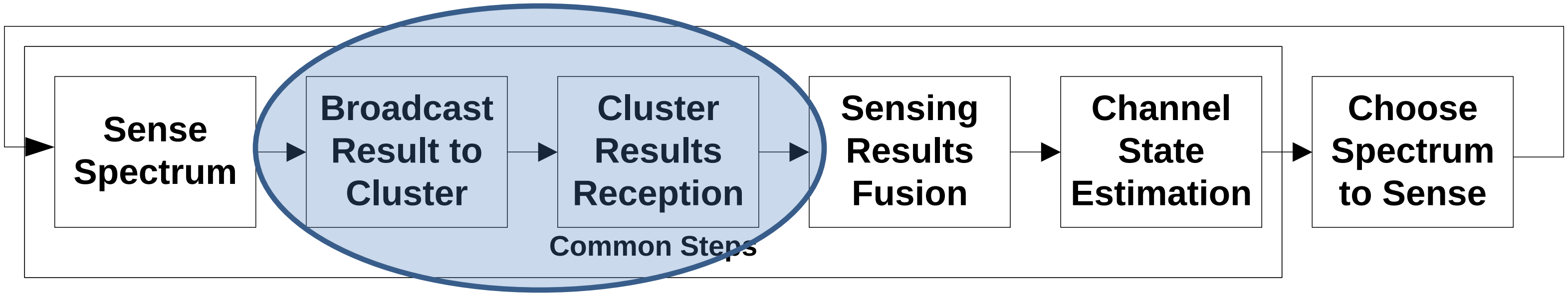
Cooperative Spectrum Sensing Mechanism



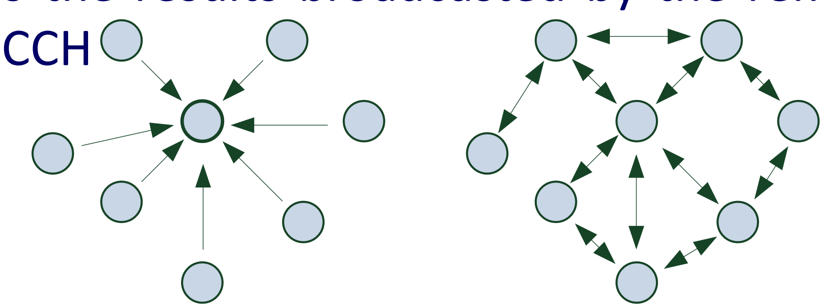
- *Sense Spectrum*
  - *Each cluster node performs the sensing through the use of a Detector (e.g. Energy Detector). Therefore at the end of the spectrum sensing a binary decision regarding the status of the sensed channel is reached in each node.*

Cooperative Spectrum Sensing

Cooperative Spectrum Sensing Mechanism

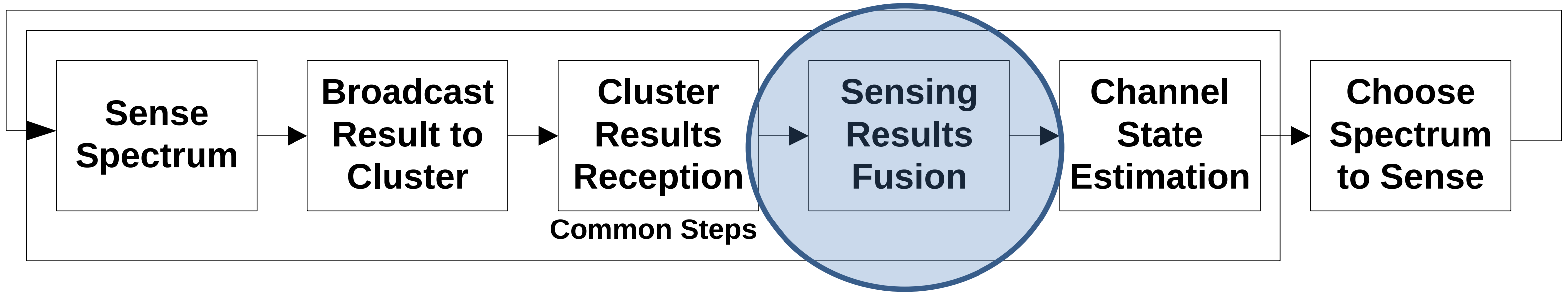


- *Broadcast Result to the Cluster*
  - Each cluster node shares the result of the binary decision reached in the spectrum sensing. The sharing is done through broadcast, which is done through the CCH during the *Sensing Exchanges* period.
- *Cluster Results Reception*
  - Each cluster node receives the results broadcasted by the remaining cluster nodes through the CCH

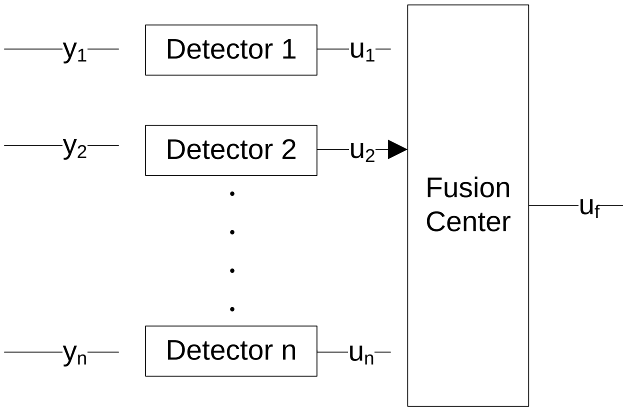


Centralized   Decentralized

Cooperative Spectrum Sensing Mechanism

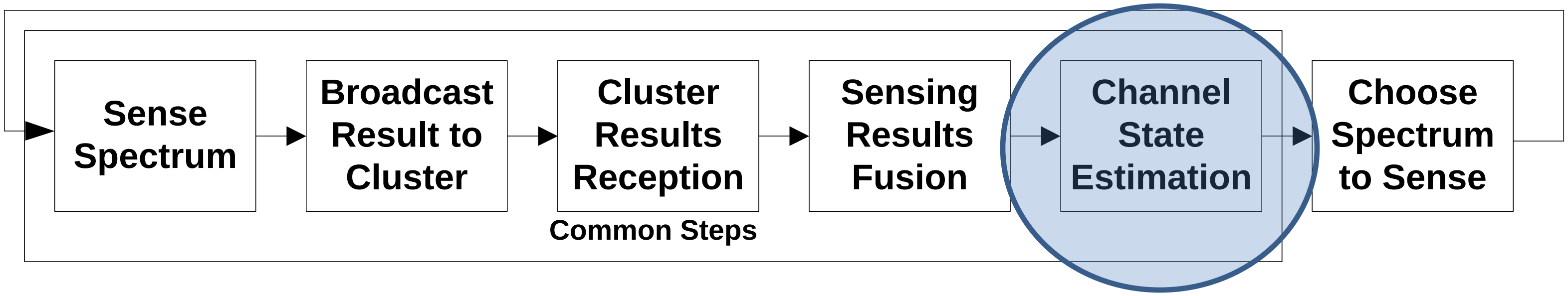


- *Sensing Results Fusion*
  - At this point, the node fuses together the sensing results received from the other cluster nodes. Note that the fusion process is done separately for each sensed channel. The data fusion scheme used is classified as a synchronous hard decision, and therefore the result is a binary decision. *Example: OR (1-of-n), AND (n-of-n),…*



Cooperative Spectrum Sensing

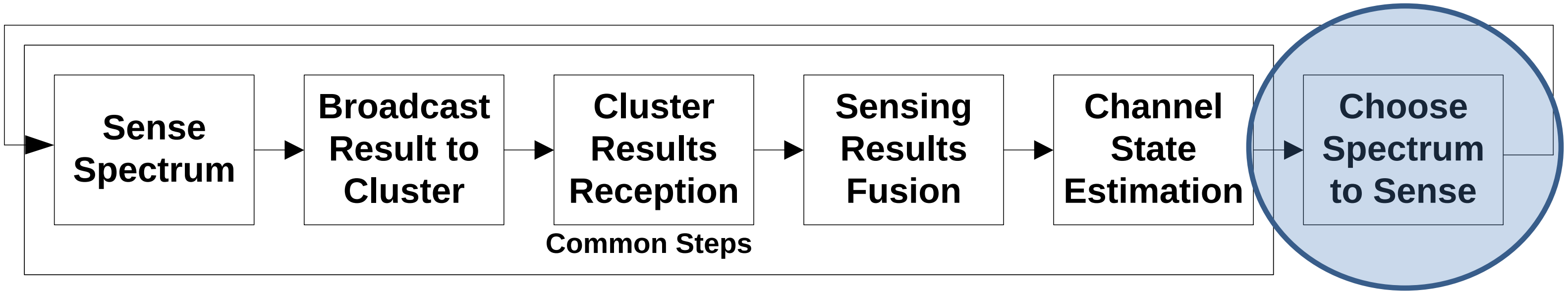
Cooperative Spectrum Sensing Mechanism



- *Channel State Estimation*
  - The estimation of the channels state is done based on past observations and current observations, when available, i.e. if the channel in question was sensed. Through this process it is possible to obtain updated statistics of the network targeted channels.

Cooperative Spectrum Sensing

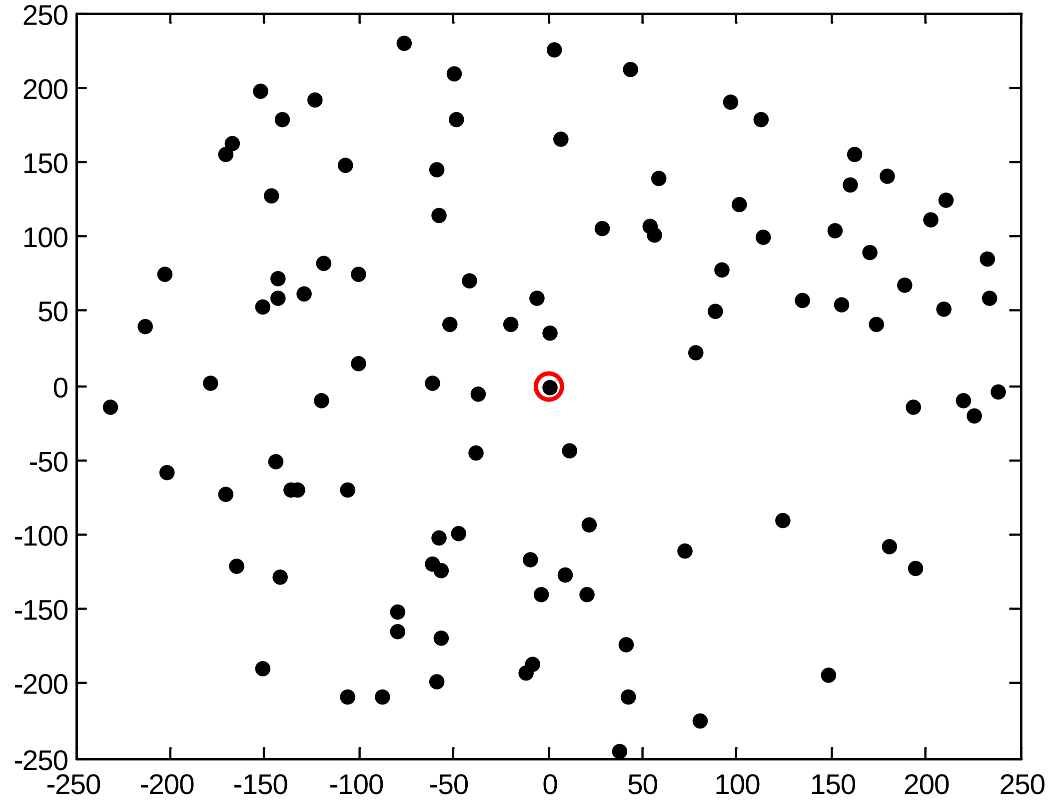
Cooperative Spectrum Sensing Mechanism



- *Choose Spectrum to Sense*
  - This step depends on the approach chosen to implement the mechanism:
    - **Centralized** - One of the cluster nodes decides which channel should be sensed by each of the cluster nodes;
    - **Decentralized** - The decision on which channel to sense is done independently by each of the cluster nodes.
  - Both approaches perform this choice according to the channels occupation statistics.

Managing cooperative sensing

- For spectrum-on-demand in cellular systems (or other coordinated systems)
- Sensing to identify spectrum opportunities and avoid unacceptable interference
- Requires multiple sensors for reliable sensing
- Problem of selection appropriate sensors for cooperative sensing



Mobile terminals in the cell, which should participate in cooperative sensing?

Optimization problem

- Formulate a quadratic integer program

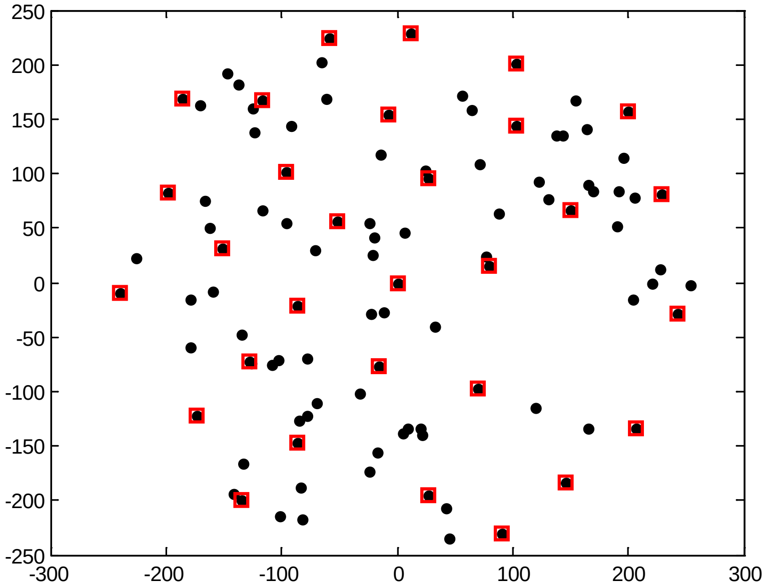
$$\begin{array}{rl} \min & \sum_{i=1}^{M} \sum_{j=1}^{M} a_i a_j c_{ij} \\ \text{subject to} & \sum_{i=1}^{M} a_i = N \\ & a_i \in \{0, 1\},\ i = 1, \ldots, M \end{array}$$

  - c_{ij}: correlation measure between sensors *i* and *j*
  - *M*: Number of sensors in candidate set
  - *N*: desired number of active sensors

Greedy optimization approach

Reduction algorithm:

1. Start with all candidate sensors active
2. Remove from the active set the sensor with the largest summed correlation measure to all active sensors
3. If size(active_set) == N, terminate, otherwise go to 2



Mobile terminals selected for participation in cooperative sensing

Joint power, rate, and channel allocation for opportunistic spectrum access

Objectives:

- TX-RX pair assumed given
- Shall allocate power, rate and channels in a CR system
- Shall consider multiple bands/channels/subcarriers
- Shall have an integrated design for the carrier allocation with power (and rate) allocation
- Basic optimization objective
  - Maximize sum rate capacity under a sum power constraint and additional constraints
- Additional Constraints
  - A maximum power allowed on each band (given by CR mechanisms, e.g. CPC, sensing,…)
  - A maximum rate (spectral efficiency) on each band (given by practical modulation and coding schemes)
- Iterative distributed algorithm desired

Spectrum Sensing

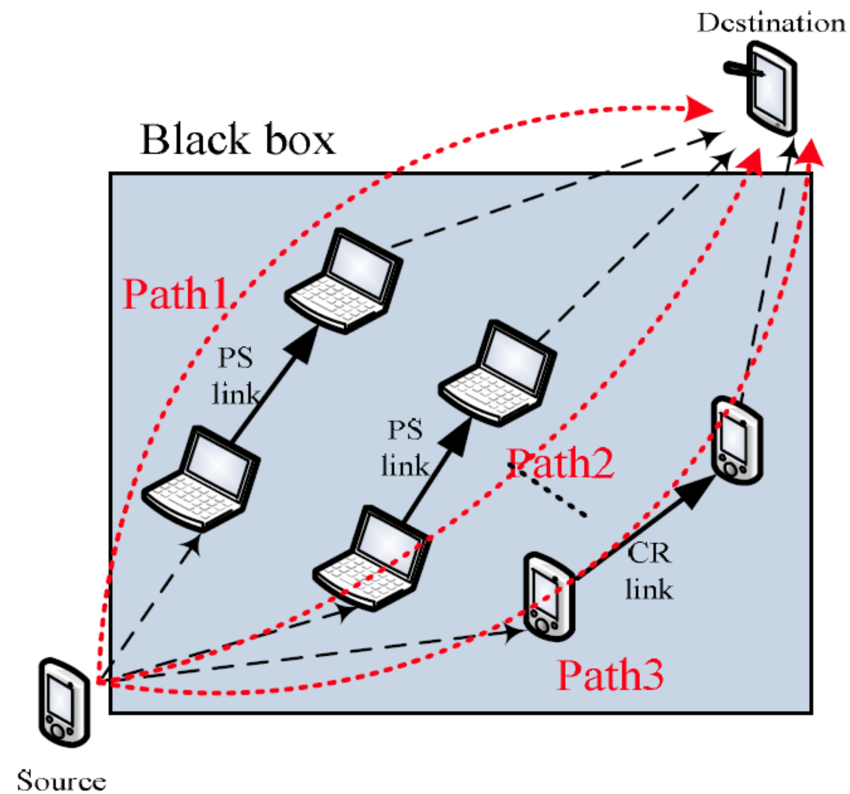
Assignment

- Choose a scenario of primary system (TV bands, Cellular, WiFi, etc…)
- Choose an architecture to your CR network (Cellular, Ad-hoc, Mesh, etc…)
- Choose which kind of individual detector you would use. Explain why.
- Would you use cooperative sensing? Why?

Network Tomography

Motivation for Network Tomography

- For routing and related network layer functions to work properly in a CRN scenario, they need information about potentially available neighboring links (potentially up to several links in depth).

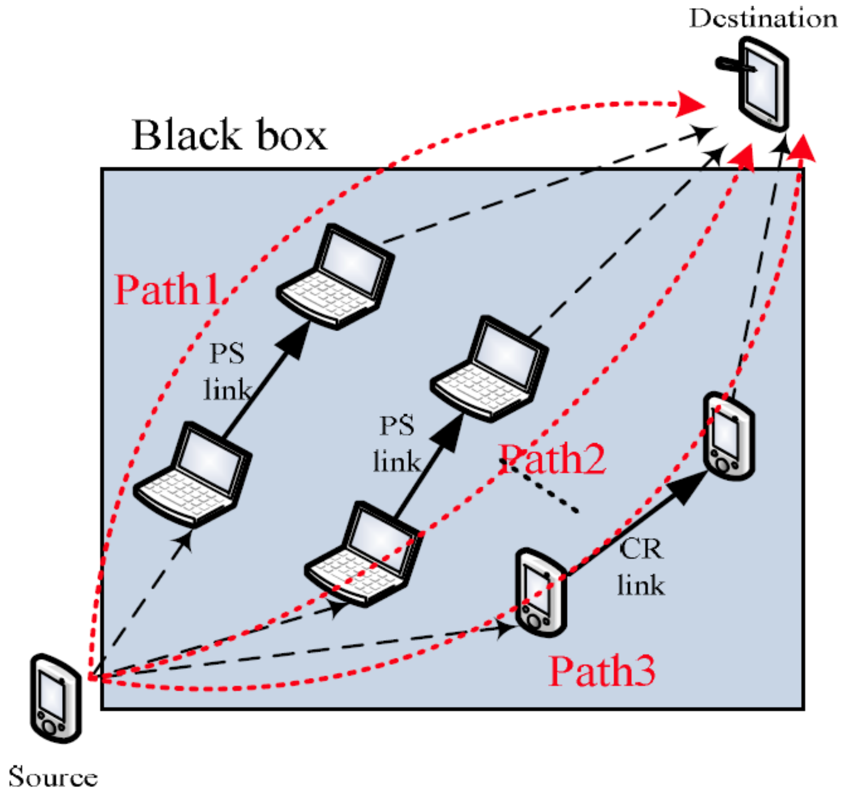


In: Chung-Kai Yu, KC Chen, Radio Resource Tomography of Cognitive Radio Networks

Network Tomography

Motivation for Network Tomography

- But, since the CRN is highly dynamic and can be inter-connected with heterogeneous networks among co-existing multi-radio networks, then end-to-end routing is unlikely and thus network-level information about localized, potentially-available links is essential.

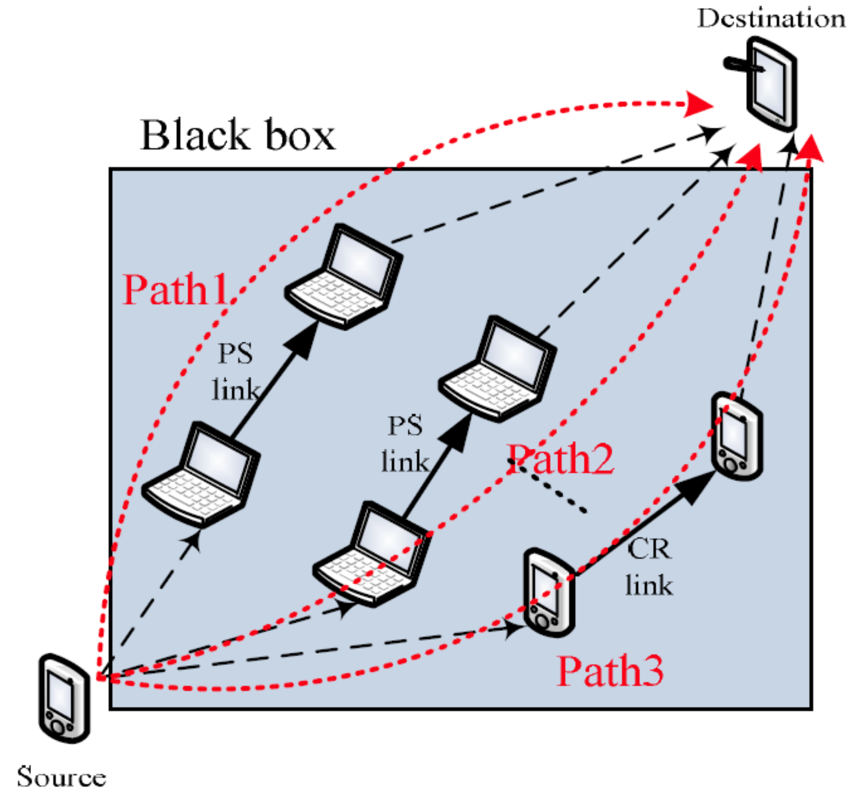


In: Chung-Kai Yu, KC Chen, Radio Resource Tomography of Cognitive Radio Networks

Network Tomography

Motivation for Network Tomography

- Information such as traffic activity to suggest link availability for the CR can be very useful in routing and other network-layer functions.

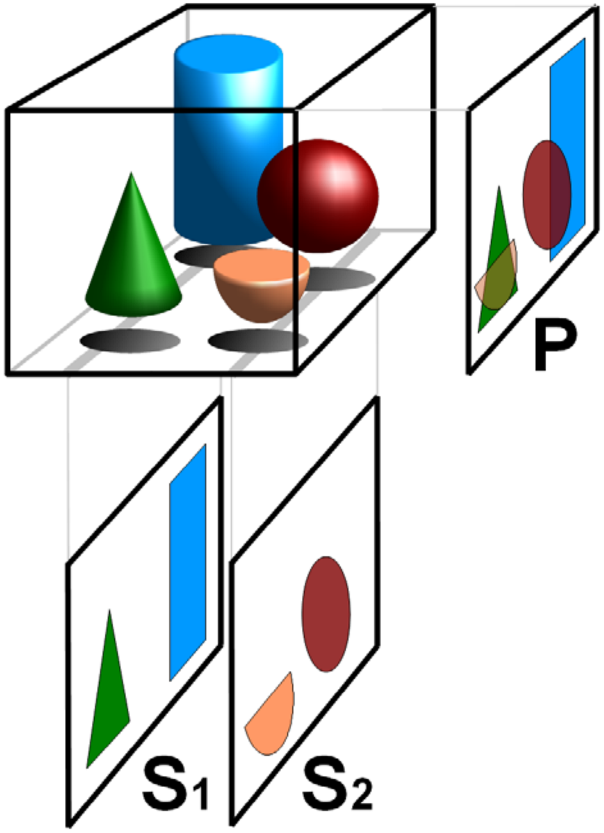


In: Chung-Kai Yu, KC Chen, Radio Resource Tomography of Cognitive Radio Networks

Network Tomography

What is Tomography?

- Tomography is imaging by sections or sectioning, through the use of any kind of penetrating wave.
- The word was derived from the Greek word *tomos* which means "part" or "section", representing the idea of "a section", "a slice" or "a cutting“.



In: Wikipedia, http://en.wikipedia.org/wiki/Tomography

Network Tomography

What is Network Tomography?

- Network monitoring and management need
  - Link packet loss probability
  - Link delay
  - Origin-Destination (OD) traffic matrix
  - Topology/connectivity discovery
  - Intrusion detection and prevention

They are not easily measured directly, but easily measurable indirectly.

- Network engineering and resource allocation include
  - Routing optimization (OD information needed)
  - Quality of service guarantee

In: Bin Yu, Internet Tomography

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Network Tomography

What is CR Network Tomography?

- Although we can use advanced spectrum sensing techniques to detect co-existing multi-radio systems together with some network information, the acquisition of such network-level information from potential links in the CRN requires different methods.
- Network tomography originally intends the acquisition of information for network monitoring and inference in large scale networks such as the Internet, without extra cooperation among nodes.
- The terminology, network tomography, is a mixture of ideas behind network inference and medical tomography, where two types of network tomography are usually considered.

Network Tomography

What is CR Network Tomography?

- Link-level parameter estimation based on end-to-end and path-level traffic measurement.
- The traffic measurements typically consist of counts of packets transmitted and/or received between two nodes, or delays between packet transmission and reception.
- The delay results from propagation, queuing and routing. The measured path delay is the sum of delays in all links.
- A packet may be dropped and the delay is generally random.

In: Chung-Kai Yu, KC Chen, Radio Resource Tomography of Cognitive Radio Networks

Network Tomography

What is CR Network Tomography?

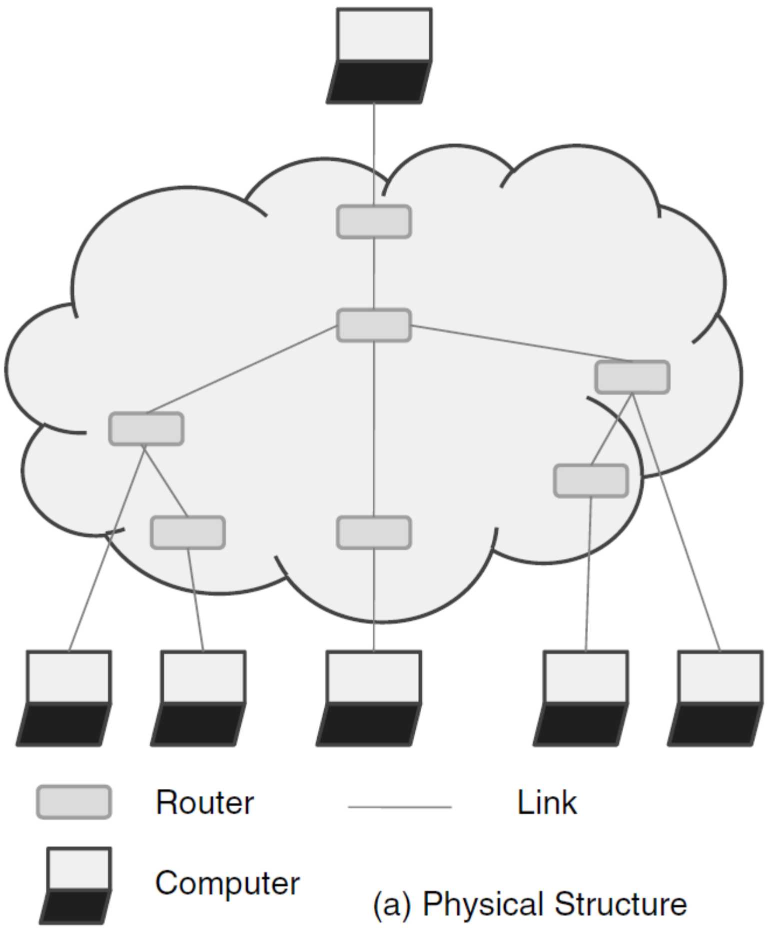
- Sender-receiver (i.e., CR course node and CR destination node in our current case of concern) path level traffic estimation based on link-level traffic measurement.
- Based on packet counts, the goal is to estimate the amount of traffic originated from a specific node and destined to a specific node.
- The combination of the traffic of all origination-destination pairs for a traffic matrix is random in nature (for both link level and path level).

In: Chung-Kai Yu, KC Chen, Radio Resource Tomography of Cognitive Radio Networks

Network Tomography

What is CR Network Tomography?

- A network tomography works as following.
- Packets from a source are sent to a number of destination nodes, as shown in the figure.
- The paths from the source to destinations may go through some regions of which we have no or limited information, the cloud region in the figure where direct probing does not work.



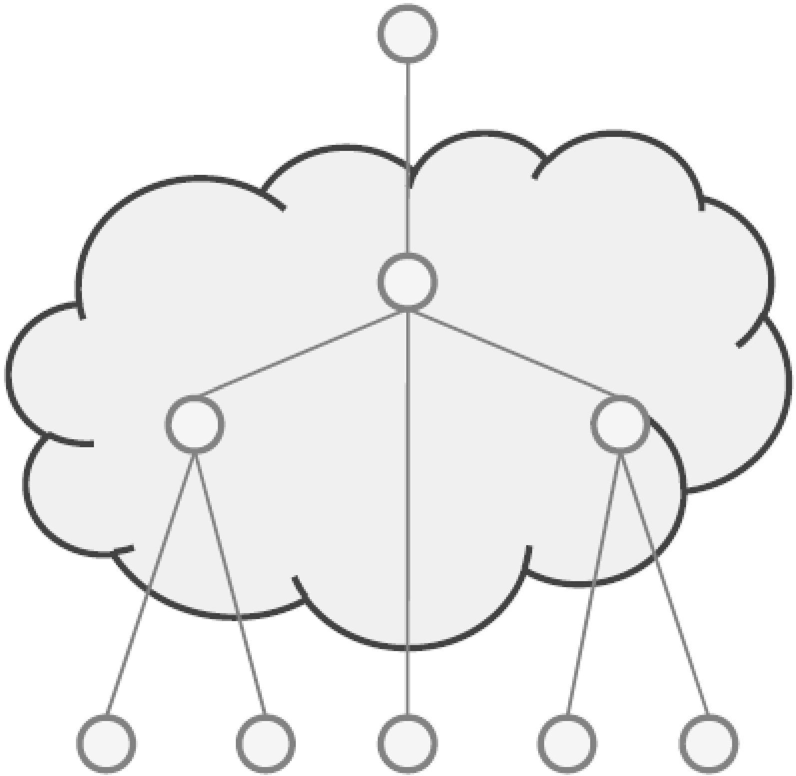
(a) Physical Structure

In: Chung-Kai Yu, KC Chen, Radio Resource Tomography of Cognitive Radio Networks

Network Tomography

What is CR Network Tomography?

- The logical link topology of that network can be represented as in the figure.



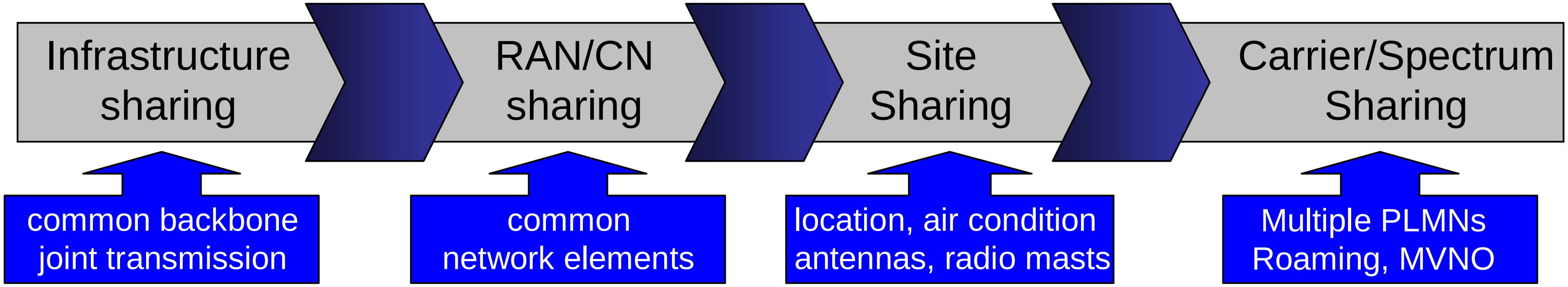
In: Chung-Kai Yu, KC Chen, Radio Resource Tomography of Cognitive Radio Networks

Spectrum Access and Sharing

SPECTRUM SHARING

Sharing Aspects in Mobile Radio Networks

Elements of the networks are realised as shared resources



Technologies for Network Planning and Optimisation

- Spectrum use and sharing:
  - cost-efficient deployment-network sharing is “a way for operators to share the heavy deployment costs for mobile networks, especially in the roll-out phase
  - Carrier and Spectrum sharing (among one or multiple operators):
    - affects directly the interface to the customer.
    - The ability for a user to function in a serving network different from the home network – (i.e.roaming [TR 21.905]) – can be seen as shared access to a foreign spectrum.
    - From an operator’s perspective, **carrier** and **spectrum** sharing is particularly interesting in low load scenarios where one operator has a running infrastructure in place but does not fully use its capacity.

Spectrum Sharing

Flexible Spectrum Use (FSU)

Goal: Handle **un-coordinated deployments:**

- No need for a complete frequency pre-planning of the whole network.
- Frequency planning of a high-density pico-cells network is not trivial.
- Possibility of adapting the spectrum resources based on the network conditions (e.g cell load):
- Aim of the FSU algorithm would be to adapt to the network conditions changes.
- Interference Coordination: The FSU algorithm can be used to increase the performance of cell-edge UEs.

FSU

Research at CTIF

- FSU feasibility study in HetNet[1]:
  - Interference detection investigation.
  - Performance trade-off (cell TH Vs cell-edge TH) investigation.
  - FSU only for pico-cells, deployed over planned macro-cells network (reuse 1/3 or ICIC with soft-reuse).

[1] C. Galiotto, A.Mihovska, N.R. Prasad: 2009-2011

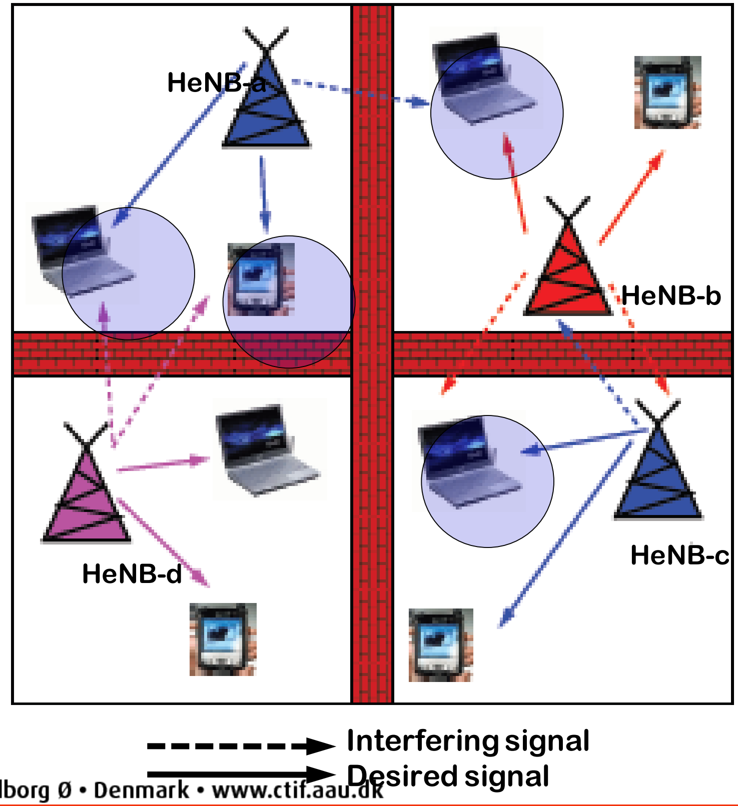
FSU

Some Research Results at CTIF

OBJECTIVES:

- Downlink Inter-Cell Interference (ICI) management by means of a Flexible Spectrum Usage (FSU) mechanism [2].
- High cell throughput.
- Fairness between users.

Good performance also for users in bad conditions

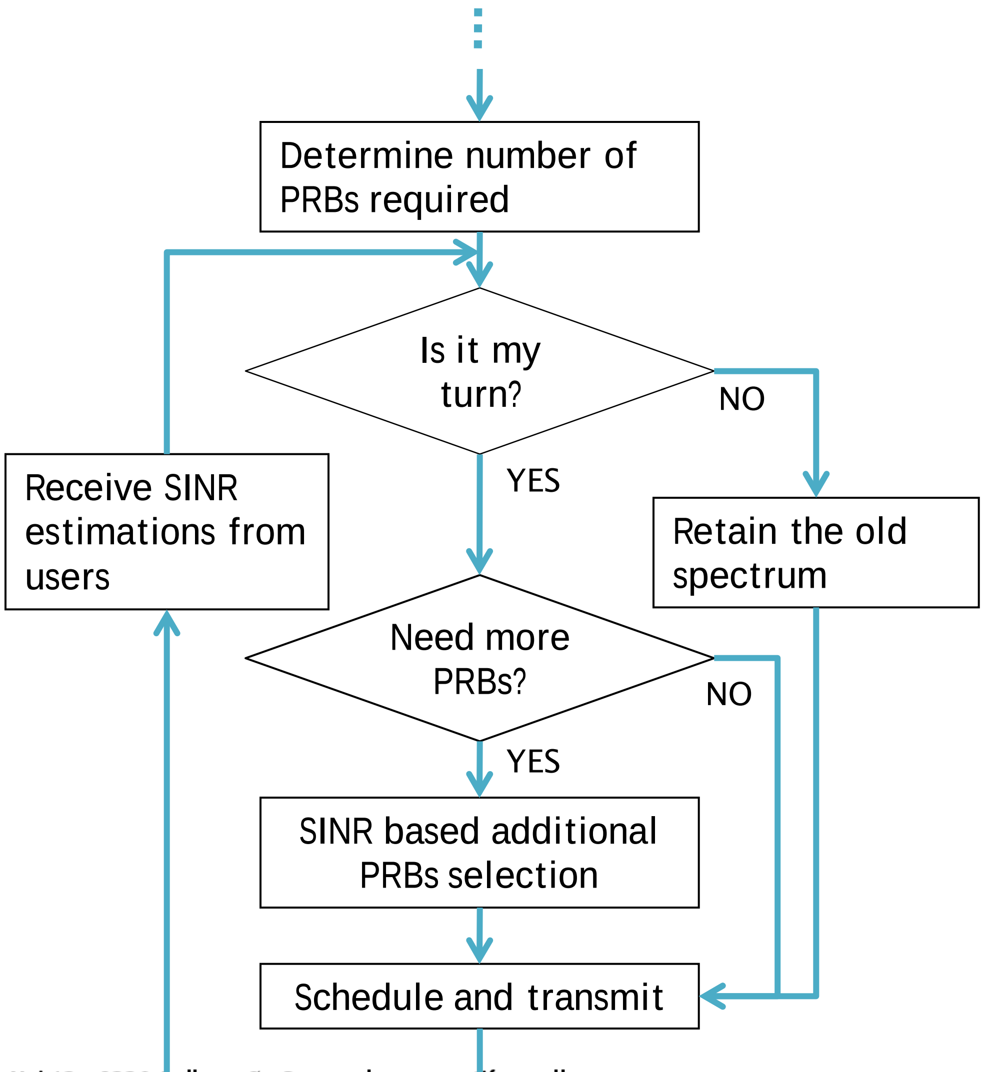


[2] C. Stocchi, N.R Prasad, 2010

FSU: Some Research at CTIF

Spectrum Selection

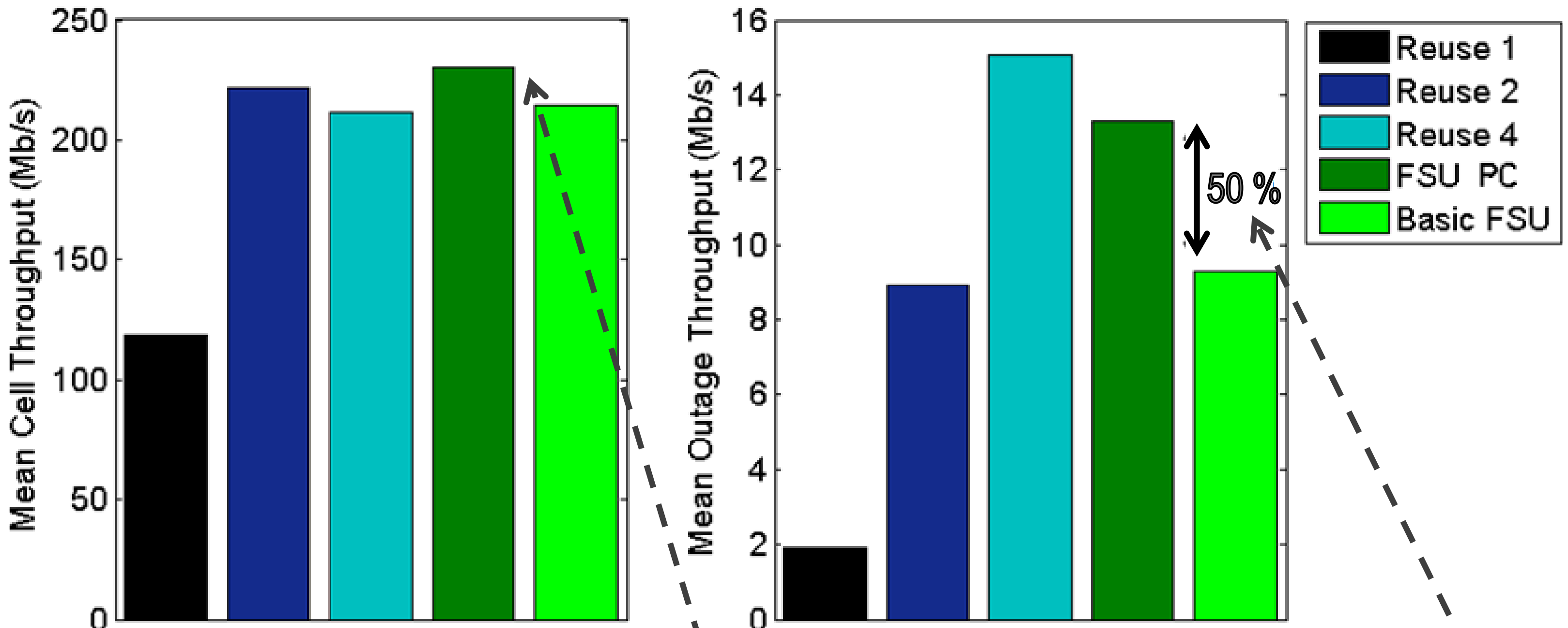
- If the PRBs in the Priority Chunk are not enough the HeNB can select additional PRBs.
- The needed PRBs with highest average SINR level are selected.
- One HeNB at each time interval selects the additional PRBs.
  - The HeNBs coordinate themselves by means of a shared queue.



Spectrum Selection

Static Simulation Results

Proposed algorithm (FSU PC) vs. fixed frequency reuse schemes and FSU without power control (basic FSU)



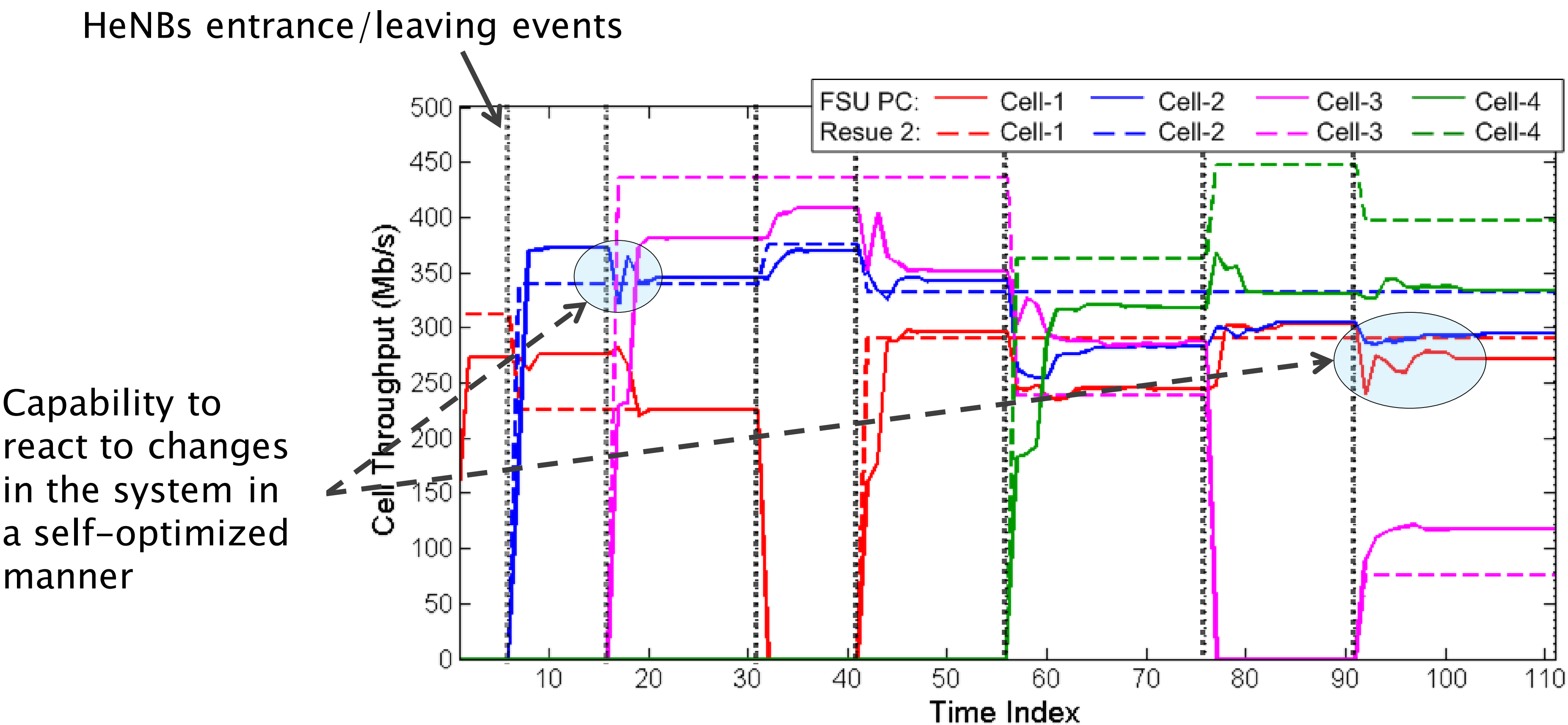
The proposed algorithm achieves the highest cell throughput

Power control use gain

Spectrum Selection

Dynamic Simulation Results

Proposed Algorithm vs. Reuse 2

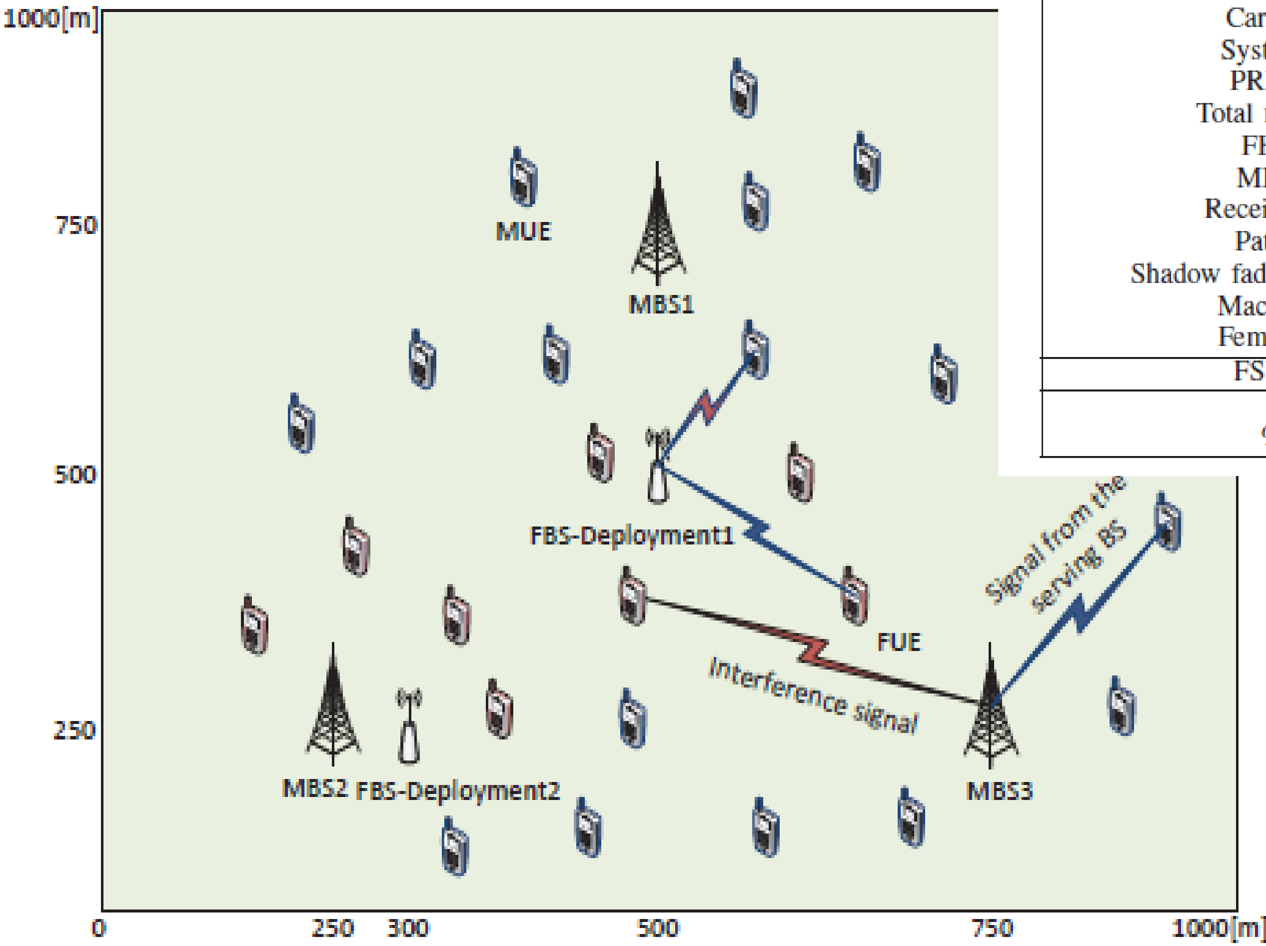


Adaptive Flexible Spectrum Usage Algorithms in Heterogeneous Cell Deployment

- Manage the interference between macro and femtocells by:
  - Use of a fixed reuse scheme in macro cell
  - Execute self-organised spectrum management technique in the femto cells
- Simulation platform S-Cogito Test-bed:
  - distributed simulator a distributed simulator, able to encompass any standardized as well as future wireless system working between 54Mhz and 6Ghz

[3] Joao Mestre∗, Nuno Pratas , Neeli Rashmi Prasad, Ant´onio Rodrigues and Ramjee Prasad, accepted at PIMRC2011, 2011

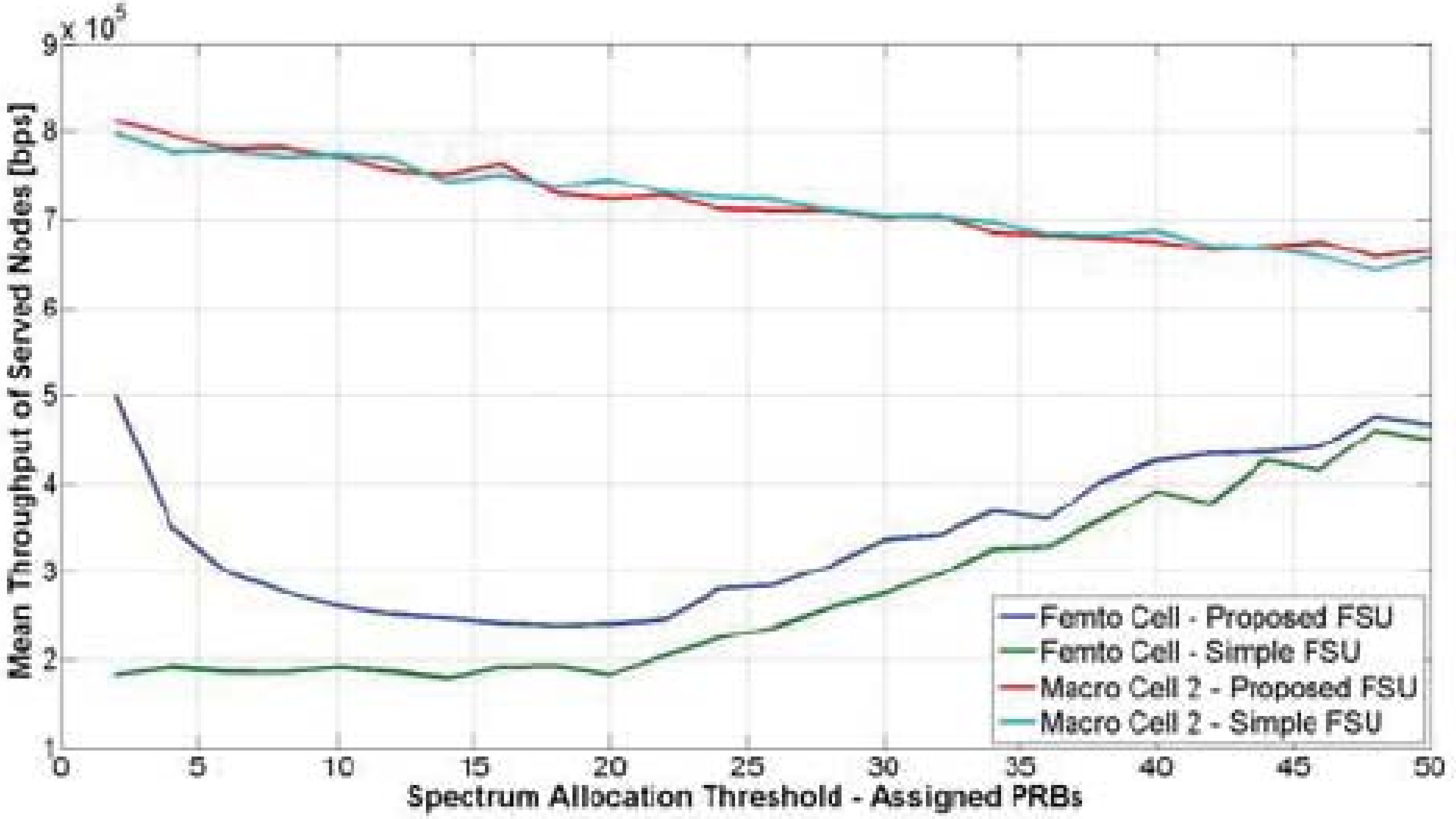
Deployment Scenario



Simulation Parameters	Settings
Number of users per femto cell	20
Number of users per macro cell	50
Minimum Number of PRBs assigned per UE	1
Carrier frequency	3.5 Ghz
System bandwidth	10 Mhz
PRBs bandwidth	200 Khz
Total number of PRBs	50
FBS Tx power	30 dBm
MBS Tx power	43 dBm
Receiver noise figure	10 dB
Path loss model	[9]
Shadow fading standard deviation	[9]
Macro Cell Radius	500m
Femto Cell Radius	200m
FSU Parameters	Settings
SAth	2 to 50
%percentile	50%

Some Results

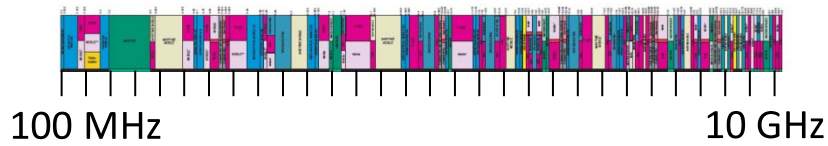
Proposed FSU VS Simple FSU when the Deployment1 is considered

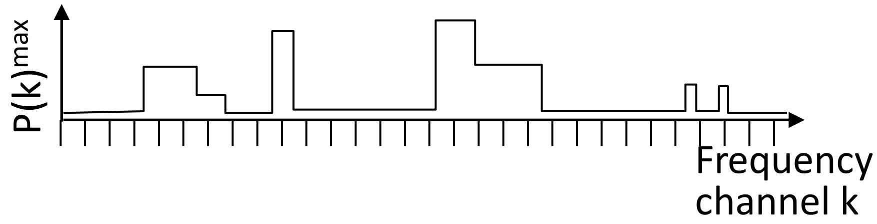


The Cognitive Radio aspect

Power limitation varies over frequency band

- A large portion of the radio spectrum is divided into frequency resources k∈{1,…,K}.
- Determine max permitted TX power $P_u^{\max}(k)$ for user *u* vs. frequency *k* based on restrictions imposed by primary users, obtained via sensing, and possibly other regulatory limit



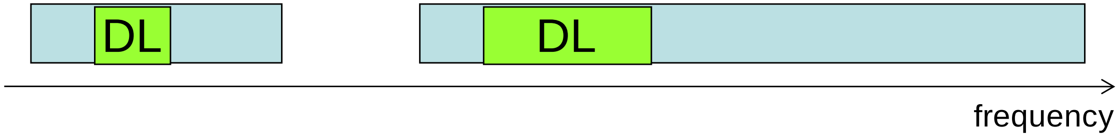


Spectrum/Carrier Aggregation

Optimisation of Spectrum planning

1. Spectrum aggregation of operator's dedicated bands in the same band, e.g. C-Band.

2. Spectrum aggregation of operator's dedicated bands in two bands, e.g. 2 GHz band and C-Band.



2 types of scenarios-contiguous and non-contiguous bands

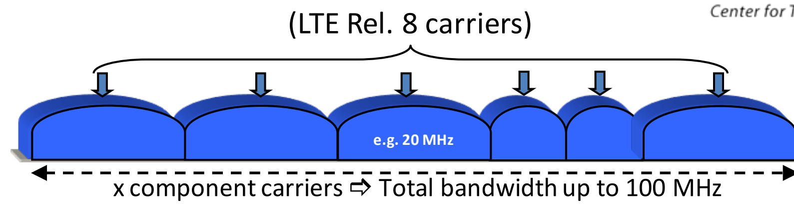
[4] A. Mihovska, F.Meucci, O.Cabral, N.R. Prasad, 2009-2011

Carrier Aggregation

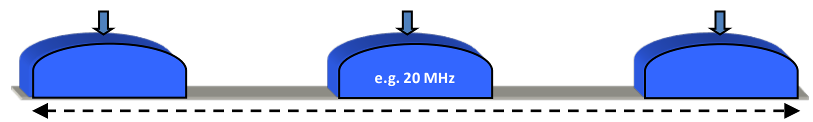
- spectrum needs: cope with fragmented spectrum
- networks deployment & their options: borrow spectrum from neighbour sites
- sharing aspects between networks : temporary spectrum usage from other operators
- preferred carrier bandwidths: support more than 20 MHz
- spectrum arrangements: flexible spectrum use
- deployment options
- etc..

What is Carrier Aggregation?

- Contiguous spectrum aggregation (single band)



- Non-contiguous spectrum aggregation (single band)



- Spectrum aggregation over multiple frequency bands

Properties

- support of larger bandwidths → higher throughput (single user, peak)
- no increase of spectral efficiency → some trunking gain due to improved

signalling/data ratio possible

- aggregated use of fragmented spectrum → more efficient/flexible load of existing spectrum

→ potential enabler for re-farming, sharing or even spectrum trading

Spectrum Aggregation Research

Center for TeleInFrastruktur

General Multiband Scheduling

- Integer Programming (IP) problem with different constraints formulation and a Profit Function giving the total throughput for the operator:

$$(PF) = \max \sum_{b=1}^{m} \sum_{u=1}^{n} W_{bu} x_{bu}$$

Service rate

Allocation variable

- All constraints defined for a multiband UE, with only one active transceiver and single code allocation

Constraints

$L_b^{\max}$ → Load constraint on each band

1.Each user can be allocated only to a single frequency band with a single allocation channel.

$$(AC) \quad \sum_{b=1}^{m} x_{bu} \leq 1, \quad x_{bu} \in \{0,1\}, \forall u \in \{0,\ldots,n\}$$

2.The total number of users on each band is upper bounded by the maximum load that can be handled in the band

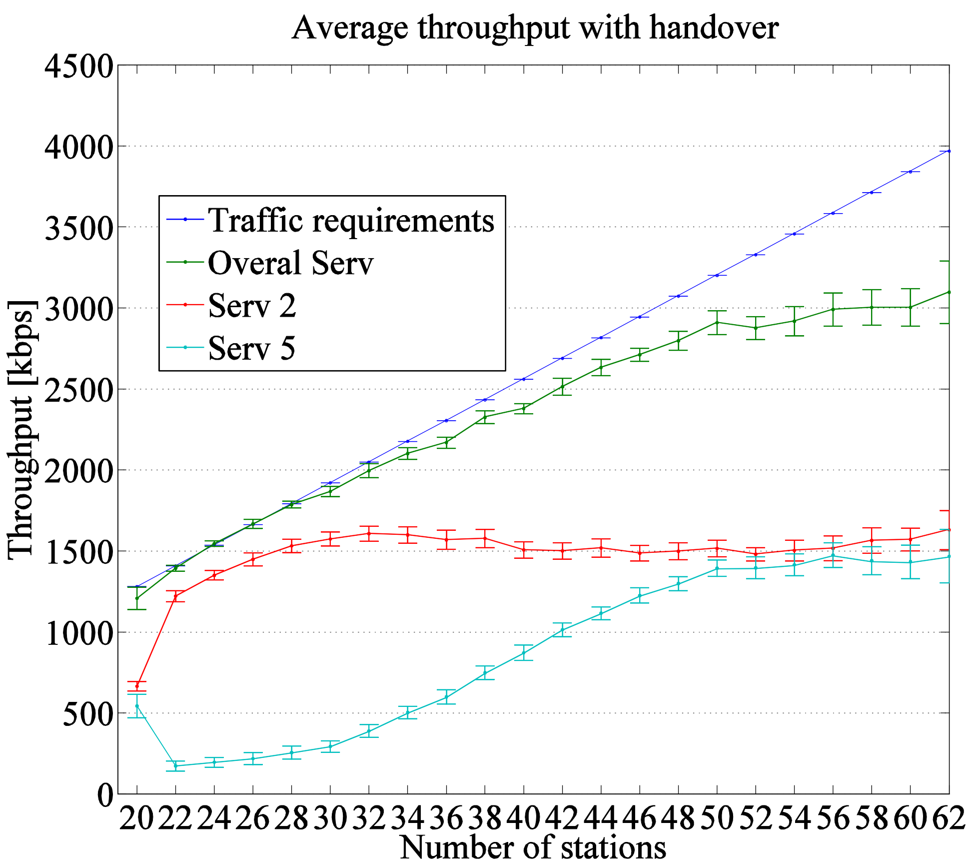
$$(BC1) = \sum_{u=1}^{n} \frac{S_{rate} \cdot (1 + 2 \cdot PER_{bu})}{R(CQI_{bu}) \cdot N_{codes}} x_{bu} \leq L^{\max}, \forall b \in \{1,\ldots,m\}$$

The system has a maximum theoretical capacity

Max data rate

$$(BC2) = \sum_{u=1}^{n} S_{rate} \cdot (1 + 2 \cdot PER_{bu}) x_{bu} \leq 331.9 \cdot 15, \forall b \in \{1,\ldots,m\}$$

Optimised MBS: switching between the bands (i.e., handover)



Optimised MBS looks for the optimal values of the allocation variable

Spectrum/Network Sharing

Among Operators

- Two or more physical signals in the same spectrum are shared by different operators

- FSU can be applied here up to the point of spectrum trading and dealing with network sharing aspects in their roll-out planning, too.
- Traditional deployments start in dense urban areas to provide mobile radio services to as many people as possible in a reasonably short time span.
- The roll-out needs to start in rural areas and only if particular coverage obligations are reached the next layer i.e. sub-urban areas can be opened up, followed by urban areas and hot spots.
- Since capacity is not a problem in the early phases, initial sharing scenarios might be attractive for boosting coverage and initial service provisioning while a dedicated, operator individual network can be extended out of the shared approach when required.

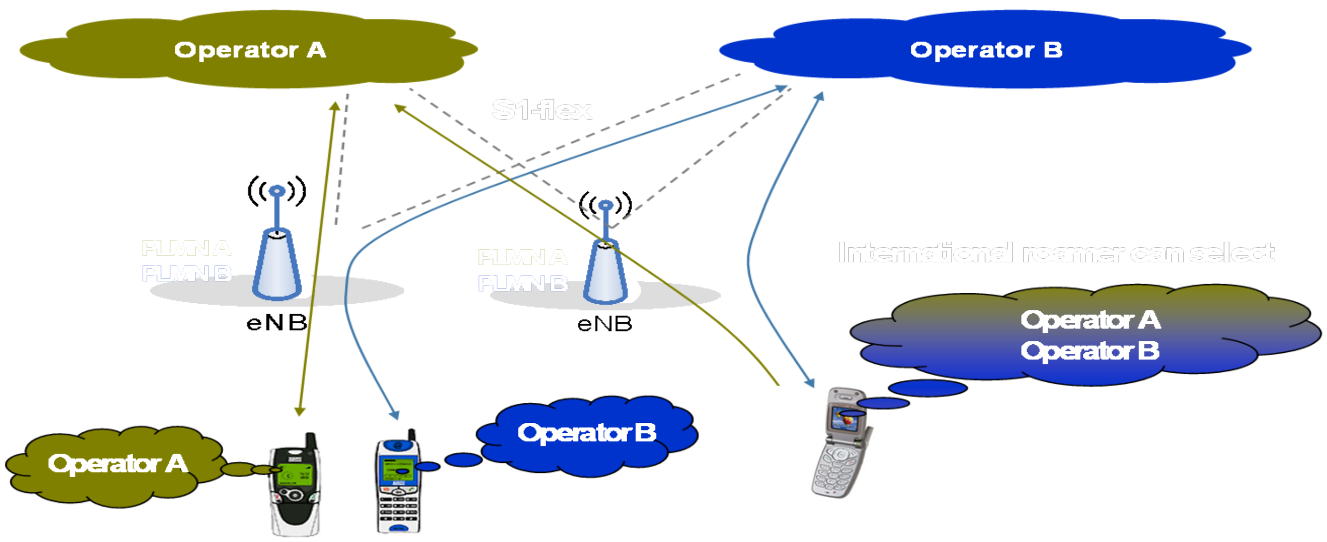
Spectrum Sharing

Mobile Virtual Network Operator (MVNO)

- Business models:
  - The MVNO can use air interface resources (and infrastructure) from “real” operators for their brand. While the MVNO in fact does not transmit any physical bit himself but relies on transception services of the license holder

RAN Sharing

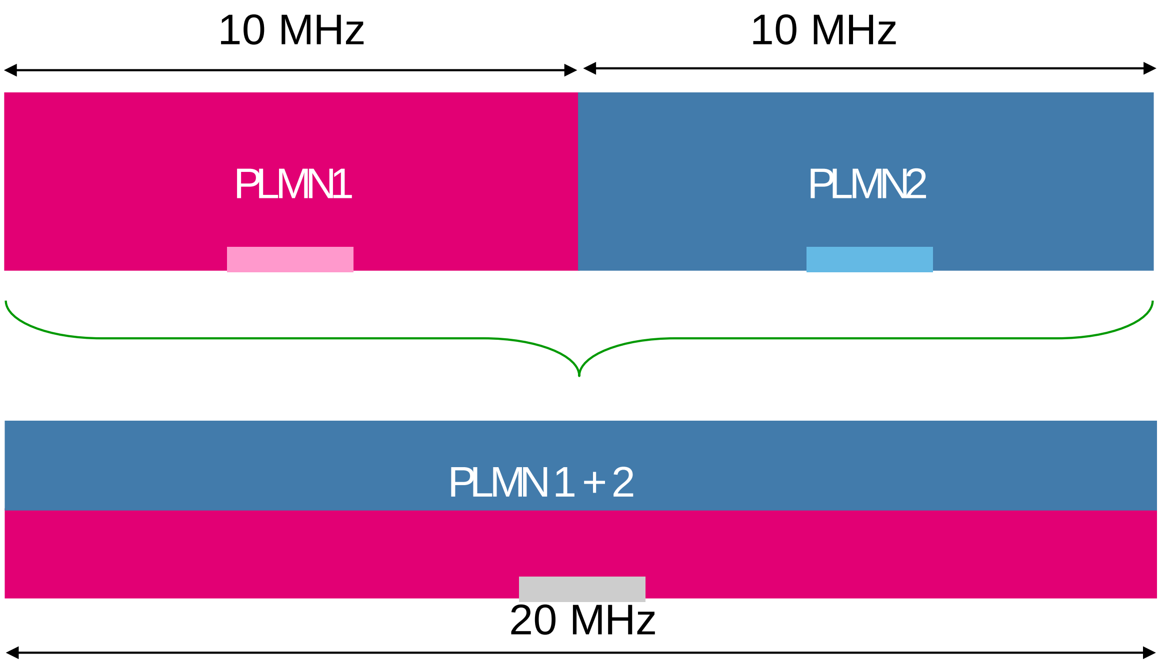
- Biunique signalling between the shared RAN and the dedicated CN is possible due to the LTE inherent S1-flex concept allowing the interconnection of a single eNB to multiple MMEs or SGWs (pooling concept).



Spectrum/Network Sharing

Carrier Aggregation

- Spectral optimised operation for larger operating bandwidths
- Bundling of spectrum from other operators for increased data rates and trunking/scheduling gain:



sharing is an interesting means to increase spectral efficiency, preferably to be applied for small bandwidth BW deployments (e.g. 900 or 1800 MHz).

Conclusions

- Sharing of spectrum and carriers can be very effective for boosting up networks performance and cost-efficient deployment
- FSU can be very effective in un-coordinated deployments
- Spectrum and carrier aggregation boost up performance without requiring spectrum refarming

END OF PART 2A

Medium Access Control

COGNITIVE RADIO NETWORKS

Medium Access Control

Enabler of CR

- The simplest concept behind the CR operation is:
  - Detect an opportunity to transmit though spectrum sensing, i.e. Identify the "Spectrum Holes";
  - Access the spectrum dynamically (known as Dynamic Spectrum Access, DSA).
- The Medium Access Control allows to coordinate multiple network nodes to access the shared medium in an opportunistic way.
- Allowing the Cognitive Radio to act as a network, i.e. to go further than just perform dynamic spectrum access for opportunistic transmission at the link level.

Medium Access Control

What is its purpose?

•How to use the identified the “Spectrum Holes”!

•How can Cognitive Radio Network use them to communicate?

Medium Access Control

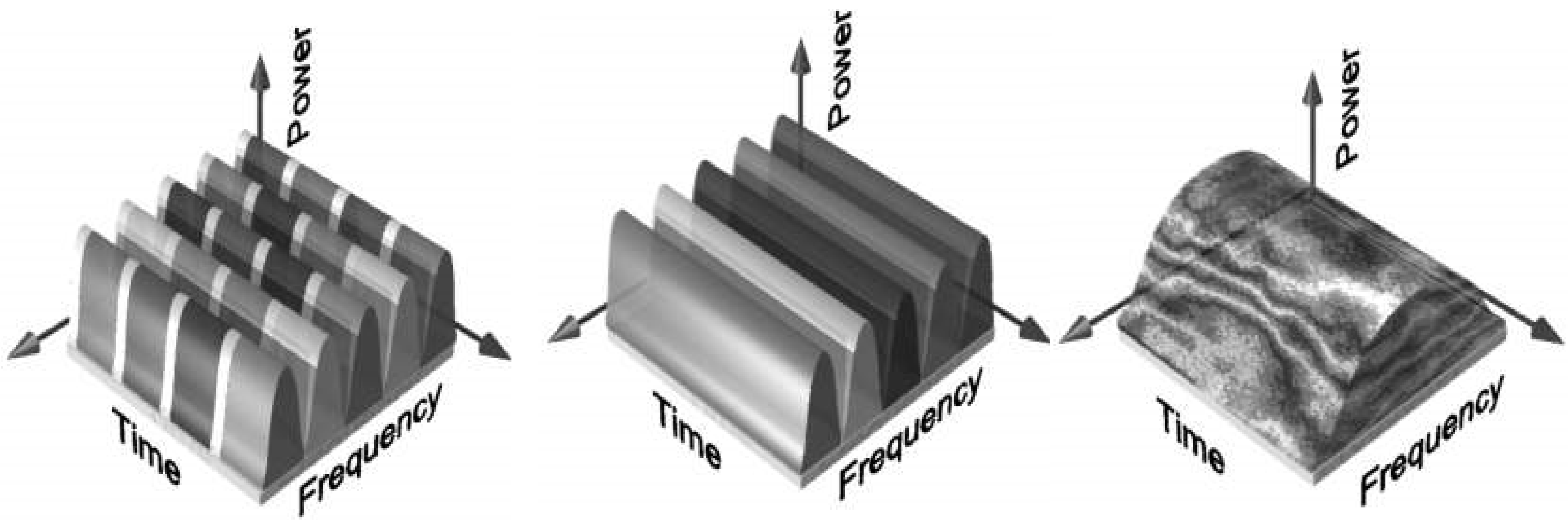
Cognitive Radio Network Architecture

- The type of network architecture dictates which kind of Medium Access Control mechanism are employed.

Medium Access Control

Channel Access Methods

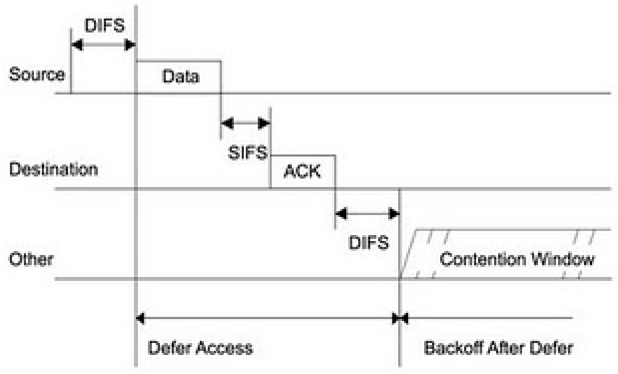
- Fixed Mode Channel Access Methods
  - Where two network nodes establish a dedicated communications channel (circuit) connecting them for the duration of the communication session before the nodes may communicate.
  - Each node is allocated a fixed fraction of bandwidth; equivalent to circuit switching; very inefficient for low duty traffic.
  - Requires a synchronization mechanism.



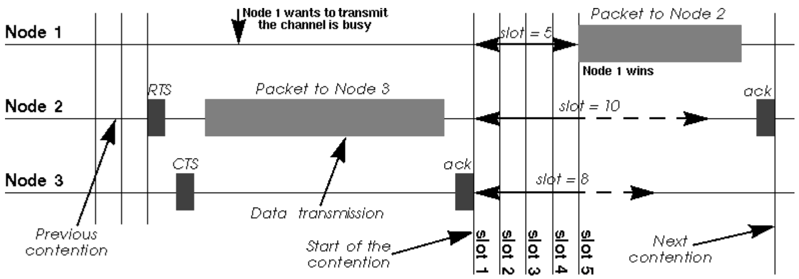
From: http://www.skydsp.com/publications/4thyrthesis/chapter1.htm

Medium Access Control
Channel Access Methods

- Packet Mode Channel Access Methods;
  - Where the transmitted data is grouped, regardless of content, type, or structure, into suitably-sized blocks, called packets.
  - Polling, Reservations and Scheduling and Random Access.
  - It is not efficient for high duty traffic, due to collisions and contention resolution schemes.



From: http://asymingt.blogspot.com/2008/06/part-i-wifi-dcf-and-performance-issues.html

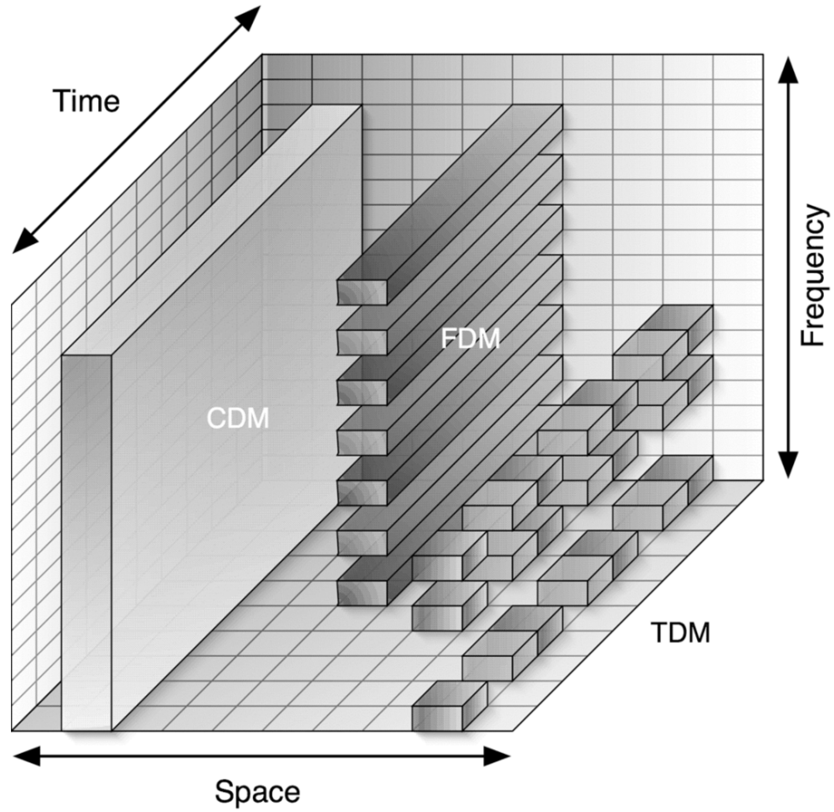


From: http://www.hpl.hp.com/personal/Jean_Tourrilhes/Linux/Linux.Wireless.mac.html

Medium Access Control

Fixed Mode Channel Access Methods

- The Fixed Channel Access Methods can be divided in:
  - Frequency Division Multiple Access (FDMA)
  - Time Division Multiple Access (TDMA)
  - Code Division Multiple Access (CDMA)
  - Space Division Multiple Access (SDMA)

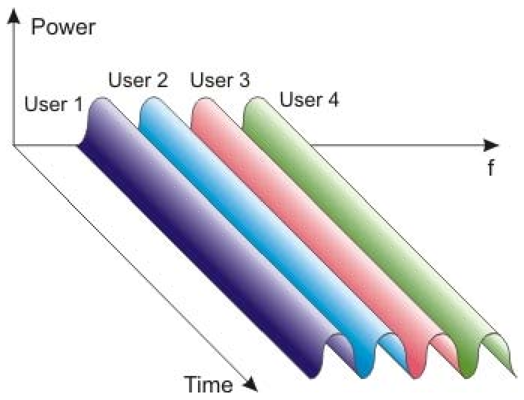


From: **Secondary use of spectrum: a survey of the issues, http://dx.doi.org/10.1108/14636690610653608**

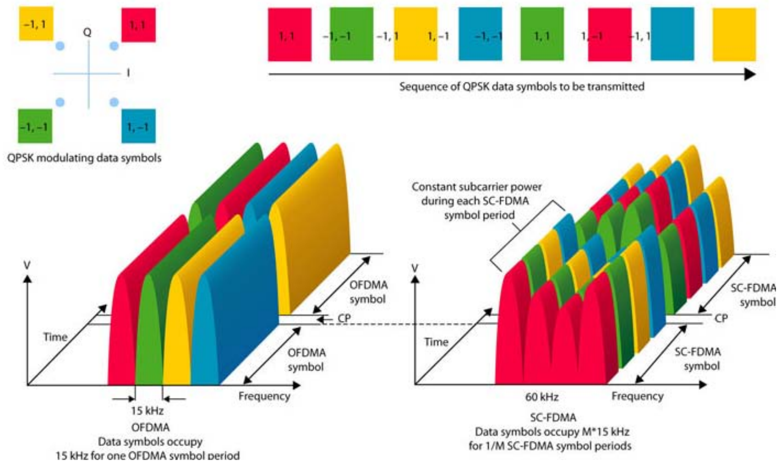
Frequency Division Multiple Access

- Based on Frequency Division Multiplexing (FDM), where the signal is multiplexed by assigning non-overlapping frequency ranges to different signals or to each "user" of a medium.

- Wavelength Division Multiple Access (WDMA)
  - Wavelength term is applied to optical carriers while Frequency term applies to radio carrier.
- Orthogonal Frequency Division Multiple Access (OFDMA)
  - The data is divided into several parallel data streams or channels, one for each sub-carrier.
- Single Carrier FDM
  - SC-FDMA can be interpreted as a linearly pre-coded OFDMA scheme, in the sense that it has an additional DFT processing preceding the conventional OFDMA processing.



From: http://www.enki.pl/index_7.php?page=711

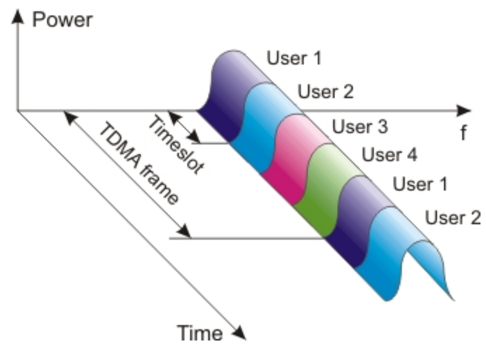


From: http://mobiledevdesign.com/tutorials/WIreless_Everywhere_Not_Quite_Yet/index2.html

Medium Access Control

Time Division Multiple Access

- Time division multiple access (TDMA) is a channel access method for shared medium networks. It allows several users to share the same frequency channel by dividing the signal into different time slots.
- The users transmit in rapid succession, one after the other, each using his own time slot.
- This allows multiple stations to share the same transmission medium (e.g. radio frequency channel) while using only a part of its channel capacity.



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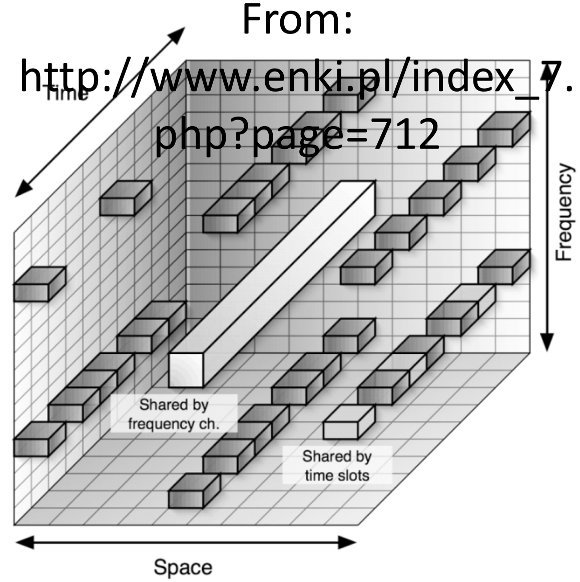
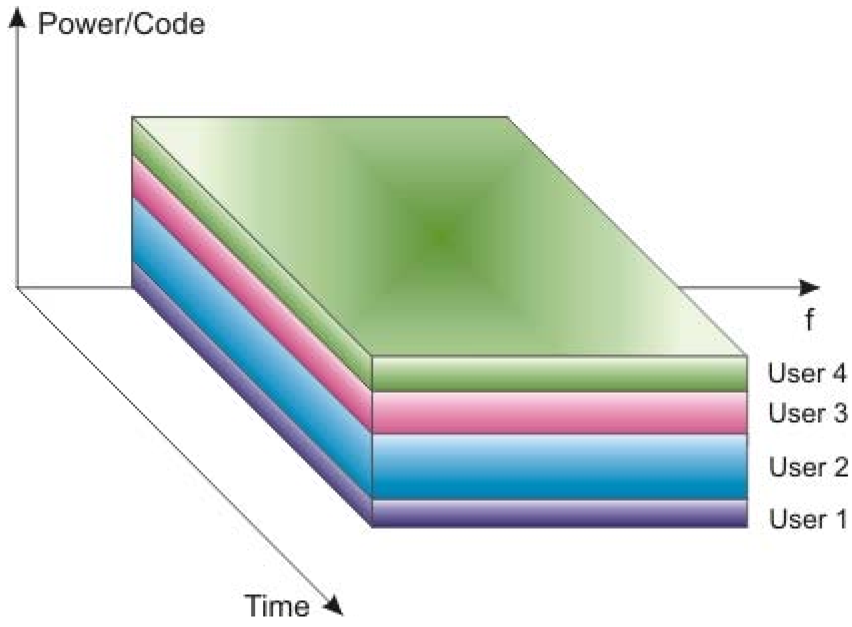


From: **Secondary use of spectrum: a survey of the issues.**

Medium Access Control

Code Division Multiple Access

- CDMA employs spread-spectrum technology and a special coding scheme (where each transmitter is assigned a code) to allow multiple users to be multiplexed over the same physical channel.
- By contrast, time division multiple access (TDMA) divides access by time, while frequency-division multiple access (FDMA) divides it by frequency.
- CDMA is a form of spread-spectrum signaling, since the modulated coded signal has a much higher data bandwidth than the data being communicated.
- Examples:
  - Direct Sequence CDMA
  - Frequency Hopping CDMA
  - Orthogonal Frequency Hopping Multiple Access
  - Multi-Carrier Code Division Multiple Access

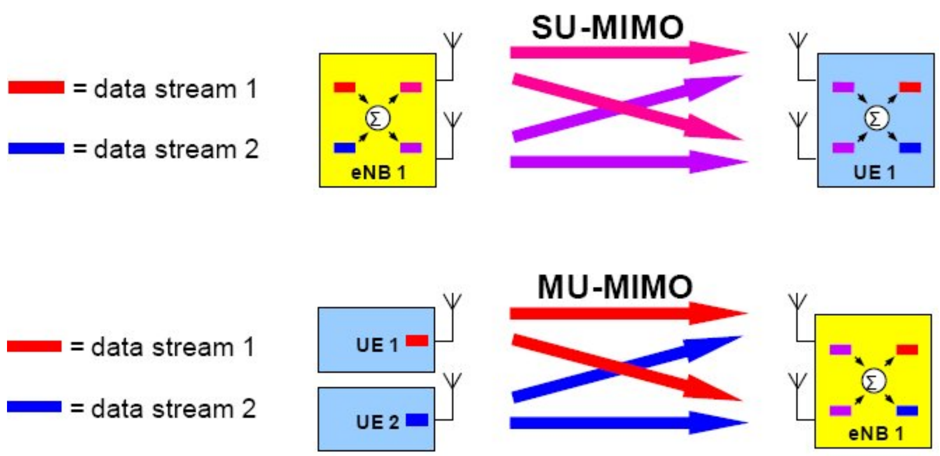


From: http://www.enki.pl/index_7.php?page=711

Medium Access Control

Spatial Division Multiple Access

- Space-Division Multiple Access (SDMA) creates parallel spatial pipes with the purpose of using the same spectrum through spatial multiplexing and/or diversity.
- In traditional mobile cellular networks, the base station has no information on the position of the mobile units and radiates the signal in all directions within the cell to provide radio coverage. This results in wasting power on transmissions when there are no mobile units to reach, in addition to causing interference for adjacent cells using the same frequency. Likewise, in reception, the antenna receives signals coming from all directions including noise and interference signals.
- By using smart antenna technology and by leveraging the spatial location of mobile units within the cell, space-division multiple access techniques offer attractive performance enhancements. The radiation pattern of the base station, both in transmission and reception, is adapted to each user to obtain highest gain in the direction of that user. This is often done using phased array techniques.
- Examples:
  - Multi User MIMO



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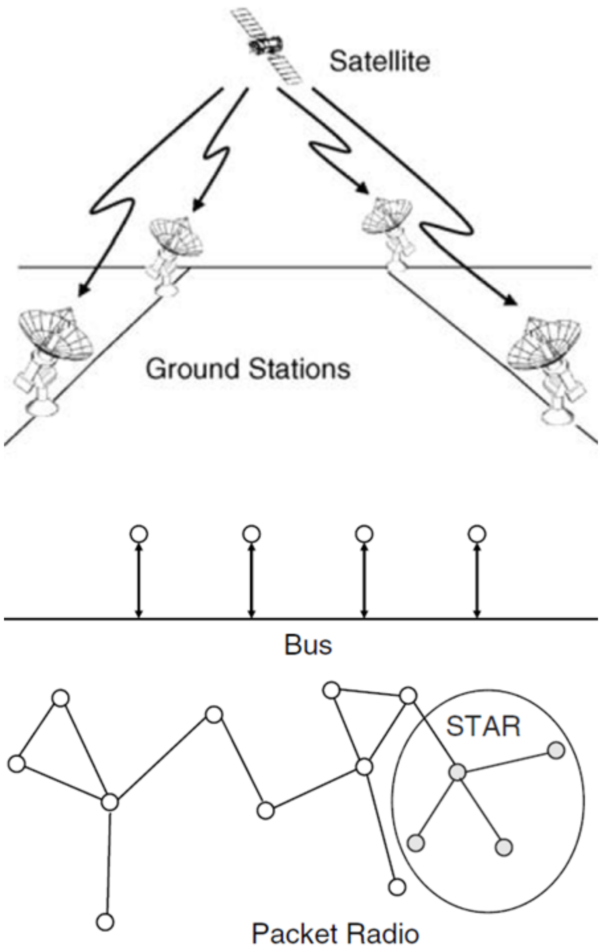
Medium Access Control

Packet Mode Methods

- Aloha Based
- Splitting Algorithms
- Carrier Sensing
- Resource Reservation (Not discussed here)



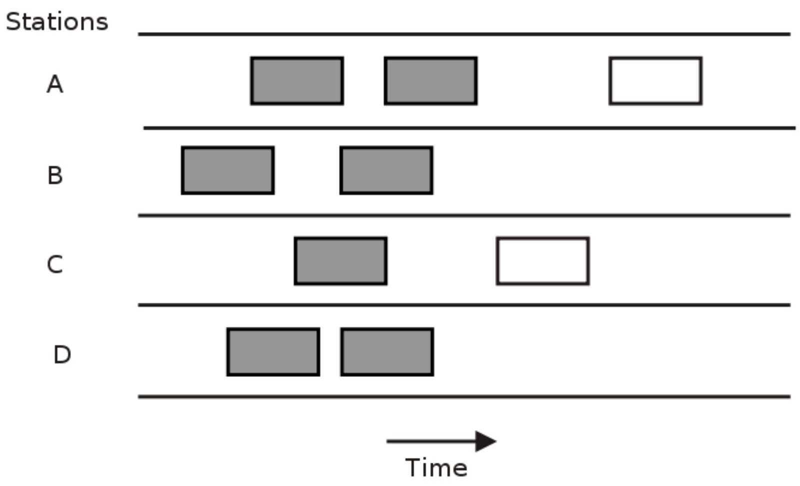
From: KC Chen et al, "Cognitive Radio Networks", Wiley, 2009

Medium Access Control

Aloha Based

- Pure / Un-slotted Aloha
  - If you have data to send, send the data
  - If the message collides with another transmission, try resending "later"

- In Pure ALOHA, only about 18.4% of the time is used for successful transmissions.



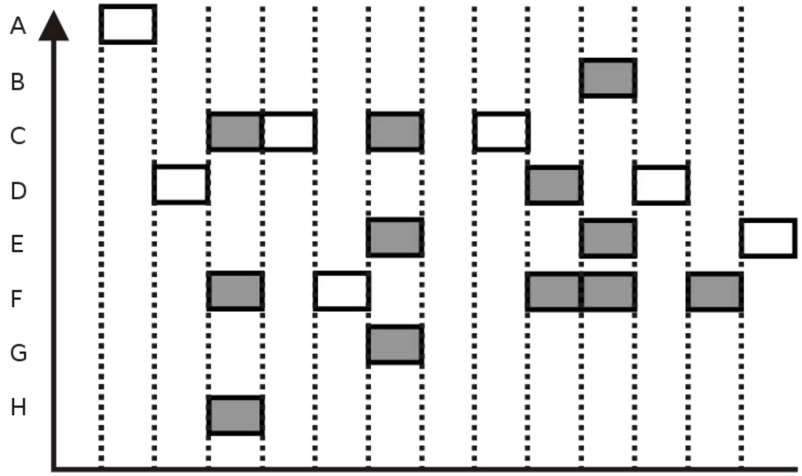
From: http://en.labs.wikimedia.org/wiki/File:Pure_ALOHA1.svg

Medium Access Control

Aloha Based

- Slotted Aloha
  - Introduces discrete timeslots and increased the maximum throughput.
  - A station can send only at the beginning of a timeslot, and thus collisions are reduced.

- Slotted ALOHA, only about 36.8% of the time is used for successful transmissions.

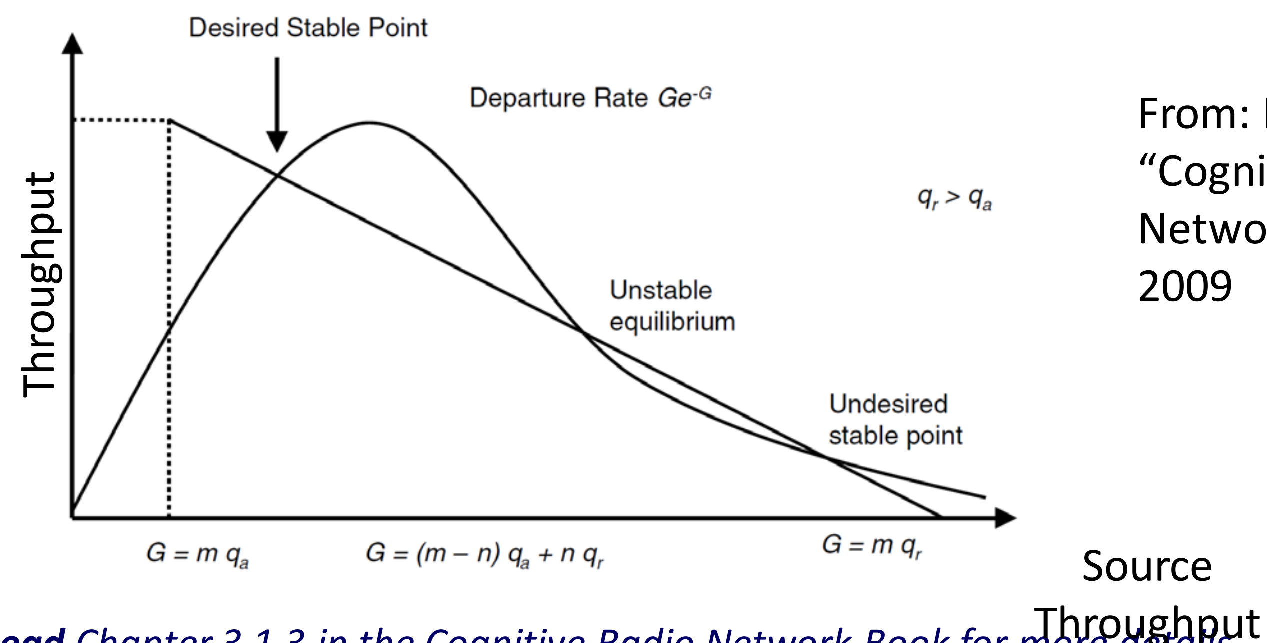


Slotted ALOHA protocol (shaded slots indicate collision)

From: http://en.labs.wikimedia.org/wiki/File:Slotted_ALOHA.svg

Medium Access Control
Aloha Based

- Stabilized Slotted Aloha
  - Random Access Protocols, like Aloha, are only stable if the packet generation rate is within a certain range.



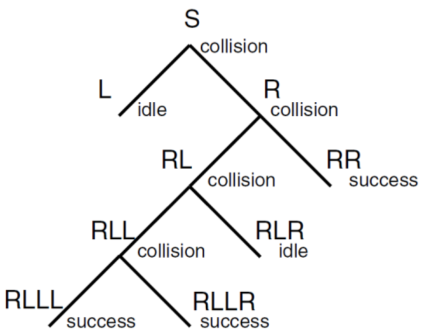
From: KC Chen et al, “Cognitive Radio Networks”, Wiley, 2009

  - ***Read*** *Chapter 3.1.3 in the Cognitive Radio Network Book for more details*

Medium Access Control

Splitting Algorithm Based

- The main issue with Aloha is the lack of a proper collision resolution scheme.
- A collision resolution scheme can be implemented by letting the nodes involved in a collision to decide when to retransmit by:
  - Flipping a coin;
  - Use the arrival time of its collided packet;
  - Etc...
- These kind of schemes are called splitting algorithms or collision resolution protocols.
- *Read Chapter 3.2 in the Cognitive Radio Network Book for more details.*



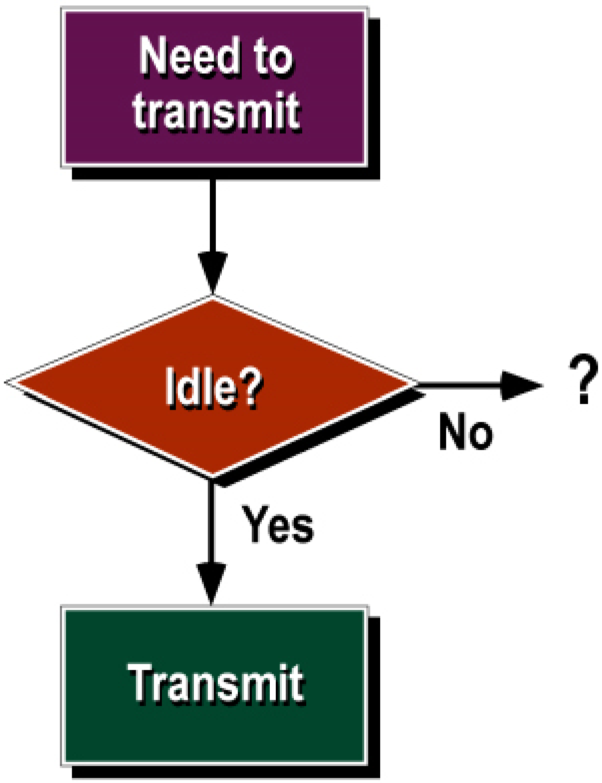
slot	TX set	Waiting	Feedback
1	S	-	e
2	R	L	e
3	RR	RL,L	1
4	RL	L	e
5	RLR	RLL,L	0
6	RLL	L	e
7	RLLR	RLLL,L	1
8	RLLL	L	1
9	L	-	0

From: KC Chen et al, “Cognitive Radio Networks”, Wiley, 2009

Medium Access Control

Carrier Sensing Based

- Carrier Sense Multiple Access (CSMA) is a protocol in which a node verifies the absence of other traffic before transmitting on a shared transmission medium, such as an electrical bus, or a band of the electromagnetic spectrum.
- "Carrier Sense" means that a transmitter uses feedback from a receiver that detects a carrier wave before trying to send. That is, it tries to detect the presence of an encoded signal from another station before attempting to transmit. If a carrier is sensed, the station waits for the transmission in progress to finish before initiating its own transmission.
- "Multiple Access" means that multiple stations send and receive on the medium. Transmissions by one node are generally received by all other stations using the medium.



From: http://wiki.hill.com/wiki/index.php?title=Image:G0165_CSMA.jpg

Medium Access Control

Carrier Sensing Based

- 1-persistent CSMA - When the sender (station) is ready to transmit data, it checks if the physical medium is busy. If so, it senses the medium continually until it becomes idle, and then it transmits a piece of data (a frame). In case of a collision, the sender waits for a random period of time and attempts to transmit again.

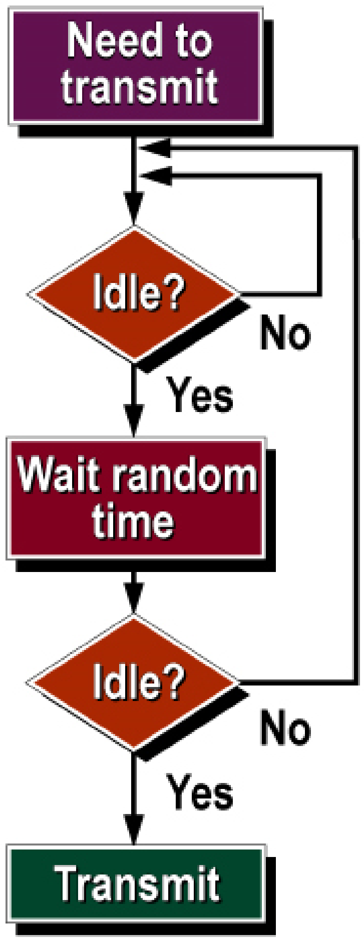
- p-persistent CSMA - When the sender is ready to send data, it checks continually if the medium is busy. If the medium becomes idle, the sender transmits a frame with a probability p. If the station chooses not to transmit (the probability of this event is 1-p), the sender waits until the next available time slot and transmits again with the same probability p. This process repeats until the frame is sent or some other sender stops transmitting. In the latter case the sender monitors the channel, and when idle, transmits with a probability p, and so on.

- Non-persistent CSMA - In non-persistent versions of CSMA, a user that generated a packet and found the channel to be busy refrains from transmitting the packet and behaves exactly as if its packet collided, i.e., it schedules (randomly) the retransmission of the packet to some point in the future. Please note that non-persistent CSMA is equivalent to p-persistent with an appropriate value of p.

Medium Access Control

Carrier Sensing Based

- Carrier Sense Multiple Access With Collision Avoidance (CSMA/CA), a node wishing to transmit data has to first listen to the channel for a predetermined amount of time to determine whether or not another node is transmitting on the channel within the wireless range.
- If the channel is sensed "idle," then the node is permitted to begin the transmission process.
- If the channel is sensed as "busy," the node defers its transmission for a random period of time.
- Once the transmission process begins, it is still possible for the actual transmission of application data to not occur.



From:
http://wiki.hill.com/wiki/index.php?

Medium Access Control

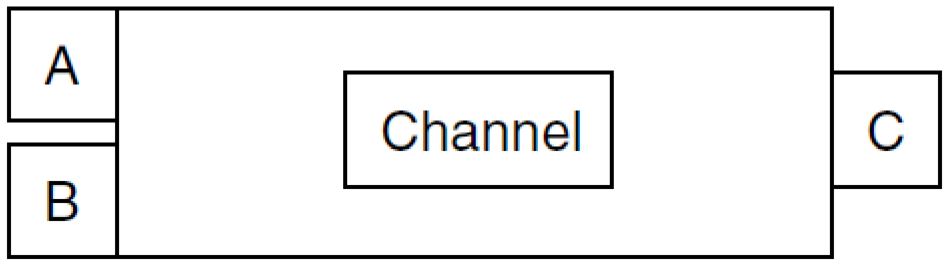
Hybrid Channel Access Schemes

- The GSM cellular system combines the use of frequency division duplex (FDD) to prevent interference between outward and return signals, with FDMA and TDMA to allow multiple handsets to work in a single cell.
- GSM with the GPRS packet switched service combines FDD and FDMA with slotted Aloha for reservation inquiries, and a Dynamic TDMA scheme for transferring the actual data.
- Bluetooth packet mode communication combines frequency hopping (for shared channel access among several private area networks in the same room) with CSMA/CA (for shared channel access inside a medium).
- IEEE 802.11b wireless local area networks (WLANs) are based on FDMA and DS-CDMA for avoiding interference among adjacent WLAN cells or access points. This is combined with CSMA/CA for multiple access within the cell.
- HIPERLAN/2 wireless networks combine FDMA with dynamic TDMA, meaning that resource reservation is achieved by packet scheduling.

Medium Access Control

One Wide Channel versus Multi Channels

- One Channel random Access MAC (Slotted Aloha):

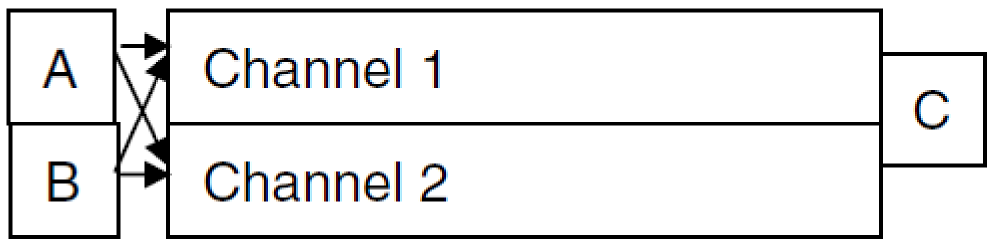


- The total throughput is given by:

$$2K(p)(1-p) = 2Kp - 2Kp^2$$

Medium Access Control
One Wide Channel versus Multi Channels

- Divided-Channel Random Access MAC (Slotted Aloha):



- The total throughput is given by:

$$2\frac{K}{2}\left\{\underbrace{p\cdot\frac{1}{2}\left[(1-p)+p\cdot\frac{1}{2}\right]}_{\text{pick channel 1, successful}}+\underbrace{p\cdot\frac{1}{2}\left[(1-p)+p\cdot\frac{1}{2}\right]}_{\text{pick channel 2, successful}}\right\}$$

$$=2Kp-Kp^2$$

Medium Access Control

One Wide Channel versus Multi Channels

- An intuitive thought is that if we divide the fixed amount of radio resource into many sub-channels, parallel transmission is possible.

- The immediate drawback is that the channel capacity/throughput is factorized. However, the overall system throughput can increase.

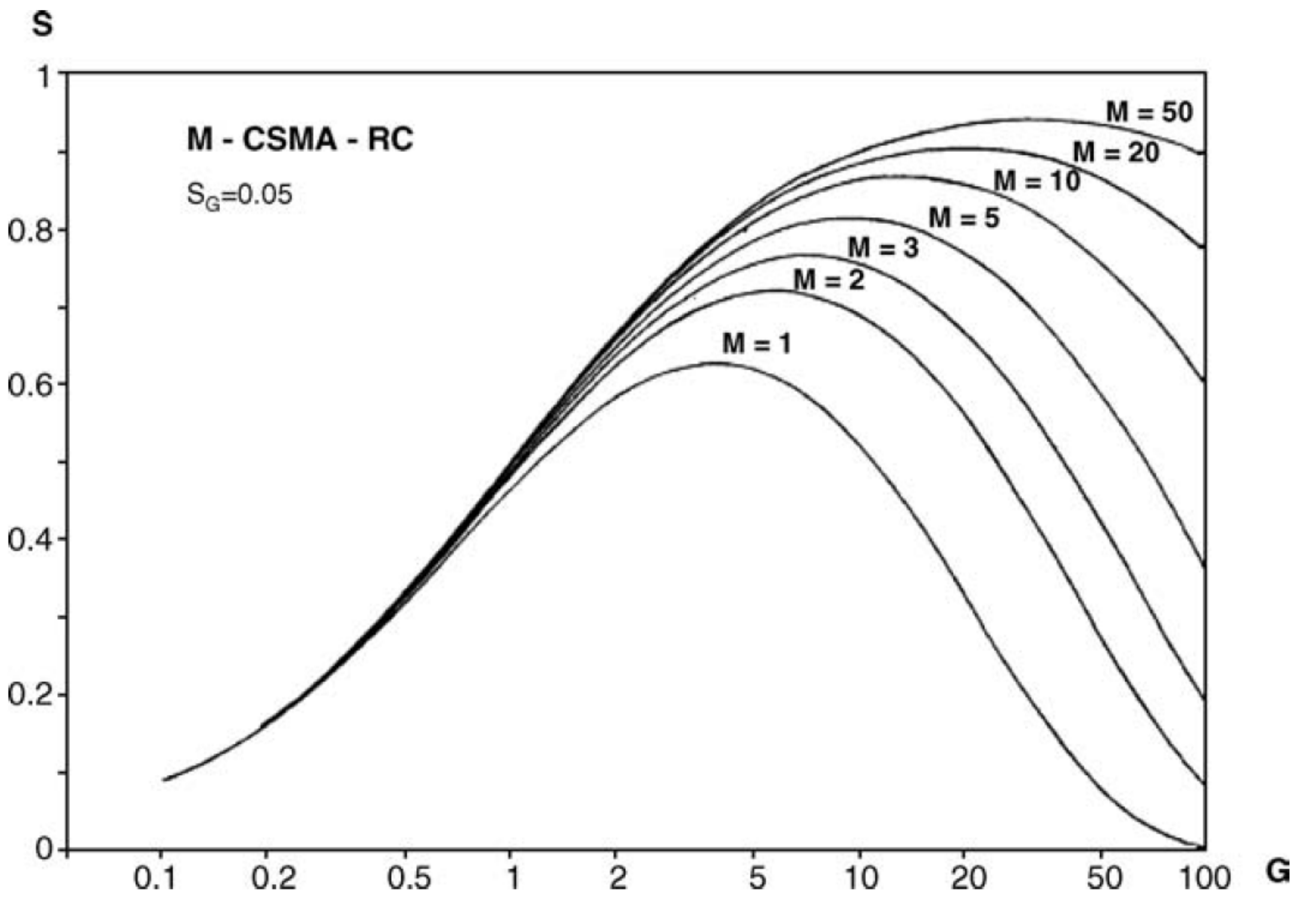
- Another point of view is that, in future communication networks, devices may be accessible to a wide range of frequency bands; instead of using a wide band that may suffer from frequency selective fading, the protocol is suitable for having multichannel selection capability to select the good channels.

- Multichannel instead of one wide-channel intuitively makes sense.

Medium Access Control

One Wide Channel versus Multi Channels

- Throughput of M-Channel multichannel CSMA versus offered traffic, for varying number of channels.



Medium Access Control

Division versus Extension to Multi-Channels

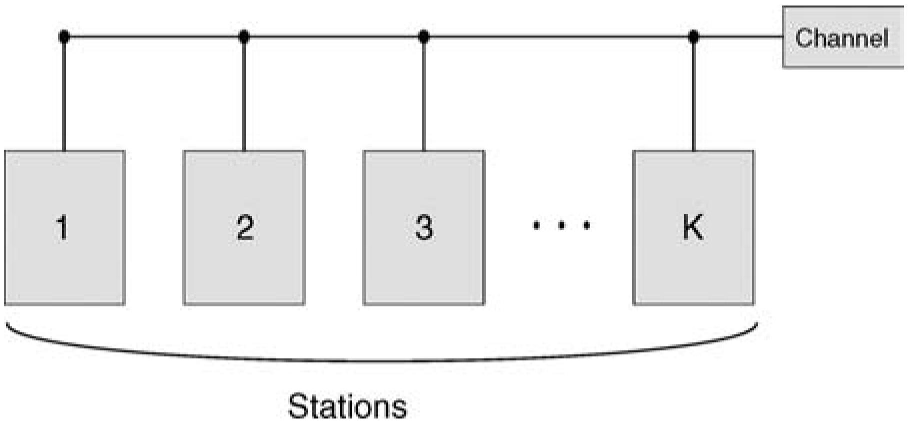
- Based on the way multiple channels are used, these protocols may be broadly classified into two classes:
  - The first class assumes a separate channel for every device in the network, formed on the basis of individual CDMA codes (or orthogonal signaling). Transmissions may be transmitter-oriented (i.e., each device transmits using its own code / signaling) or receiver-oriented (i.e., all transmissions made to the same receiver using the same code / signaling). In the first class, all channel are dedicated, that is, every device has one and only one unique channel with respect to its code.
  - The second class of multichannel MAC protocols does not assume dedicated channels for every node. Instead, the available bandwidth is assumed to be divided into a number of channels whose number is smaller than the number of devices. A device may transmit and receive on any channel.

- There are some advantages of using a smaller number of shared channels over unique channels for every device in the mobile ad-hoc network. For example, this does not require every device to know the whole set of codes used in the network that can increase the design complexity significantly.

Medium Access Control

Multi Channel Access

- One Channel (LAN Example)



- Nodes share the same channel devices

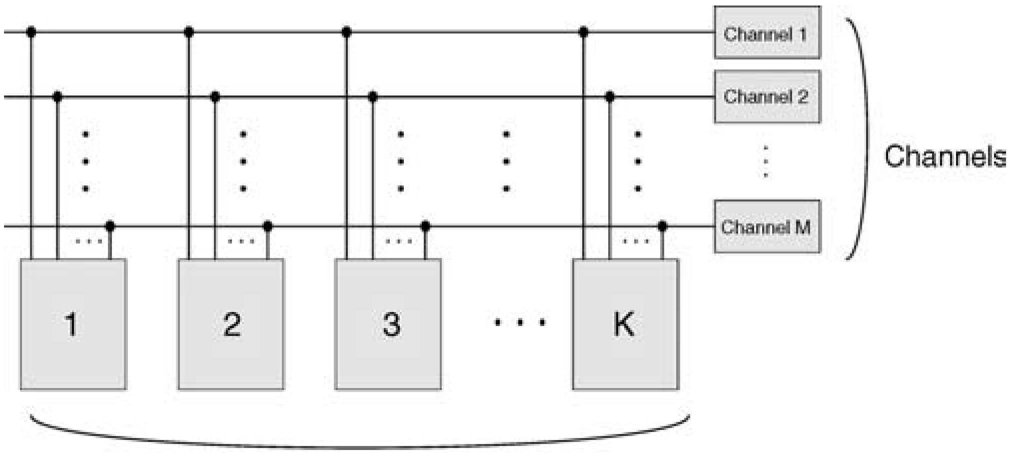
- If More than two access the channel a collision occurs

- There is contention for the same resource, i.e. the channel access time.

Medium Access Control

Multi Channel Access

- Multi Channel (LAN Example)

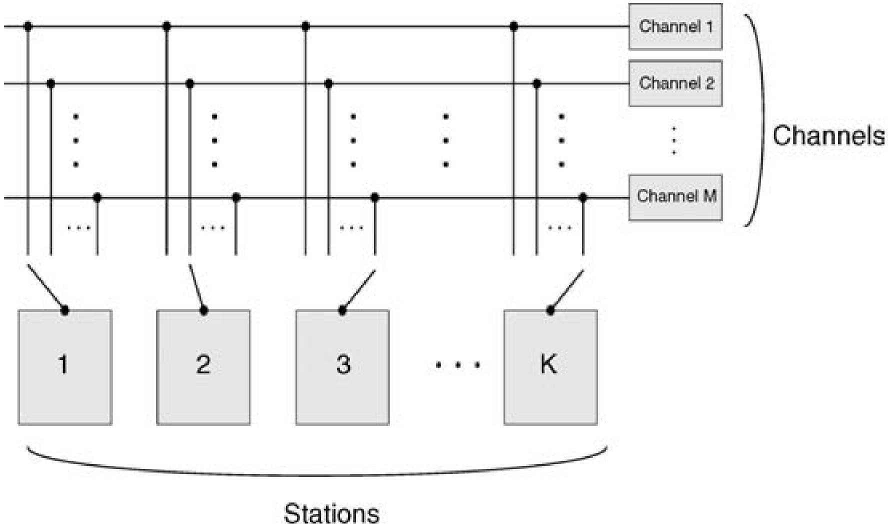


- Every node is capable of: Sensing Transmitting over multiple channels;
- Collision occurs if any co-channel transmission occurs.
- In Wireless Network this is not possible, because nodes are not capable of listening while transmitting.
- Number of radios is limited (many case there is only one radio per device, active at least)

Medium Access Control

Multi Channel Access

- Multi Channel Wireless

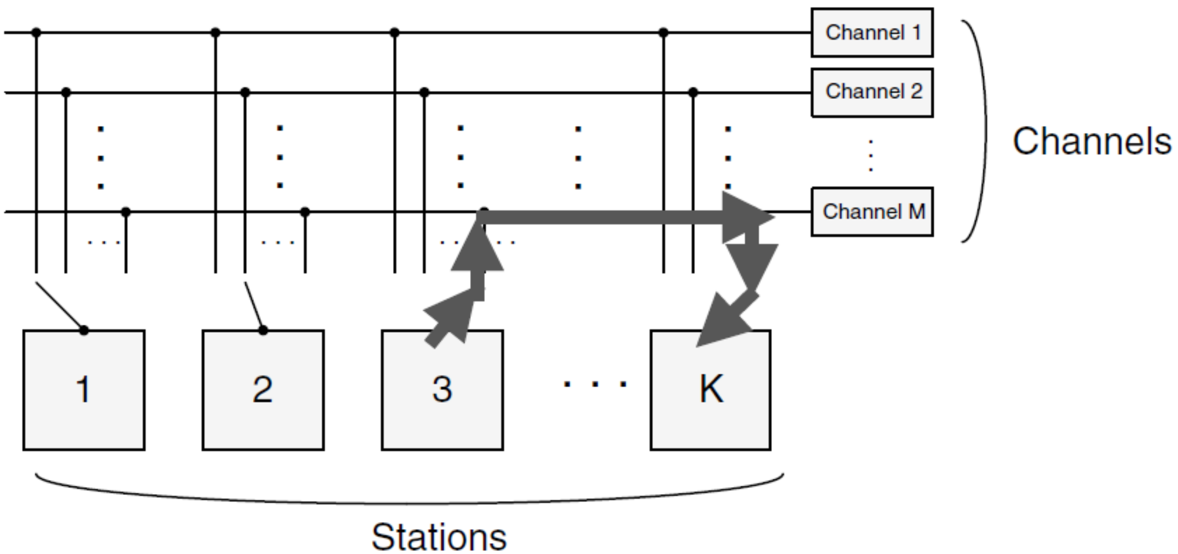


- A collision still occurs if there are more than 2 transmitters over the same channel

Medium Access Control

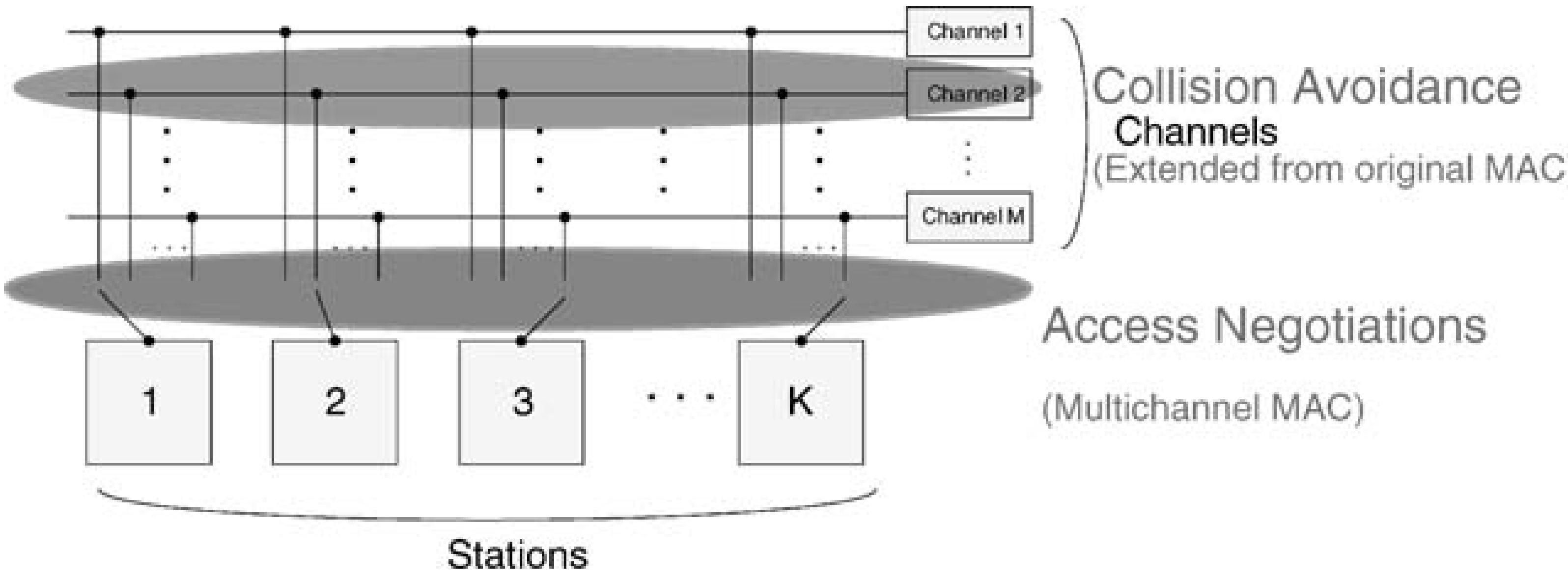
Multi Channel Access

- To transmit a packet successfully, the following must occur:
  - Transmitter Can find the receiver (Access Negotiation)
  - No simulation transmission on the same channel (Collision Avoidance/n Resolution)
  - Receiver be on the same channel than the transmitter (Access Negotiation)



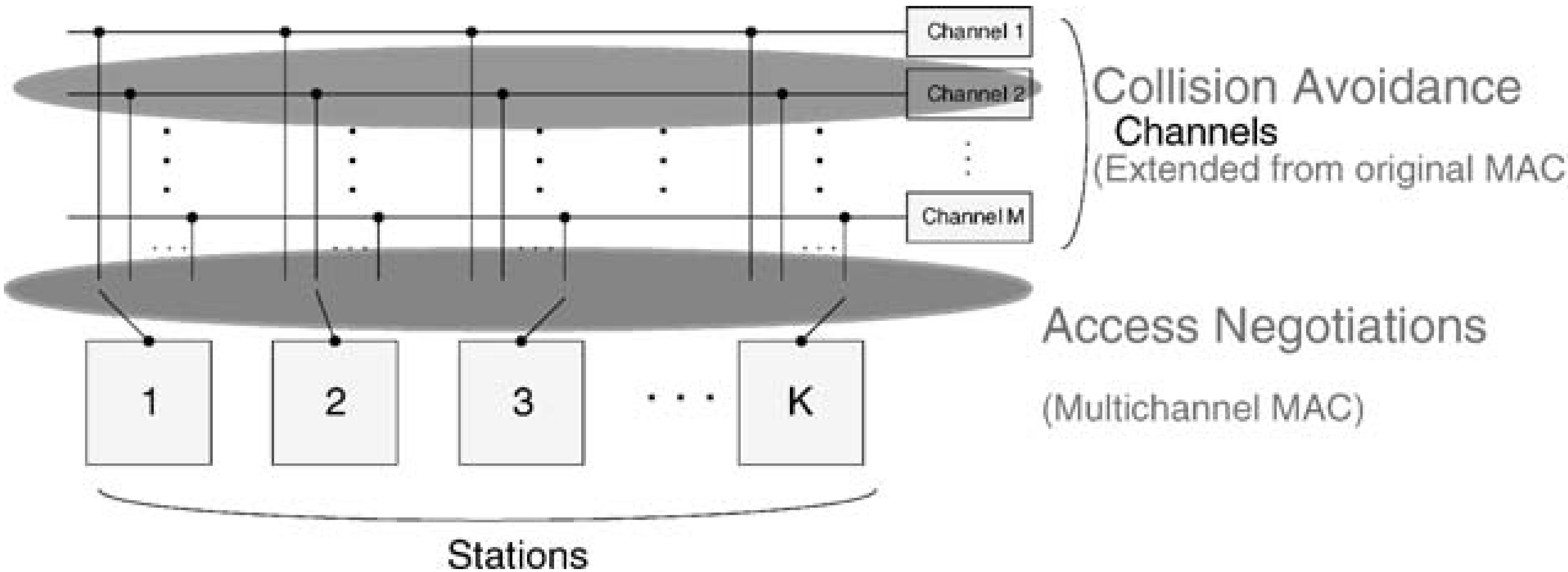
Medium Access Control

Multi Channel Access



Medium Access Control

Multi Channel Access



Medium Access Control

Collision Avoidance/Resolution

- The collision avoidance/resolution in the multi channel MAC protocols are an extension of the single channel MAC.
- But it brings extra challenges.
- The number of competing nodes may not be fixed over one channel, that is, a transmitter may ‘leave’ the current channel where contention occurs and try to access its receiver on other channel in the next frame.
- The channels may be asymmetric, with different capacity, delay, jitter, etc. Thus, an adaptive structure of the MAC protocol may be required to increase the efficiency over different channels.

Collision Avoidance

Multi-Layer Collision Avoidance/Resolution

- The aim of the fundamental MAC design is to reduce the impact of collisions over the shared medium either by avoidance of anticipating traffic or by resolution of collisions, which exactly suggests carrier sensing and collision resolution.

- In the CSMA family, listen-before-transmit is used to avoid the anticipated collision.

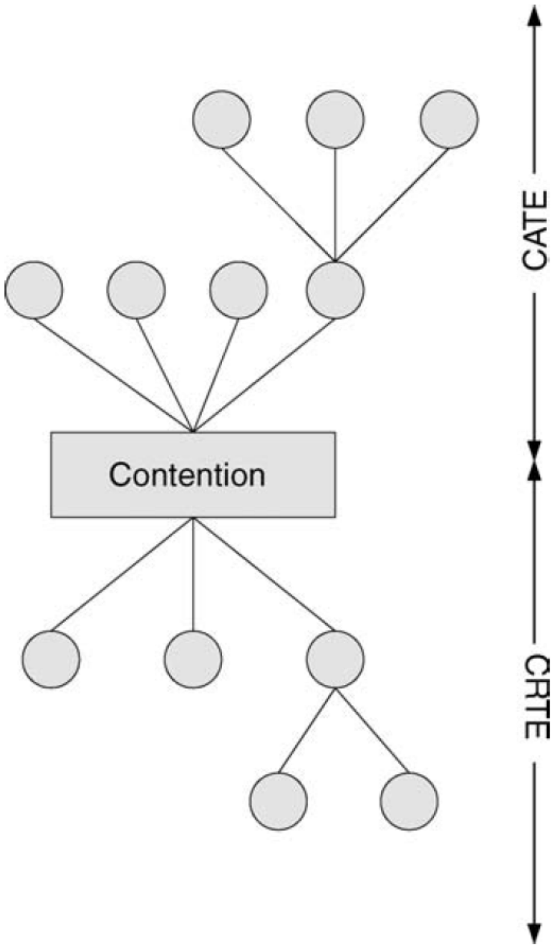
- The idea behind collision resolution is to resolve collision effectively to enhance the efficiency of multiple access through the splitting algorithm of the tree expansion structure.

- There are two generalized types of multiple access protocols based on tree expansion structure.

Collision Avoidance

Multi-Layer Collision Avoidance/Resolution

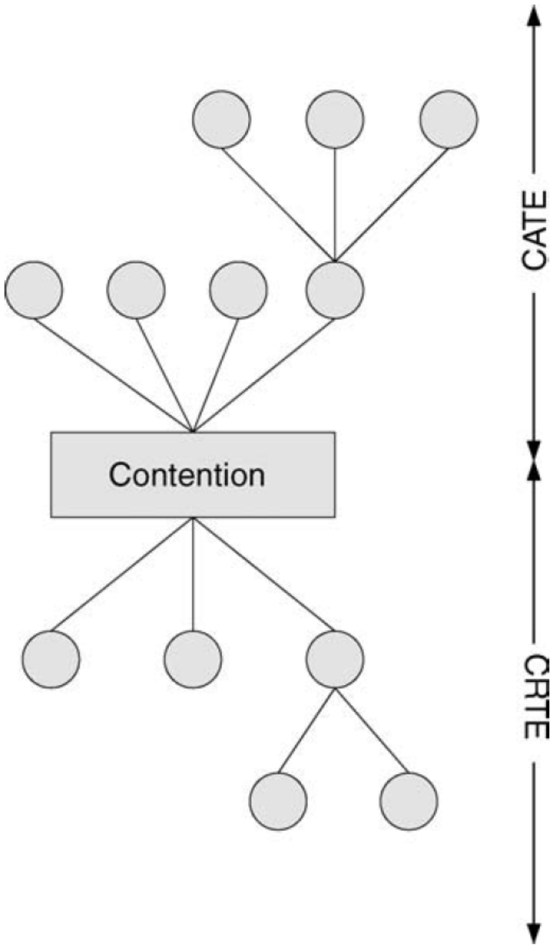
- Collision Anticipation Tree Expansion (CATE).
- This tree structure avoids/reduces possible collision, which is the primary reason prohibiting channel efficiency. Such a tree expansion provides a number of subsets (leaves) to split contending users before the transmission or identification phase.



Collision Avoidance

Multi-Layer Collision Avoidance/Resolution

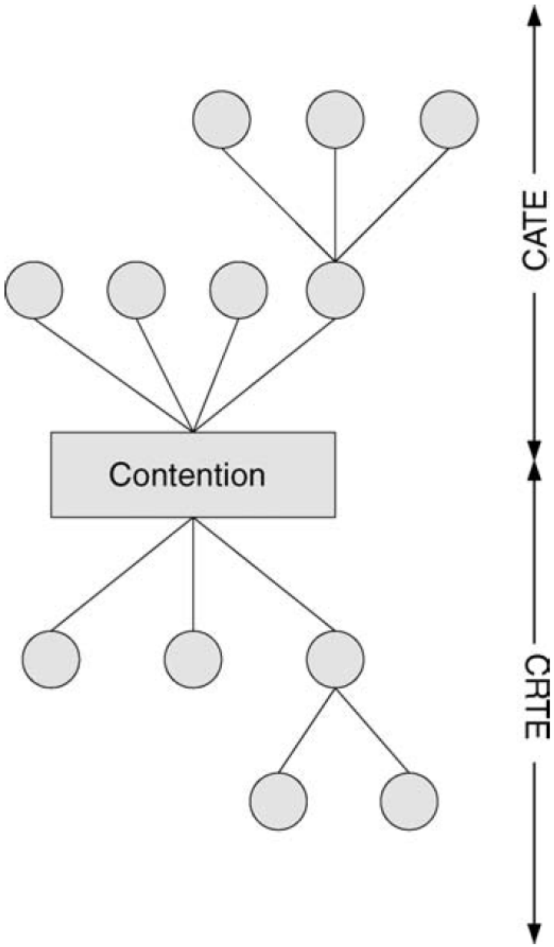
- Collision Resolution Tree Expansion (CRTE).
- In contrast to CATE, CRTE only generates a tree after the transmission or identification phase with some collisions being detected. The devices wait for channel response and try to resolve the collisions.
- Read about CRP in Chapter 3.



Collision Avoidance

Multi-Layer Collision Avoidance/Resolution

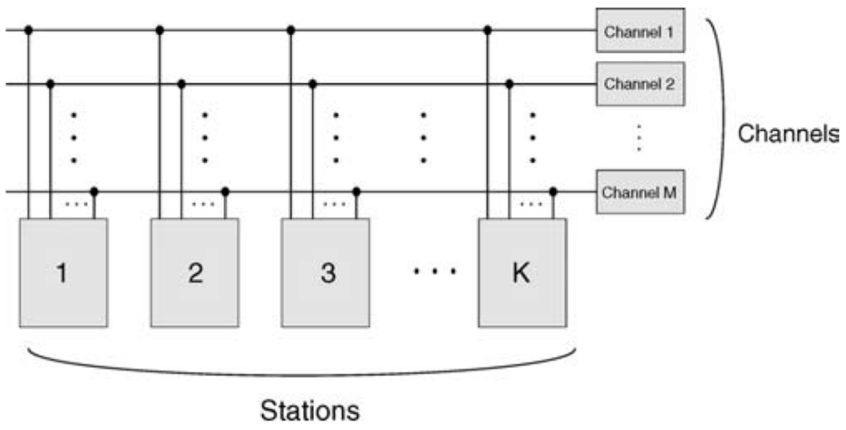
- Multi-Layer Collision Avoidance/Resolution (MULCAR).
- Generalized and combined version of CATE and CRTE.
- The idea is simple: create several independent groups and then try to avoid/resolve contentions.
- MULCAR may consist of the following layers of effective expansion:
  - frequency domain expansion;
  - time domain expansion;
  - spatial domain expansion;
  - communication channel/bands;
  - probability domain as random back off;
  - signalling domain.



Collision Avoidance

CSMA based Multi Channel MAC

- We can use in these cases both versions of CSMA, the persistent and non-persistent.
- Read in sub-chapter 8.2.2.2 and 8.2.2.3 about the difference in performance



Medium Access Control

Access Negotiation

- Access Negotiation in multichannel is a new problem in a wireless multichannel environment, where a node can only listen/transmit over one channel.

- The protocol must guarantee the transmission/ reception accessibility. In other words the nodes must be able to find each other.

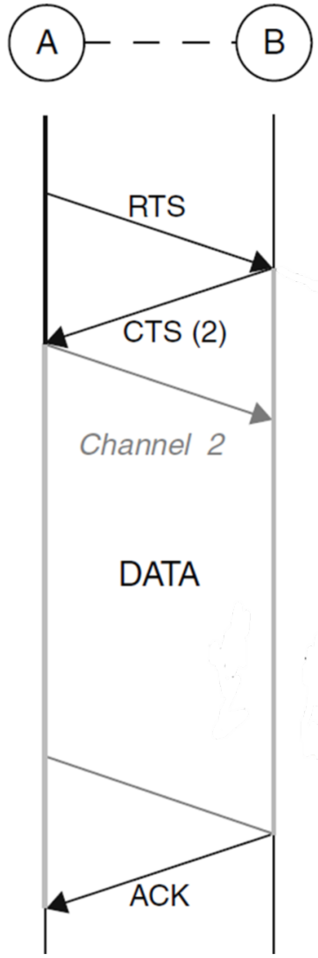
Hidden Node Problem in Multichannel MAC

- Consider a MAC protocol similar to the MAC of the 802.11 with Distributed Control Function (DCF).
- DCF means that the transmitter and receiver exchange Request to Send (RTS) and Clear to Send (CTS) messages before accessing the channel to transmit.
- There are N channels available. One channel is dedicated for exchanging control messages (control channel), and all the other channels are for data.
- When a node is neither transmitting nor receiving, it listens to the control channel.

Medium Access Control

Hidden Node Problem in Multichannel MAC

- When node A wants to transmit a packet to node B, A and B exchange RTS and CTS messages to reserve the channel, as in IEEE 802.11 DCF.
- When sending an RTS, node A includes a list of channels it is willing to use.
- Upon receiving the RTS, B selects a channel and includes the selected channel in the CTS.



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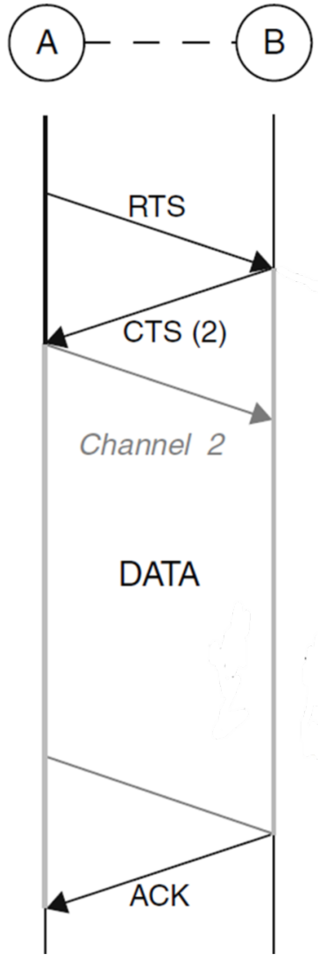
Medium Access Control

Hidden Node Problem in Multichannel MAC

- Then the node A and B switch their channels to the agreed data channel and exchange the DATA and ACK packets.

- After the handshake is completed, node A and B switch immediately to the control channel.

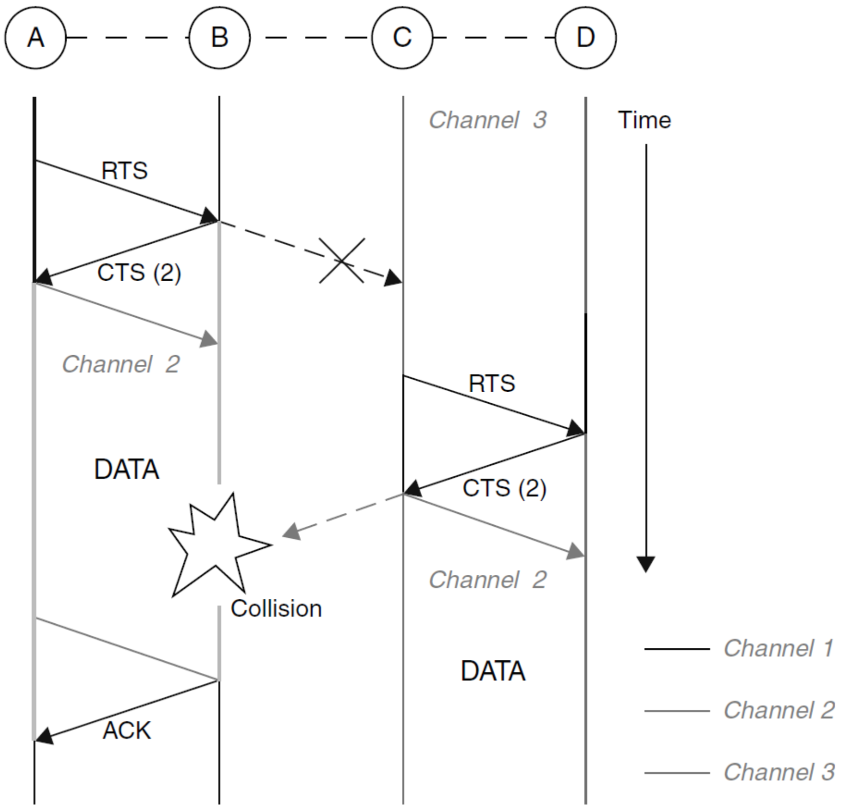


Medium Access Control

Hidden Node Problem in Multichannel MAC

- Node A has a packet for B, so A sends a RTS on the control channel. B selects channel 2 and sends the CTS back to A.

- The RTS and CTS messages should reserve channel 2 in the transmission ranges of node A and B, and no collision occurs.



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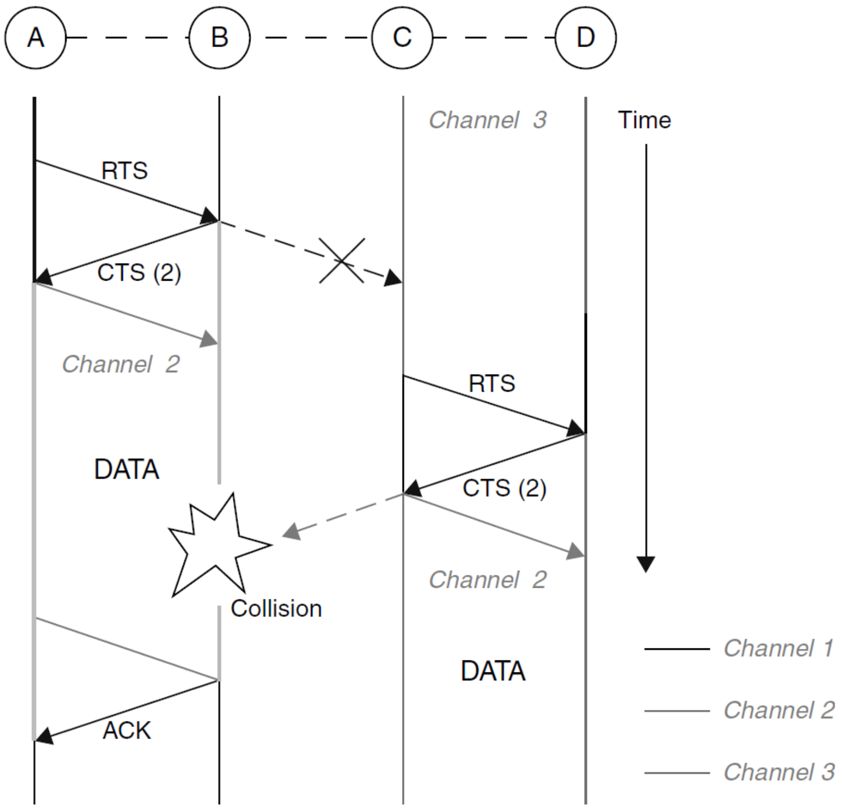
Medium Access Control

Hidden Node Problem in Multichannel MAC

- When node B sends the CTS to node A, node C is busy receiving on another channel, and thus it does not hear the CTS.
- Node C initiates a communication with node D, and end up selecting channel 2.
- This results in a collision at node B.



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Hidden Node Problem in Multichannel MAC

- This problem occurs because the nodes may listen to different channels, which makes it difficult to use "virtual carrier sensing" (RTS/CTS scheme) to avoid the hidden node problem.

- Since if each node would listen just to one channel, node C would have heard the CTS and thus deferred its transmission.

- The described problem is named the multi-channel hidden problem.

Access Negotiation

Scheme Type

- Access negotiation schemes in multichannel MAC protocols fall into two categories:
  - Narrow band;
  - Wide band.

- With Narrow band transmitter and receiver, the frequency band to be used for transmission can be predetermined, or dynamically chosen.

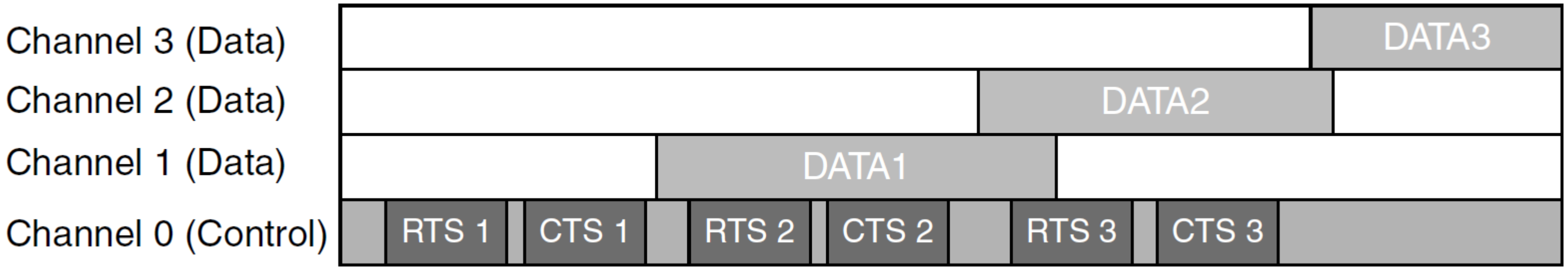
- With a wideband system, the transmitter can transmit over multiple frequency bands that are detected to be unoccupied.

- In a wide band system, each device may need more than two radios to achieve the parallel transmissions over multiple bands/channels, whereas it may require less than two radios in narrow band systems.

Access Negotiation

Narrow Band Dedicated Control Channels

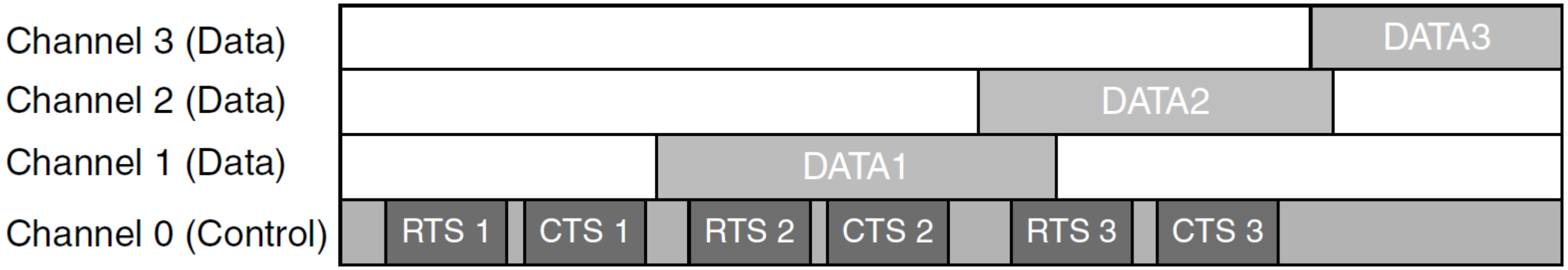
- In this solution, a protocol assigns channels dynamically, in an on-demand style.
- This protocol is called Dynamic Channel Assignment (DCA), they maintain one dedicated channel for control messages and other channels for data.
- Each host has two transceivers, so that it can listen on the control channel and the data channel simultaneously.
- RTS/CTS packets are exchanged in the control channel while data packets are exchanged in the data channel.



Access Negotiation

Narrow Band Dedicated Control Channels

- In the RTS packets, the sender includes a list of preferred channels.
- On receiving the RTS, the receiver decides on a channel and includes the channel information in the CTS packet.
- Then Data and ACK packets are exchanged in the agreed data channel.
- Since one of the two transceivers is always listening on the control channel, the multichannel hidden terminal problem does not occur.



Access Negotiation

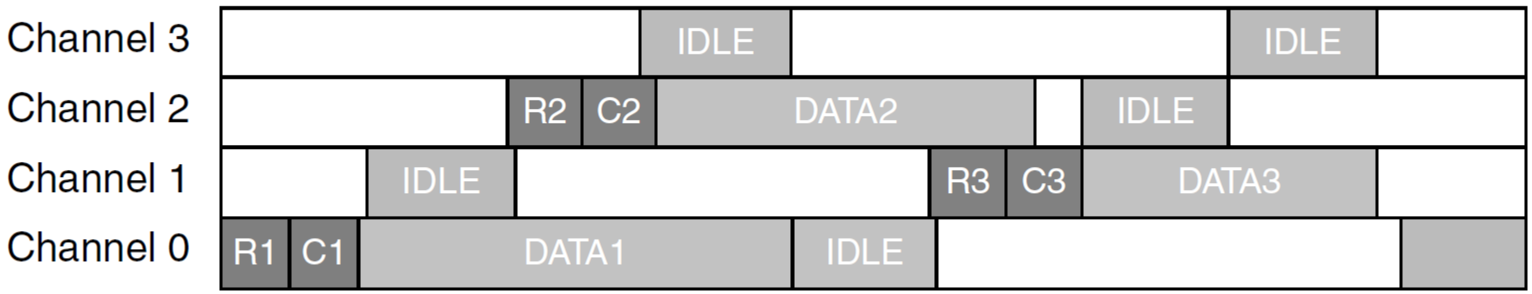
Narrow Band Dedicated Control Channels

- This protocol does not need synchronization and can use multiple channel with little control message overhead.
- It does not perform well in an environment where all channels have the same bandwidth. When the number of channels is small, one channel dedicated to control messages is costly.
- In the case of IEEE 802.11b, only three channels are available, and so having one control channel results in 33% of total bandwidth as the control overhead.
- If the number of channels is large, the control channel can become a bottleneck and prevent data channels from being fully utilised.

Access Negotiation

Narrow Band Common Hopping

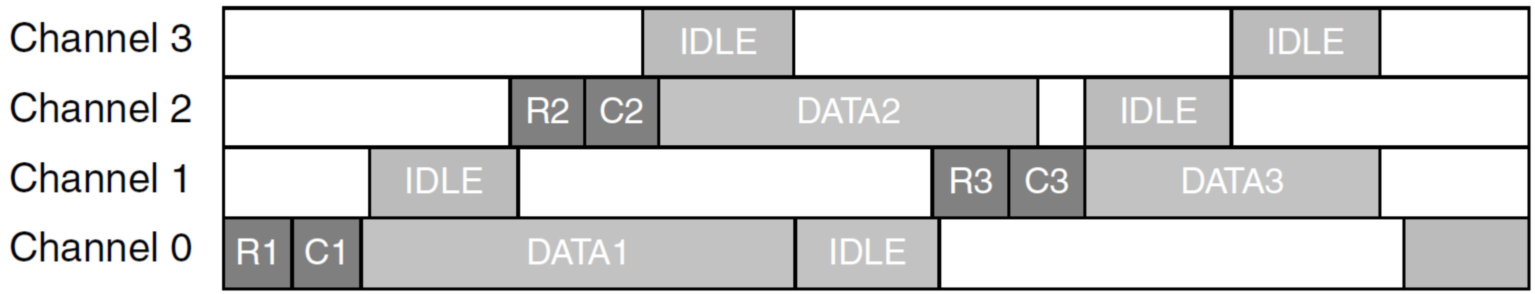
- The idea of hopping protocols is to use the hopping nature to separate the traffic into multiple channels/bands.
- Hop Reservation Multiple Access is a multichannel protocol for networks using the slow frequency hopping spread spectrum (FHSS).
- The nodes hop from one channel to another according to a predefined hopping pattern.



Access Negotiation

Narrow Band Common Hopping

- When two nodes agree to exchange data by an RTS/CTS handshake, they stay in the current frequency hop for communication, while the other nodes continue to hop.
- More than one communication can take place on different frequency hops.



Access Negotiation

Narrow Band Common Hopping

- Receiver Initiated Channel Hopping with Dual Polling takes a similar approach, except that the receiver initiates the collision avoidance handshake instead of the sender.

- These schemes can be implemented using only one transceiver for each host, but they only apply to frequency hopping networks, and cannot be used in systems using other mechanisms such as direct sequence spread spectrum (DSSS) communications.

Access Negotiation

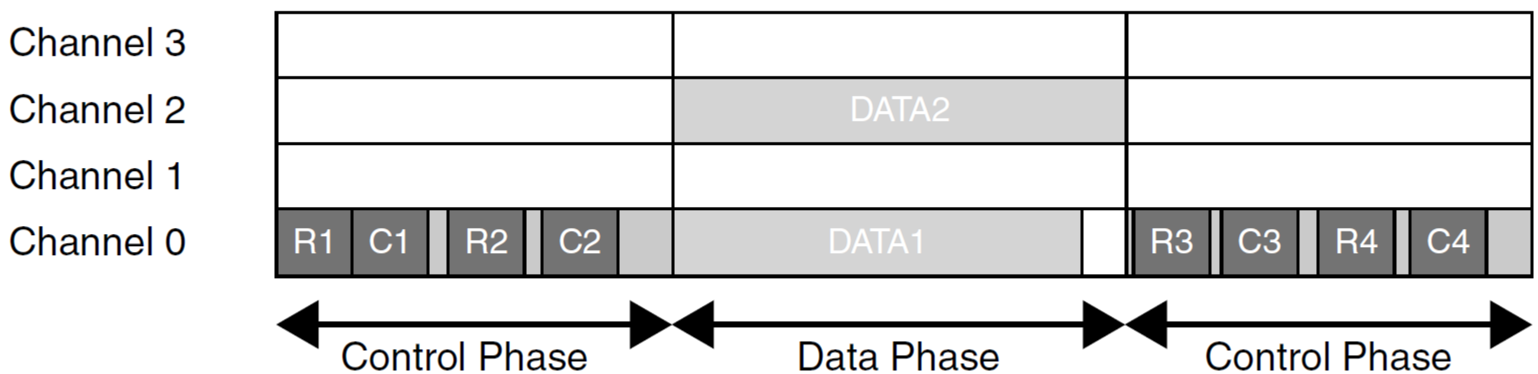
Narrow Band Split Phase

- The nodes use a single radio.
- Time is divided into an alternating sequence of control and data exchanges phases.
- During control phase, all devices tune to the control channel and attempt to make agreements for channels to be used during the following data exchanging phase.
- If device A has some data to send to device B, it sends a packet to B on the control channel with the ID of the lowest numbered idle channel, say, i.
- Device B then returns a confirmation packet to A.
- So A and B have agreed to use a channel, in the upcoming data phase.

Access Negotiation

Narrow Band Split Phase

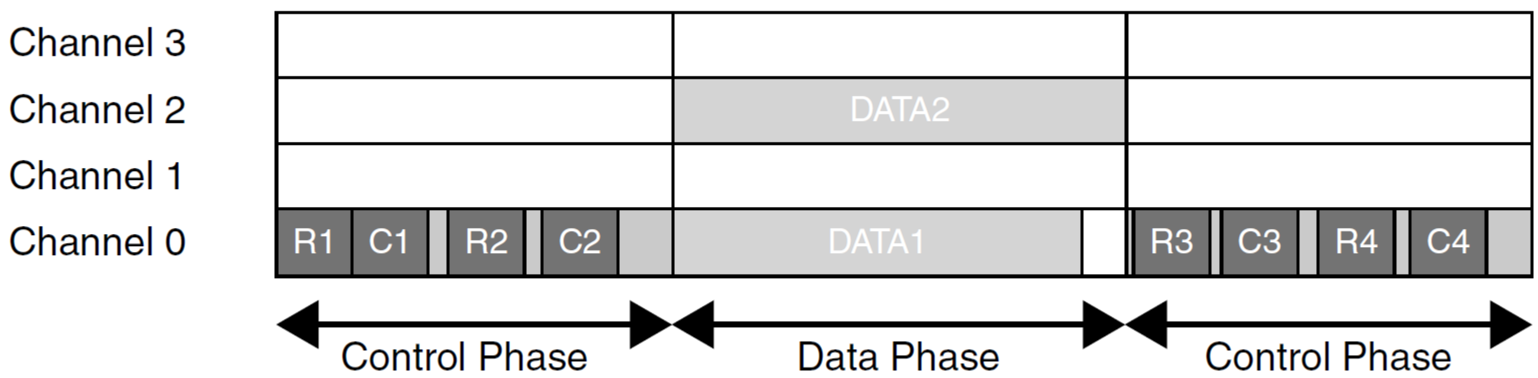
- Once the node is committed, it cannot make any other agreements that conflict with earlier agreements.
- When hidden nodes are prevalent, the sender and the receiver might have very different views of which channels are free.
- A more sophisticated agreement is then needed, see MMAC



Access Negotiation

Narrow Band Split Phase

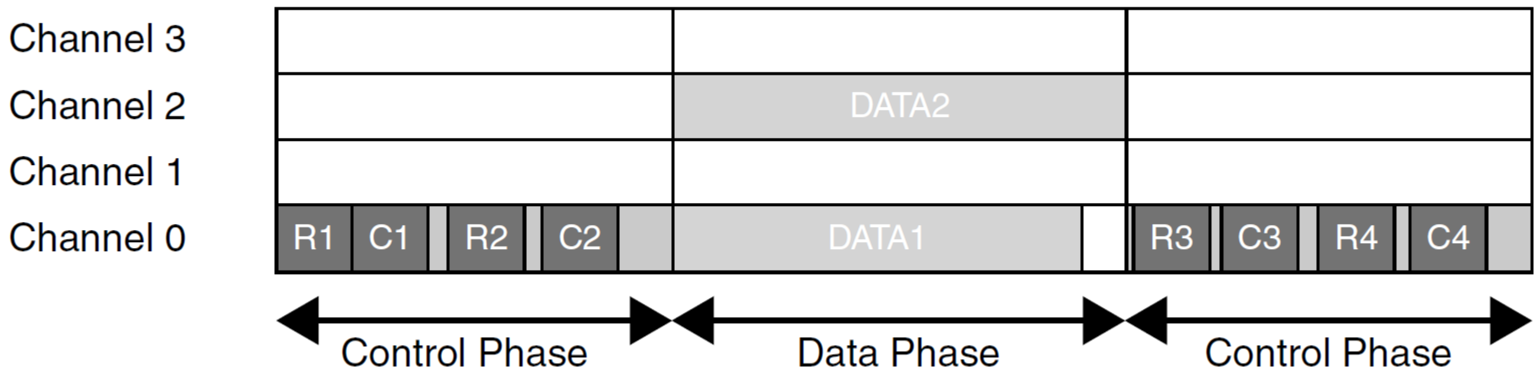
- In the second phase, the nodes tune to the agreed channel and start the data transfer.
- The protocol allows for multiple pairs of nodes to choose the same channel because each pair might not have enough data to use up the entire data phase.
- So, the different nodes need to either schedule themselves or contend to access the channel.



Access Negotiation

Narrow Band Split Phase

- The advantage of this approach is that it requires only one radio per node.
- It requires time synchronization among all nodes, although the synchronization can be looser than in Common Hopping because devices hop less frequently.



Access Negotiation
Narrow Band Others

- Hybrid
  - These consider the multichannel multi-radio channel assignment and interfaces assignment in a multi-layer approach

- Slotted Seeded Channel Hopping
  - Each node follows his own channel hopping sequence, existing as many hopping sequences as the number of nodes. Each sequence is uniquely determined by a uniquely seed of a pseudorandom generator. Each node picks multiple sequences and follows them in a time-multiplexed manner.
  - When A wants to talk with B, A waits until on the same channel as B. If A frequently wants to talk to B, A adopts one or more of B´s sequences, thereby increasing the time they spend on the same channel. For this mechanism to work, the sender learns the receiver´s current sequences via a seed broadcast mechanism.

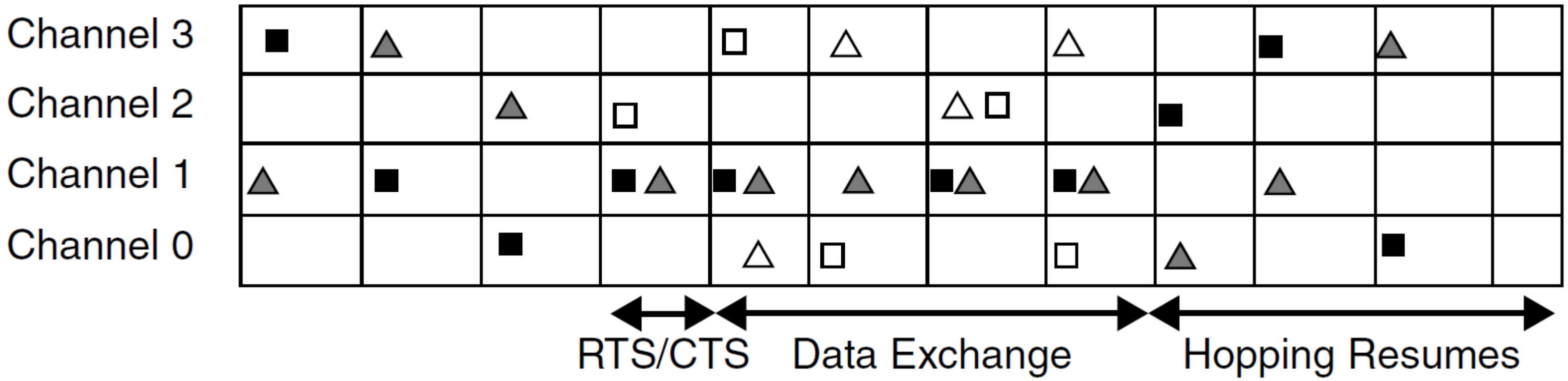
Access Negotiation

Narrow Band Multi Channel MAC

- Each node picks a seed to generate a different pseudorandom hopping sequence.

- When a node is idle, it follows its “home” hopping sequence. Each node puts its seed in every packet that it sends, so its neighbours eventually learn its hopping sequence.

- But, the node are not required to align their hopping boundaries in practice.

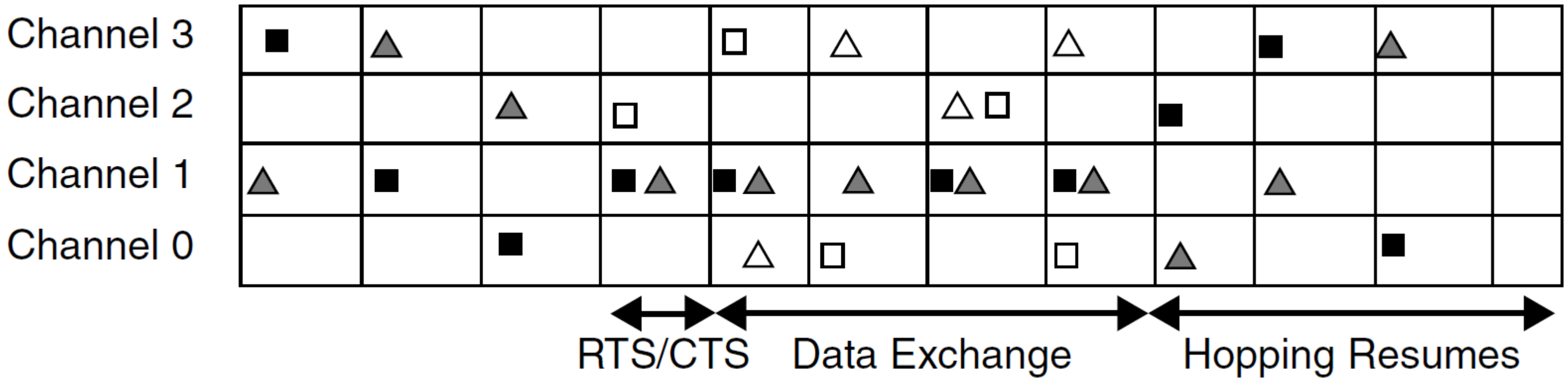


Access Negotiation

Narrow Band Multi Channel MAC

- When node A has data to send to node B, A flips a coin and transmits with some probability p during each time slot. If it decides to transmit, then it tunes to the current channel of B and sends an RTS. If B replies with a CTS, both A and B stop hopping to exchange data. Data exchange normally takes place over several time slots.

- After the data exchange is over, A and B return to their original hopping sequence, as if no pause in hopping had happened.



Access Negotiation

Narrow Band Multi Channel MAC

- The SSCH and McMAC are similar since they allow nodes to rendezvous simultaneously on different channels.

- They differences are:
  - In SSCH, each node selects four different hopping sequences and time multiplexes them to form a single hopping sequence. Nodes adapt their hopping sequences over time to the traffic but are not allowed to deviate from their hopping sequences. In SSCH, a sender must wait until its current channel overlaps with that of the receiver before it can send data.
  - In McMAC, each node has one hopping sequence, which never changes. However, nodes are allowed to deviate from their default hopping sequence temporarily to accommodate sending and receiving. In McMAC, the sender can temporarily deviate from its sequence to jump to the receiver's channel to send.

Access Negotiation

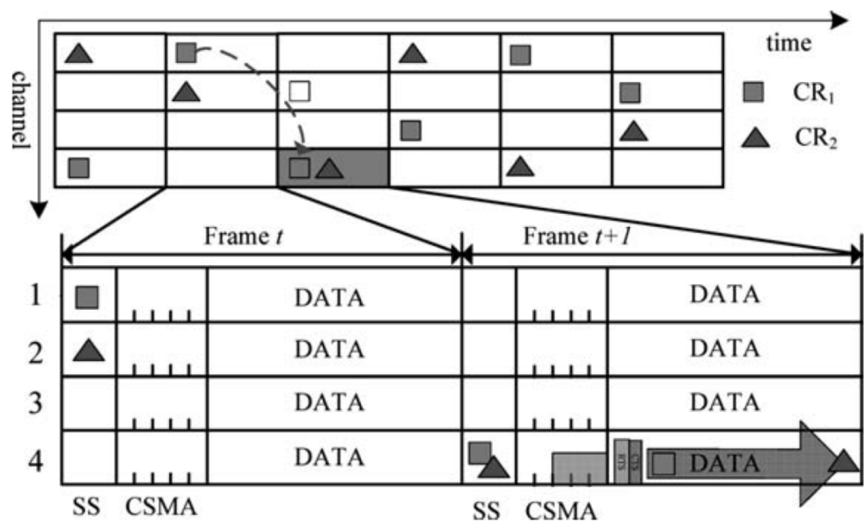
Narrow Band Cognitive Multi Channel MAC

- Following the idea of cognitive radio, nodes should be able to sense the environment and reconfigure its structure. The cognitive multichannel MAC appears as an enhanced version of McMAC.

- Every protocol operating frame is divided into three phases: the spectrum sensing (SS) phase, the CSMA contention phase and the data transmission phase.

Access Negotiation
Narrow Band Cognitive Multi Channel MAC

- In the cognitive Multichannel MAC, devices are able to sense the outer environment, the information of the network and the information of other interference resources (i.e., primary systems). After gathering and exchanging such information, nodes are able to set transmission probabilities to maximum the system throughput.



Access Negotiation

Wide Band CDMA

- The idea of using the CDMA approach in the multichannel system is simple. Instead of using divided bands, these kind of protocols utilize the orthogonal property of CDMA as ‘multiple channels’.

- By different spreading codes, nodes are able to transmit in different rates, that is, a shorter code represents a larger bandwidth just like wideband CDMA cellular.

- However, the main drawback of this approach is that it is almost impossible to have the global codeword information and the efficiency is low.

Access Negotiation

Wide Band M-channel selection

- Nasipuri et al. proposed a multi-channel CSMA protocol with ‘soft’ channel reservation.
- If there are N channels, the protocol assumes that each host can listen to all N channels concurrently. A host wanting to transmit a packet searches for an idle channel and transmits on that idle channel.
- Among the idle channels, the one that was used for the last successful transmission is preferred.
- The protocol can be extended to select the best channel based on the signal power observed at the sender.
- These protocols require N transceivers for each host, which may be a concern.

Access Negotiation

Wide Band Frequency Coding

- This is an enhanced version of the M-channel selection protocol. Within a wideband system, the transmitter can transmit over multiple frequency bands that are detected to be unoccupied, i.e., signals/codewords are sent over several frequencies.

- The receiver monitors all the frequencies that are detected to be available at its end.

- Please note that such a frequency coding scheme, unlike frequency hopping, requires the channel availabilities in all the different frequency bands before every transmission.

- The main drawback of the N-transceiver requirement remains, as in M-channel selection.

Access Negotiation

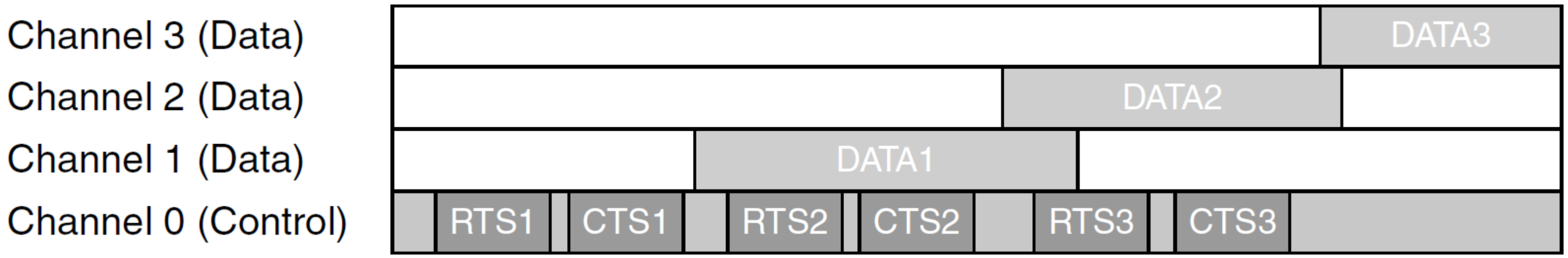
Wide Band Frequency Cooperation

- This is a new multichannel MAC protocol combining two prospective ideas: multichannel and cooperative communication.
- One of the open questions in the multichannel problem is the asymmetric nature: some channels are better for transmission. However, another question lies in the routing: what if the destination is not the neighbor?
- The two questions can be considered to be the same question: which channel/device to send?
- Cooperative communication/networks have been proven that will improve the throughput performance by repeat/relay of the information from the transmitter

Access Negotiation

Wide Band Frequency Cooperation

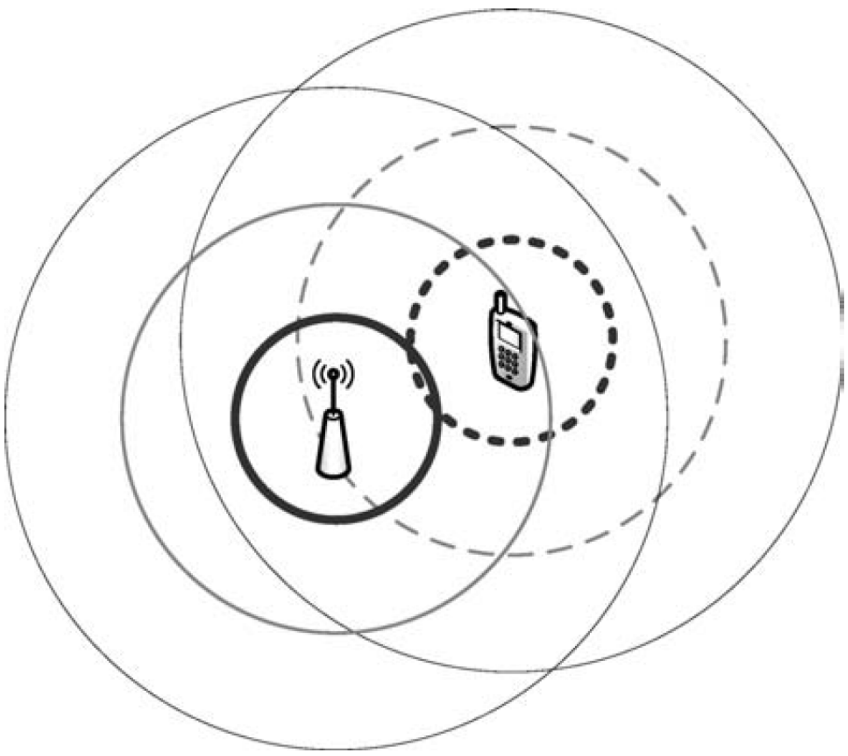
- The general MAC design follows the dedicated control channel scheme where each device is assumed to have radio/interfaces.
- Note that the data transmits on different channels with different rates. The multichannel hidden terminal problem is solved because every node continuously listens to the same control channel.
- In the practical MAC design, there are two types of transmissions: cooperative channel selection or direct transmission. The selection of different types is determined by the minimum transmission time/delay or the maximum throughput.



Access Negotiation

Wide Band Frequency Cooperation

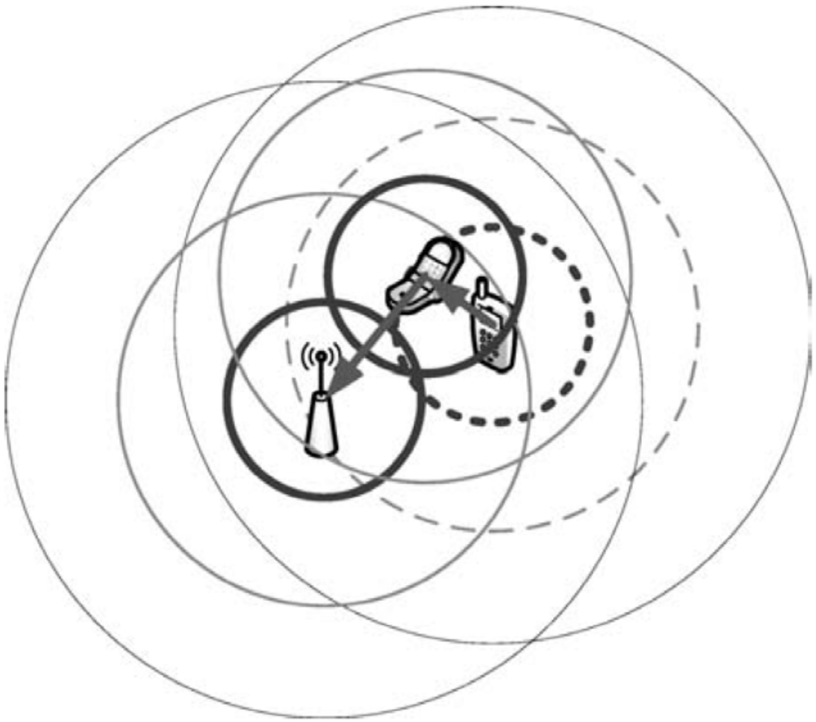
- The different circles indicate the different transmission channel/systems.
- In this case, the lighter-colored channel is used as the selected channel.
- If there is more communication in the lighter-colored channel/system, then the dark-colored channel/system is selected as the communication channel/system.



Access Negotiation

Wide Band Frequency Cooperation

- The transmitter may calculate the expected transmission time. If there is a cooperative node in a high transmission rate channel/system, it sends a request for help.
- If the cooperative node replies with accessibility of cooperation, the transmitter will send the data to the cooperative node, and the cooperative node will help the relay. The locations/status of these nodes result in different types of cooperation.
- In the figure the overall time is saved.



Access Negotiation

Wide Band Frequency Cooperation

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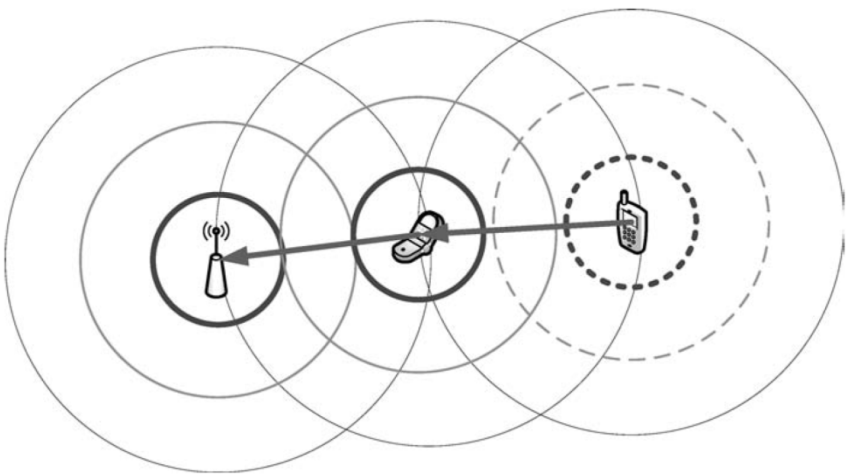
- If the cooperative node replies with accessibility of cooperation, the transmitter will send the data to the cooperative node, and the cooperative node will help the relay. The locations/status of these nodes result in different types of cooperation.
- In the figure the transmitter is able to access the node out of its transmission range.



Spectrum Sensing

Assignment

- Choose a scenario of primary system (TV bands, Cellular, WiFi, etc…)
- Choose an architecture to your CR network (Cellular, Ad-hoc, Mesh, etc…)
- Choose which kind of individual detector you would use. Explain why.
- Would you use cooperative sensing? Why?

Wireless Technology for Autonomic Networks-Part 2

July 4, 2011

PhD School on Information Engineering

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Outline

Center for TeleInFrastruktur

Part 2: Specific Technologies and Challenges

- Spectrum access and sharing
- Cognitive Radio Networks:
  - Protocol Architectures for Cognitive Networks
  - Routing;
  - Security
  - CRN and the Internet
- Self-Organisation

COGNITIVE RADIO NETWORKS

Protocol Architectures for Cognitive Networks

Routing;

Security;

Cognitive Radio Networks

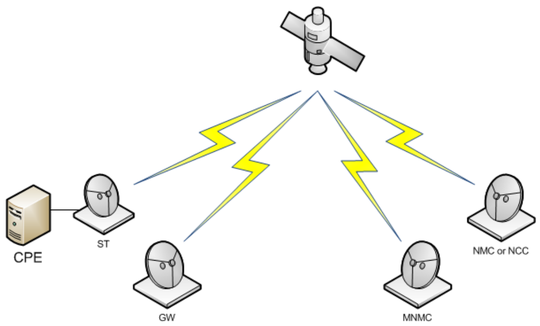
The concept

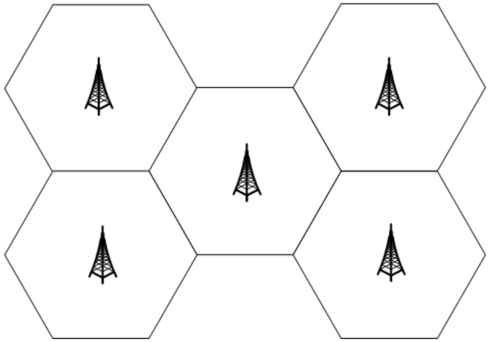
- The CRN is generally a heterogeneous wireless network (with part wired network), which fundamentally differs from ad-hoc or sensor networks.

Cognitive Radio Network Architecture

Traditional Wireless Networks

- Infrastructure / Satellite / Cellular Wireless Network





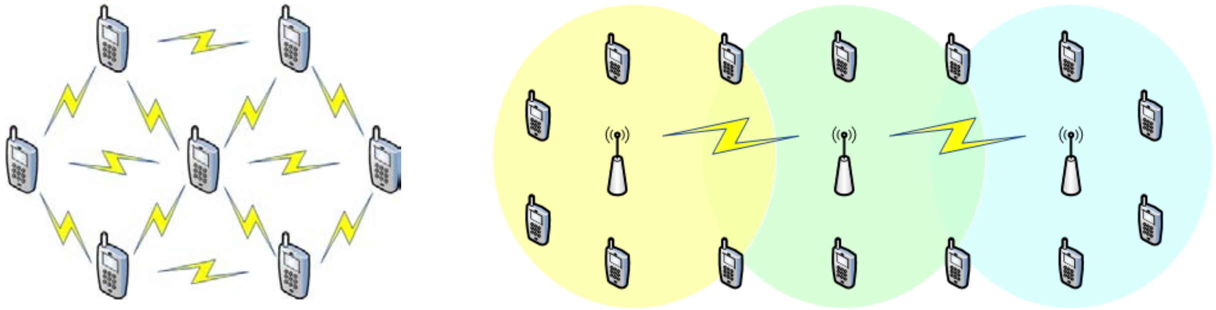
- Tends to be hierarchical, meaning that there are base stations which serve a large number of user nodes, in a point to multipoint fashion.

- Unless there is multi-hop, routing is not needed, at least in the wireless links. If there is the routing is normally of the hierarchical type.

Cognitive Radio Network Architecture

Ad Hoc Networks

- Ad-hoc/Mesh Wireless Network



- Tends to be decentralized, meaning that each of the nodes has the same functionalities than the others.

- The routing tends to follow a flat approach, although when clusters are created it might follow a hierarchal one.

Medium Access Control

COGNITIVE RADIO NETWORKS

Medium Access Control

Enabler of CR

- The simplest concept behind the CR operation is:
  - Detect an opportunity to transmit though spectrum sensing, i.e. Identify the “Spectrum Holes”;
  - Access the spectrum dynamically (known as Dynamic Spectrum Access, DSA).
- The Medium Access Control allows to coordinate multiple network nodes to access the shared medium in an opportunistic way.
- Allowing the Cognitive Radio to act as a network, i.e. to go further than just perform dynamic spectrum access for opportunistic transmission at the link level.

Medium Access Control

What is its purpose?

•How to use the identified the “Spectrum Holes”!

•How can Cognitive Radio Network use them to communicate?

Medium Access Control

Cognitive Radio Network Architecture

- The type of network architecture dictates which kind of Medium Access Control mechanism are employed.

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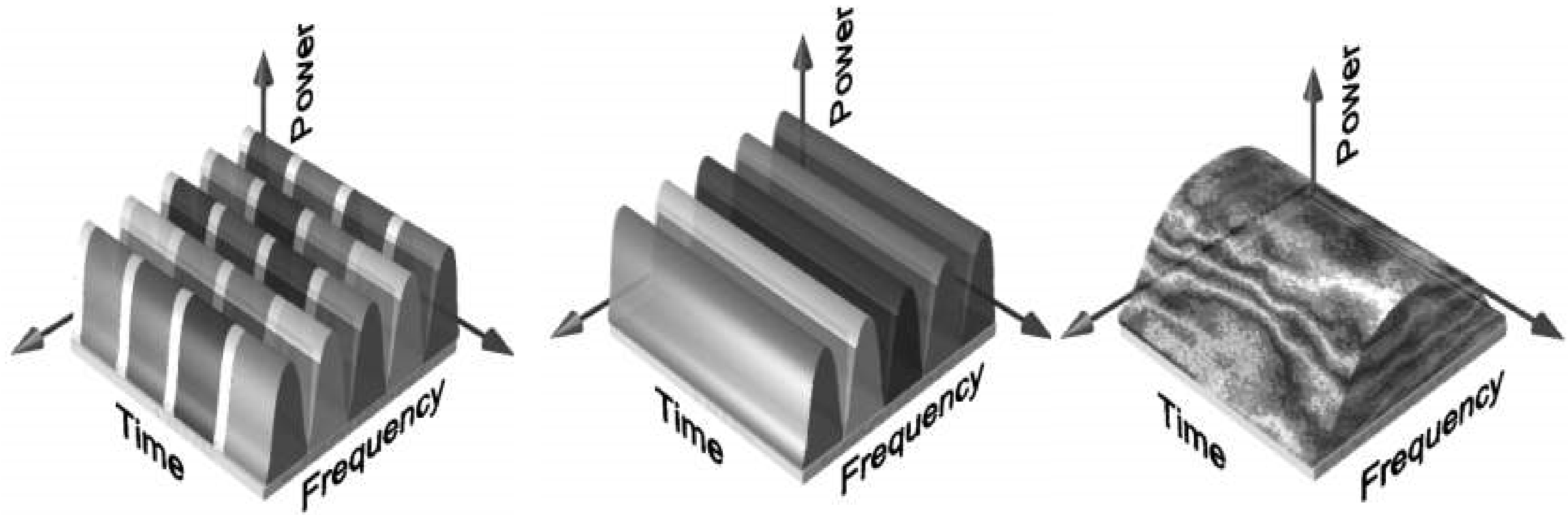
Medium Access Control

Channel Access Methods

- Fixed Mode Channel Access Methods
  - Where two network nodes establish a dedicated communications channel (circuit) connecting them for the duration of the communication session before the nodes may communicate.
  - Each node is allocated a fixed fraction of bandwidth; equivalent to circuit switching; very inefficient for low duty traffic.
  - Requires a synchronization mechanism.



From: http://www.skydsp.com/publications/4thyrthesis/chapter1.htm

The Network Layer

COGNITIVE RADIO NETWORKS

Network Layer

The Role of Routing

- After the Cognitive Radios (CRs) have established the links for opportunistic transmissions, the core function of a cognitive radio network (CRN) lies in the network layer.
- The main focus of the network layer, is on how to perform the routing of packets between the network nodes.
- There are many design issues affecting routing: flow control, network radio resource management and network mobility management.

Network Layer

Routing in Mobile Ad-hoc Networks

- Mobile Ad-hoc Networks (MANET) are a sort of multi-hop packet radio network.

- MANET are composed by a collection of mobile nodes communicating over wireless links without infrastructure.

- Due to potentially shorter-range for direct radio communications than network coverage, a MANET relies on multi-hop to transport the packets, and therefore each node acts as a router.

Network Layer

Routing in Mobile Ad-hoc Networks

- Routing protocols are based on either link-state or distance vector algorithms aimed at identifying optimal routes to every node in the network.

- When there are frequent topological changes, the routes need to be updated periodically.

- But these route updates use significant portion of the available bandwidth as well as energy.

Network Layer

Routing in Mobile Ad-hoc Networks

- Routing protocols can be generally categorized as *proactive* or reactive, depending on whether the protocol continuously updates the routes or reacts on demand.
- Proactive protocols, are also known as table-driven protocols, determine continuously the network connectivity and the already-available routes to forward a packet.
- This kind of routing protocol is infeasible to frequently re-configurable mobile networks such as CRN, due to the extreme dynamics of affecting the available links.

Network Layer

Routing in Mobile Ad-hoc Networks

- Reactive protocols, also known as *on-demand* protocols, invoke determination of routes only when it is needed (i.e., on-demand).

- There are two well known reactive protocols: *dynamic source routing (DSR)* and *ad-hoc on demand distance vector (AODV)*.

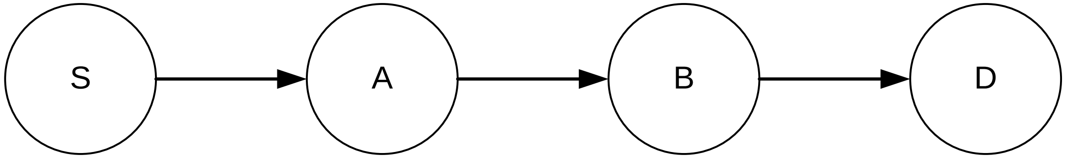
- When a route is needed, reactive protocols conduct some sort of global search such as flooding, at the price of delay to determine a route, but reflecting the most updated network topology (i.e., availability of links).

Dynamic Source Routing

Route Discovery

- DSR is an on-demand ad-hoc routing protocol that uses a route discovery cycle to search routes. DSR uses source routing and each node maintains a complete topology of routes in its route cache

Destination	Route Cache
D	{S,A,B,C,D}
….	….



Dynamic Source Routing

Route Discovery

- When a source node needs to transmit data packets to a certain destination and has no route in its route cache, it will initiate a route discovery procedure.
- The source node first prepares a Route Request (RREQ) packet.
- This packet contains the Source ID, the Destination ID, a unique Request ID, the value of Maximum Hops and a Node List listing the address of each intermediate node through which the RREQ has been forwarded

RREQ
Source ID
Destination ID
Request ID
Max. Hops
Node List Node_1 Node_2 ...

(a) Data structure of RREQ

Dynamic Source Routing

Route Discovery

- The task of the destination node is simply to tell the source node which route is valid for routing.
- Thus, it prepares a Route Reply (RREP) message, which contains the accumulated route record in the RREQ just received.

RREP
Request ID
Route List Route_1 Route_2 ...

(b) Data structure of RREP

Dynamic Source Routing

Properties

- The RREP is not necessarily forwarded through the reverse order of the path that the RREQ has passed through.

- If each intermediate node only re-broadcasts the first received RREQ of the RREQs that belong to the same route discovery, no route loop can be formed.

- If no duplicated RREQs can be re-broadcast, two routes are node-disjoint if they have different first hop nodes.

Dynamic Source Routing

Properties

- If no duplicated RREQs can be re-broadcast, two routes can only separate once and have no intersection.
- If re-broadcasting duplicated RREQs is allowed but each node checks the Node List and drop RREQs if they are in the list, no loops can be formed and any route that is within Maximum Hops (maximum time-to-live (TTL)) can possibly be discovered.
- If using the Node List scheme, except for those nodes before the first separation of paths, a node that is passed by k different paths needs to re-broadcast duplicated RREQs k times.

Ad Hoc On Demand Distance Vector (AODV)

Route Discovery

- AODV is an on-demand ad-hoc routing protocol and routes are discovered by a route discovery cycle.

- AODV uses hop-by-hop routing, which means routing information is distributed over network nodes.

- Each node only maintains the next-hop node in its routing table.

Destination	Next Hop	Distance
D	A	3
...	...	...

Destination	Next Hop	Distance
D	D	1
...	...	...

Destination	Next Hop	Distance
D	B	2
...	...	...

AODV

Properties useful for CRN

- In AODV, the Route Reply (RREP) must be forwarded through the reverse order of the path that the RREQ has passed through.
- The basic AODV can only discover node-disjoint routes.
- AODV can only work in bidirectional networks if no bidirectional link abstraction or unidirectional link elimination mechanisms are performed.

Routing in CRN

Routing Challenges

- There are different challenges between routing of CRNs and routing of wireless ad-hoc (or sensor) networks.
- CRN links are available under the idle duration of the primary system(s) so that DSA can effectively fetch such opportunities, after the spectrum sensing.
- So the links in CRNs are stochastically available in general, which allows the CRN topology to be random even when all nodes are static.

Routing in CRN

Routing Challenges

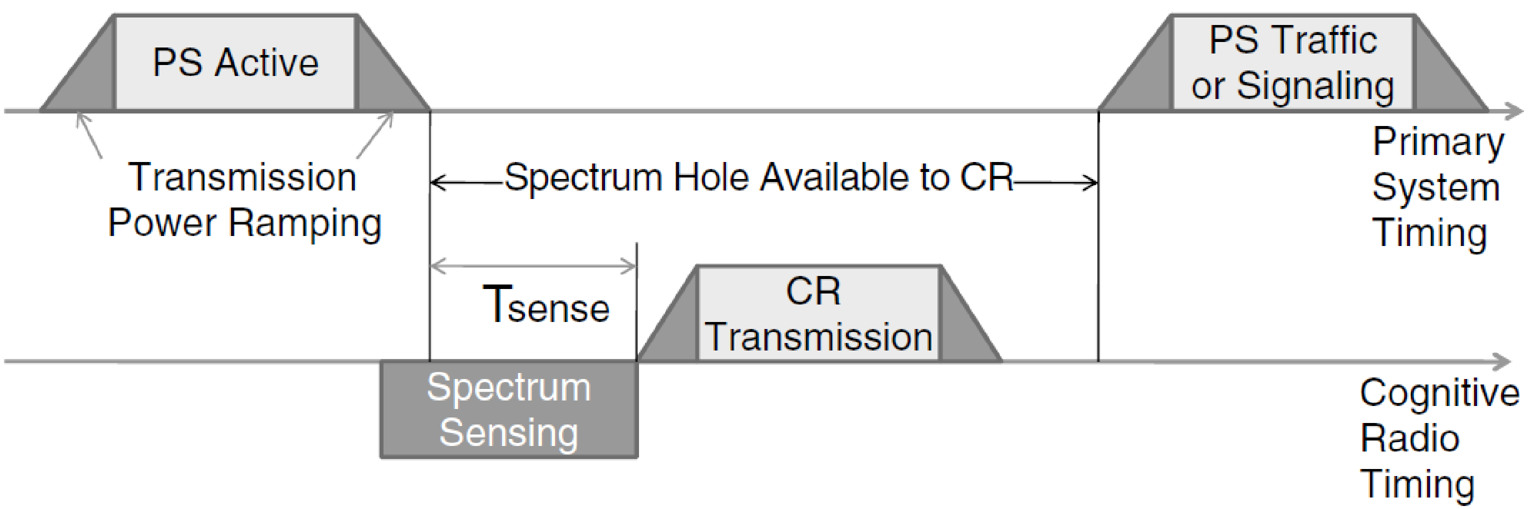
- Although wireless ad-hoc networks and sensor networks have similar phenomena, links in the CRN can vary much more rapidly because link available duration is only a fraction of the inter-arrival time for traffic and control signaling packets.
- The link available period in the CRN is in the range of *milliseconds*, instead of seconds, minutes, hours or even days, as in its wireless networking counterparts.

Routing in CRN

Routing Challenges

- To ensure a CRN link is available for network layer functioning, we go back to the hardware operation of accessing the available channel.

- Assuming the CRN operation is observed for both the primary system (PS) and the CR, the CR must use the spectrum hole window to complete packet(s) transmission.



Routing in CRN

Routing Challenges

- **Traditional wireless networks have bi-directional links.**

- In wireless ad-hoc and sensor networks, unidirectional links might be possible due to the asymmetric transmission power and/or different interference levels at receivers.

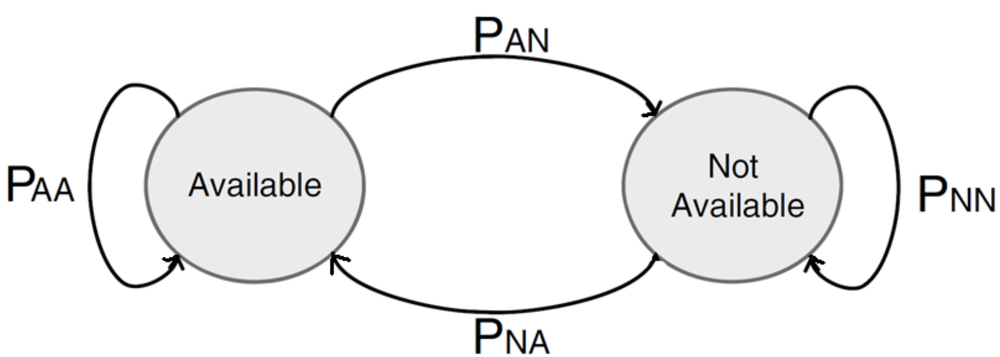
- In CRNs, unidirectional links occur due to the fact that a CR node may just have an opportunity to transmit in one time duration and there is no guarantee to allow the opportunity for transmission from the other direction.

- Or a CR node wants to leverage an existing PS to (cooperatively) relay packets, but the other direction might not be permitted, and vice versa.

Routing in CRN

Routing Challenges

- The availability of a link in a CRN can be modeled as an embedded continuous-time Markov chain, where the rates can be obtained from the statistics gathered from the spectrum sensing.



Routing in CRN

Routing Challenges

- A link between node X and node Y in the CRN can define two unidirectional links X -> Y and Y <- X.

- The link can be modeled as a 2-state embedded Markov chain model, allowing to study the nature of the network layer functions for the CRN, and thus effective design, under the challenges of link availability and unidirectional links.

Routing in CRN

Routing and Security Challenges

- In contrast to typical wireless ad-hoc or sensor networks, CRNs are generally formed by heterogeneous wireless networks (co-existing primary systems and CR nodes to form ad-hoc networks).

- Inter-system handover is usually required for routing in such heterogeneous wireless networks.

- However, CR links might be available for an extremely short duration and the successful networking lies in cooperative relaying among such heterogeneous wireless networks.

- From the perspective of network security, the enabling of CRNs for spectrum efficiency in wireless networks at the price of losing security is debatable, because there is not enough time for a CR node to get a secure certificate within the short opportunistic window.

Routing in CRN

Trusted Cognitive Radio Networking

- Security in CRN lies on the ground of end-to-end nodes, and intermediate nodes in CRN (either CRs and/or nodes in primary systems) can simply forward the CR traffic packets (i.e., cooperative relay inside CRN).

- Such a cooperative relay of packets can be facilitated as amplify-and-forward (AF) and decode-and-forward (DF), while intermediate nodes in CRN have limited security treats by relaying packets.

- Compress-and-forward (CF) cooperative networking might jeopardize the security of the intermediate nodes due to mixing relay packets and own traffic together.

Routing in CRN

Trusted Cognitive Radio Networking

- A node in CRN and thus its traffic/control packets can be classified into <u>three</u> categories during the operation of CRN:
  - Secure
  - Trusted
  - Lure

Routing in CRN

Trusted Cognitive Radio Networking

- The node is <u>Secure</u>.
- The node executed a security check that is good throughout the entire heterogeneous wireless networks. The packets and messages from this node can go all the way in CRN with a secure clearance.
- A node classified as ‘secure’ can be a CR and a node in a co-existing PS.

Routing in CRN

Trusted Cognitive Radio Networking

- The node is <u>Trusted.</u>

- The node is not able to complete a security check of several rounds of the handshaking protocol within the timing window of an available link.

- The node generates packet(s) for opportunistic transmission, and the CR receiver node recognizes such source node as ‘trusted’ and can relay packets towards a CR sink node via the appropriate routing mechanism.

- A CR receiving node should always maintain a table of trusted/secure nodes, based on security checks and historical update.

- In other words, any node in the CR only allows reception of packets from its secure and trusted neighboring node. Such a table is localized and is not large in the number of neighboring nodes.

Routing in CRN

Trusted Cognitive Radio Networking

- The node is a Lure.

- The node is neither secure nor trusted by its target receiving node, and it is classified as ‘lure’.

- The major reason to be rated as lure shall be from bad historical actions, such as spreading virus, wasting bandwidth in a wireless network, attacking wireless network, selfish behaviors, etc.

- Such a lure node actually loses its cognitive radio capability in practice of CRN operation

Routing in CRN

Trusted Cognitive Radio Networking

- To create a homogeneous networking functioning environment in a heterogeneous wireless network is necessary to introduce a trust mechanism

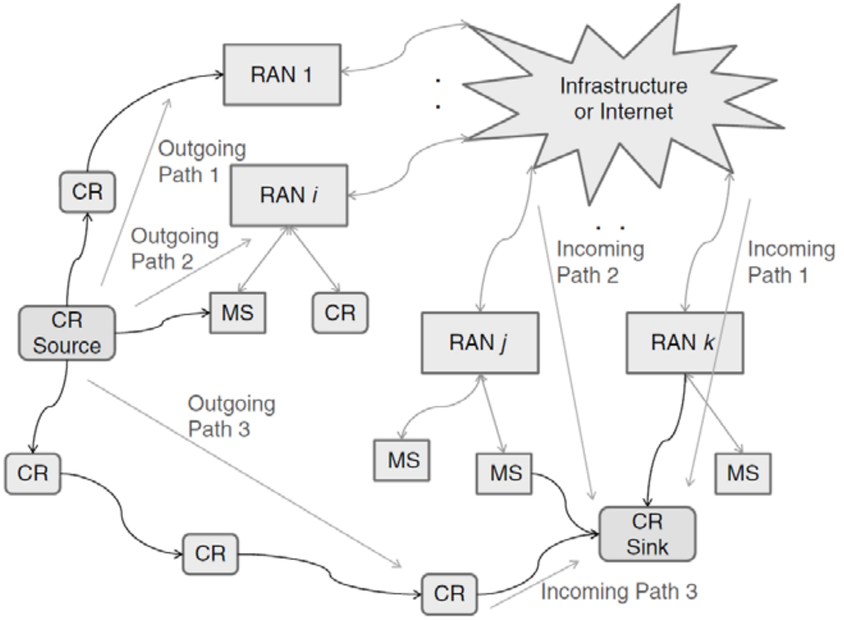
- Through this mechanism is then possible to cooperatively relay packets in spite of the opportunistic and extremely dynamic link availability of CRN, therefore creating a large scale of homogeneous multi-hop ad-hoc network under the same trust level across different wireless networks

Routing in CRN

Trusted Cognitive Radio Networking

- The CRN consists of CRs and nodes from various co-existing primary systems, which may operate using different communication parameters, in different frequency bands and in different geographical locations.

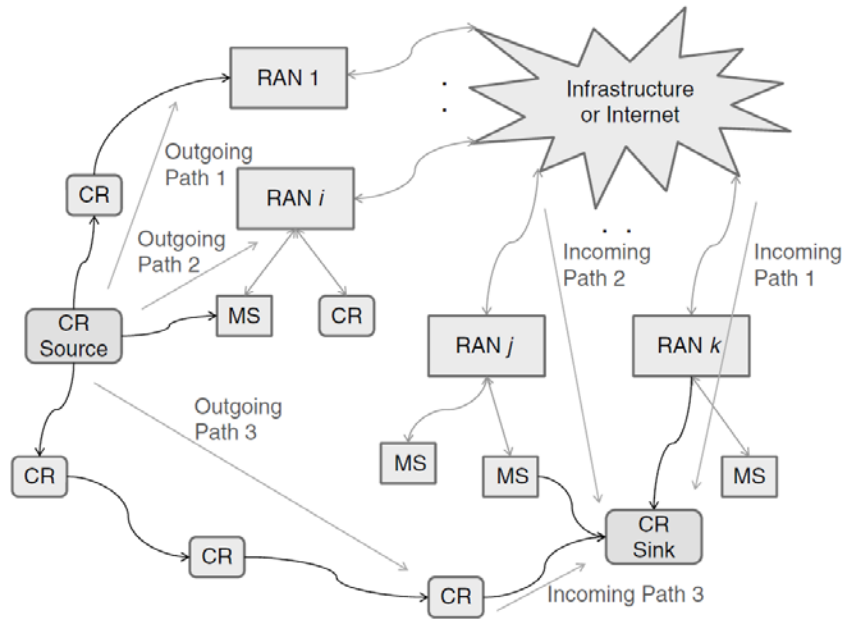
- SDR inside a CR is capable of reconfigurable realization for multiple systems operating at multiple frequency bands.



Routing in CRN

Trusted Cognitive Radio Networking

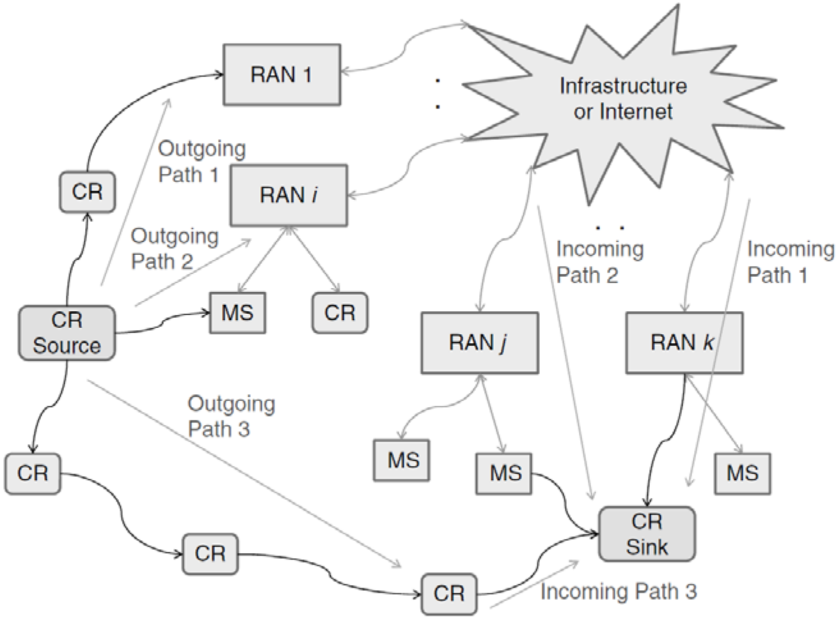
- The CR source node (initiation point of traffic) and CR destination (termination point of traffic) node should conduct their own end-to-end security beyond trust level by employing CRN nodes to complete bidirectional verification.



Routing in CRN

Trusted Cognitive Radio Networking

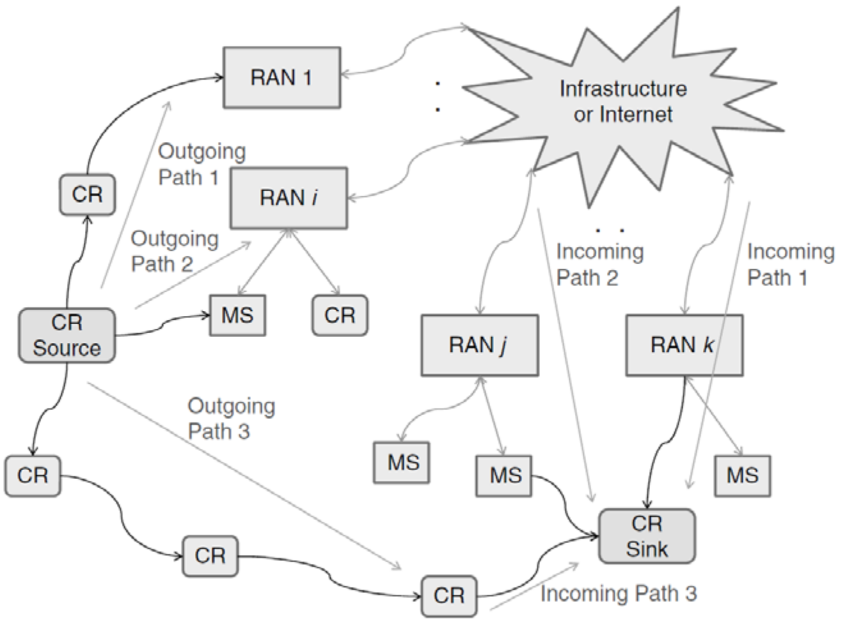
- CRN nodes are assumed to conduct only Amplify and Forward (AF) or decode and forward (DF) cooperative relaying, under the trust domain of CRN.
- Nodes in the secure domain may reject relays from trusted nodes, which suggests that such links are not available in trusted multi-hop packet radio network routing.
- Similarly, nodes in trusted domain (i.e., typical nodes in CRN) may reject connection requests from lure nodes.



Routing in CRN
Trusted Cognitive Radio Networking

- Any packet from a CR source node, once getting into a primary system or infrastructure, follows the operation of the primary system or infrastructure, to enjoy the benefits from existing systems and networks.

- Assume, for example, that a CR source node wishes to relay its packets through nearby WiFi to access a web site of the Internet, where nearby means radio accessibility as a kind of localization.

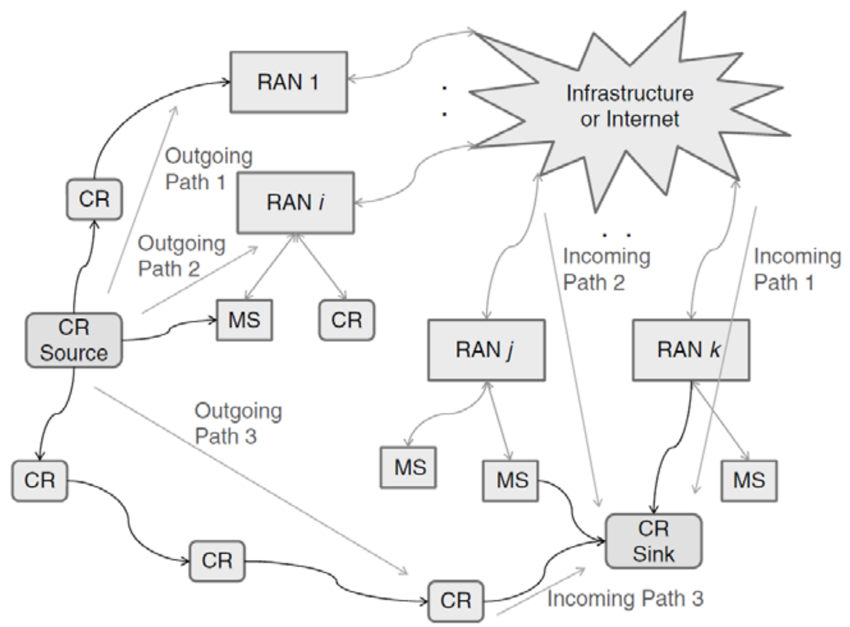


Routing in CRN

Trusted Cognitive Radio Networking

- As long as the packets from the CR source node are allowed to the access point of the WiFi, these packets transport as WiFi packets.

- A CR terminal device is therefore capable of conversion/re-configurability among multiple physical layer transmissions and multiple medium access control schemes.



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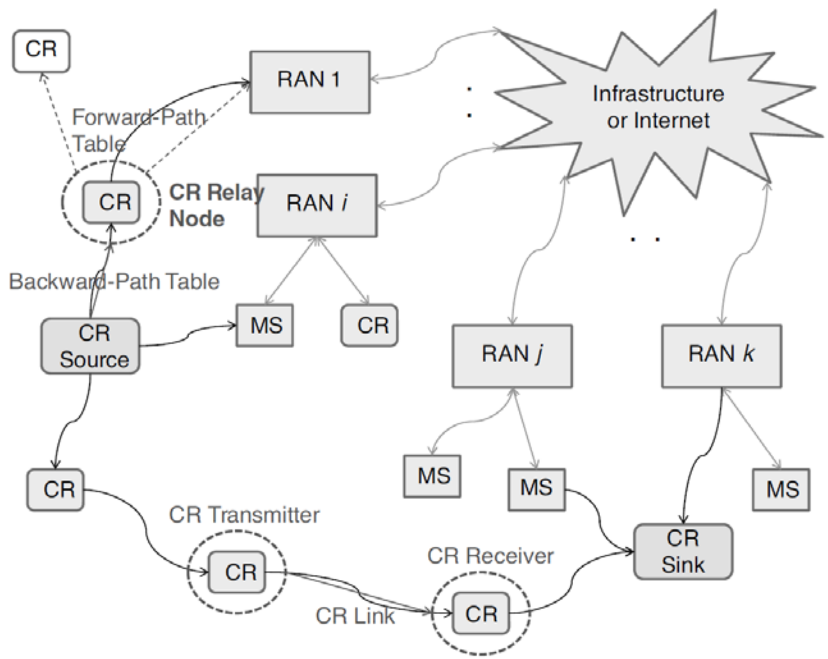
Routing in CRN

Routing of Dynamic and Unidirectional Links

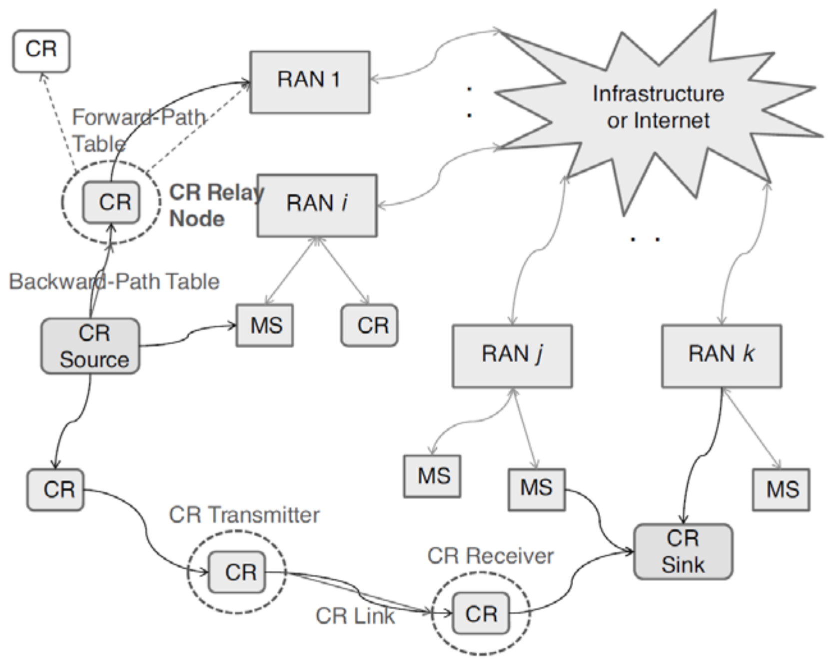
- To conduct CRN routing over unidirectional CR links and usually bidirectional links in the PS (mobile stations in the PS can form ad-hoc with possible unidirectional links) as per earlier descriptions, we can extend on-demand routing protocols of MANET for CRN routing.



Routing in CRN
Routing of Dynamic and Unidirectional Links

- Each CR link is modeled by a 2-state Markov chain, independent of other CR links.

- Without knowing the specific PS, all links in the PS are assumed to be bidirectional and can support the routing protocol. As a matter of fact, the entire behavior inside a PS can be treated as a 'link' by the queuing model of this PS if we just follow the PS operation.

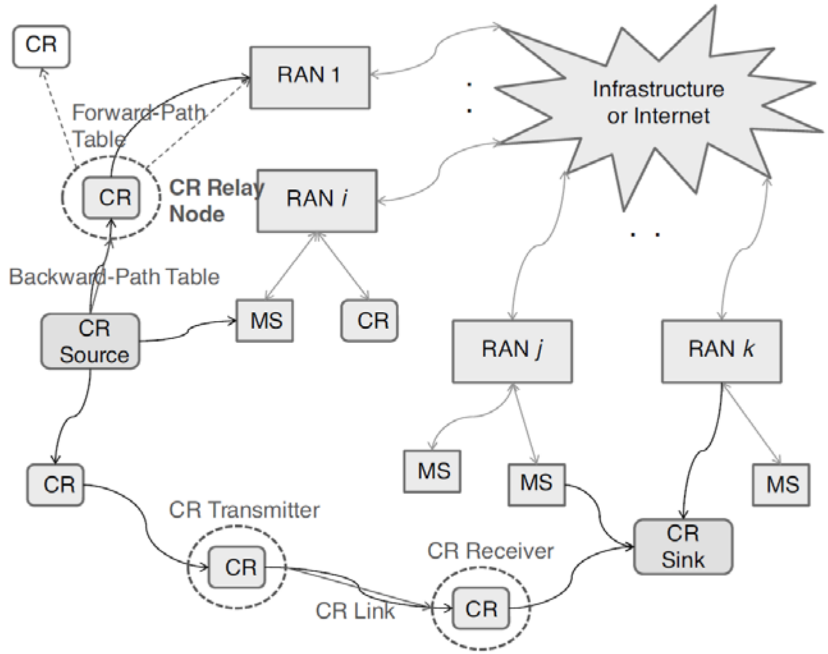


Routing in CRN

Routing of Dynamic and Unidirectional Links

- Typical MANET routing algorithms are trying to isolate unidirectional links, because they are likely to be very localized.

- However, unidirectional links are inevitable in CRN. Fortunately, we may assume the depth (i.e., number of hops) from CR to PS to be within D hops, due to their roles in wireless access to the infrastructure or purely ad-hoc.

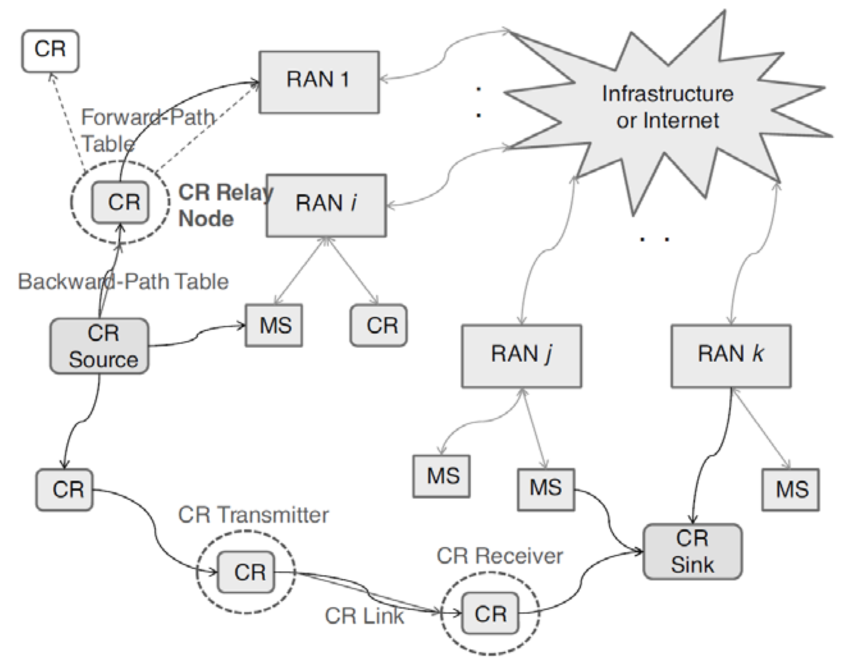


Routing in CRN

Routing of Dynamic and Unidirectional Links

- The fact of CR links being unidirectional is usually true at one instant. At the next instant, this CR link might be still unidirectional but reverse its direction depending on network situations.

- By introducing the trust mechanism, the CRN would function pretty much like an ad-hoc network with 'temporary' unidirectional links.

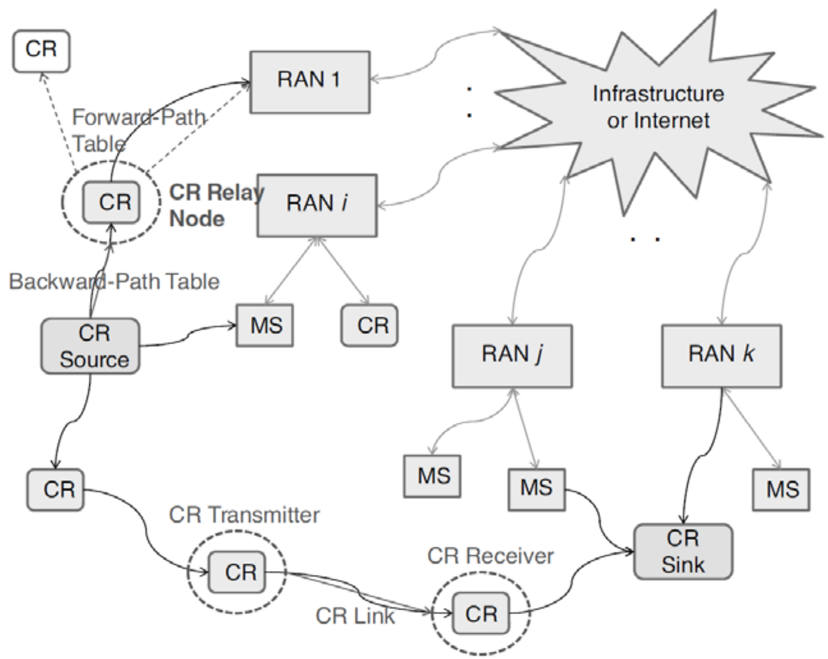


Routing in CRN

Routing of Dynamic and Unidirectional Links

- There are a few issues of which the CR routing needs to overcome.

- Since CR does not interfere with the PS(s), we should avoid the global or periodic advertisement of any CR node, though such advertisement is common in ad-hoc network routing.

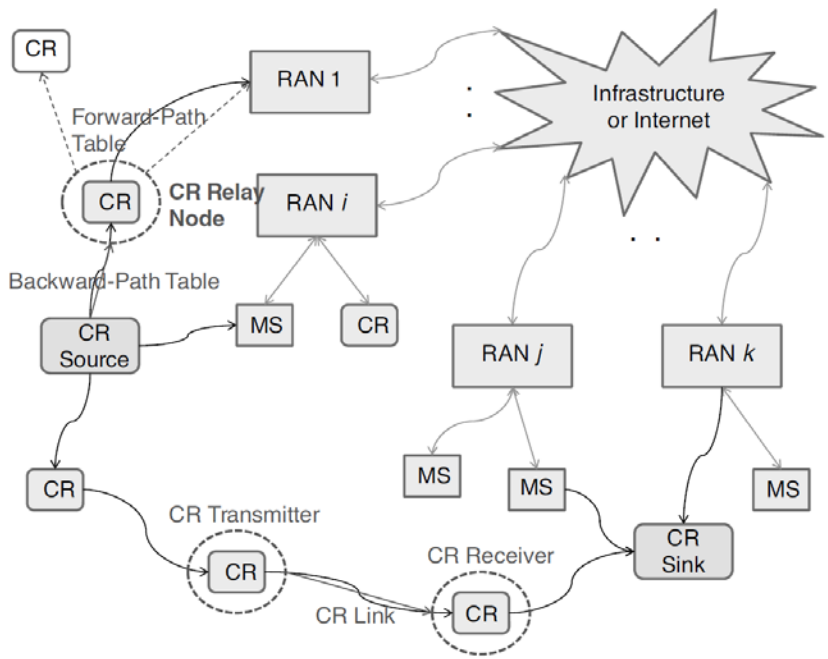


Routing in CRN

Routing of Dynamic and Unidirectional Links

- For a CR link that is the link with the CR as transmitter, we will avoid acknowledgement over the link, because there might not be enough opportunistic time window to execute this acknowledgement.

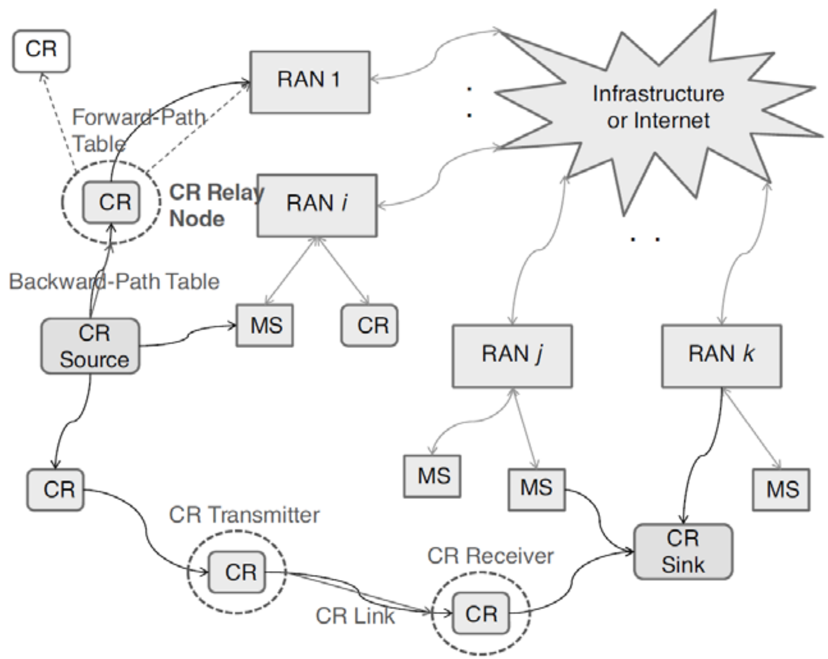
- For the same reasons, we will not use hello packets in common ad-hoc network routing.



Routing in CRN

Routing of Dynamic and Unidirectional Links

- CRN routing must be able to detect and to minimize the possibility of any loop or any dead-end, where dead-end means 'no way to forward the packet further within a reasonable amount of time', and loop means 'the packet that was forwarded to another route will come back in a repeated way'.



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CRNs

Summary

- CR nodes can detect available spectrum in its locality: however-
  - Due to mobility the spectrum environment can change rapidly! Means for the provision of continious updates are necessary
- CRN routing must be aware of performance and enviromental information; routing protocol updates, and end-to-end requirements

CRNs

Summary

- Should be able to adapt radpidly to dynamic changes of the spectrum and node mobility environment: e.g., having more than one channel assigned per flow enables the MAC to react to such changes.

Self-Organization

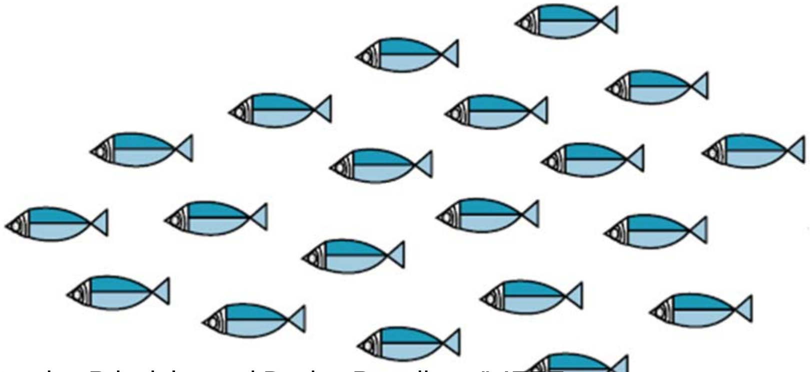
What is Self-organization?

A system, composed of several entities, is organized if it has a certain structure and functionality.

Structure means that the entities are arranged in a particular manner and interact with each other in some way.

Functionality means that the overall system fulfils a certain purpose.

Example: a school of small fish tries to achieve a group structure that protects the fish against enemies



In: Prehofer and C. Bettstetter, “Self Organization in Communication Networks: Principles and Design Paradigms”, IEEE Communication Magazine, July 2005

Self-Organization

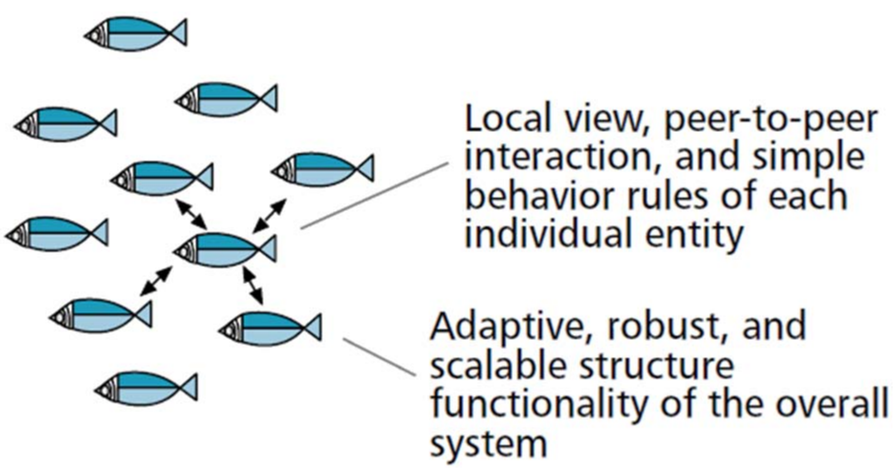
What is Self-organization?

A system is self-organized if it is organized without any external or central dedicated control entity.

The individual entities interact directly with each other in a distributed peer-to-peer fashion.

Interaction between the entities is usually localized.

Example: Each individual fish bases its behaviour on its observation of the position and speed of its immediate neighbours.



In: Prehofer and C. Bettstetter, “Self Organization in Communication Networks: Principles and Design Paradigms”, IEEE Communication

Self-Organization

What is Self-organization?

Self-organization is the process where a structure or pattern appears in a system without a central authority or external element imposing it. This globally coherent pattern appears from the local interaction of the elements that makes up the system, thus the organization is achieved in a way that is parallel (all the elements act at the same time) and distributed (no element is a coordinator).

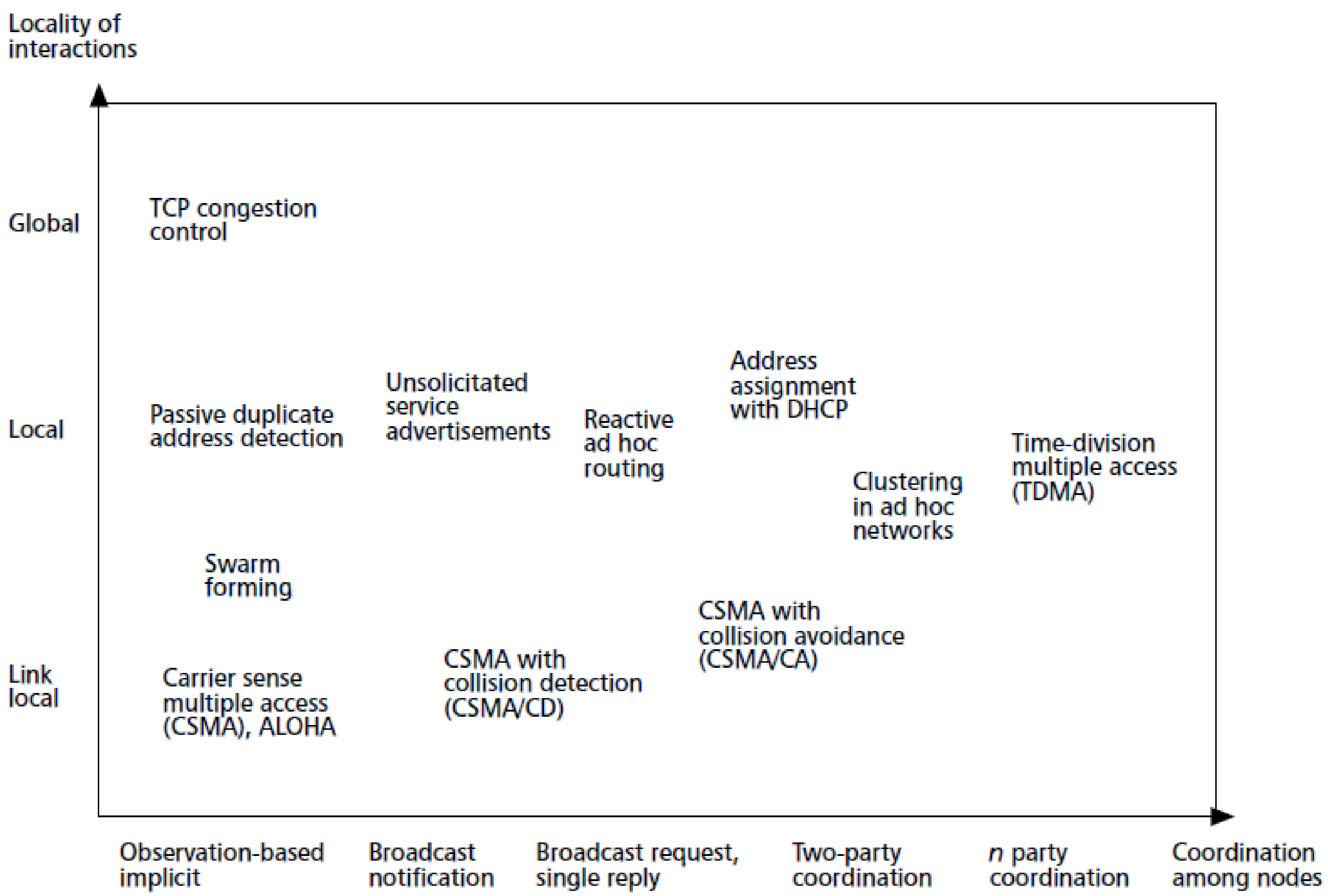
(School of Fish)

(Flock of Birds)

In: *http://en.wikipedia.org/wiki/Self-organization*

Self-Organization

Self-Organization in Communication Networks



In: Prehofer and C. Bettstetter, “Self Organization in Communication Networks: Principles and Design Paradigms”, IEEE Communication

Self-Organization

Self-Organization in Communication Networks

Two on-going efforts for Self-Organization in Communication Networks are:

Autonomic Networks

Supported by the IETF and its focus is to create self-managing networks to overcome the rapidly growing complexity of the Internet and other networks and to enable their further growth, far beyond the size of today.

Self-Organizing Networks

Supported by the 3GPP and NGMN, and its focus is to create future radio access networks where minimal human involvement in the network planning and optimization tasks will be required.

Both are based somehow on the Autonomic Computing Initiative started by IBM in 2001.

Self-Organizing Networks

Supported by the 3GPP and NGMN, and its focus is to create future radio access networks where minimal human involvement in the network planning and optimization tasks will be required.

In this presentation we focus on the Self-Organizing Networks (SONs) approach and how it relates to the Cognitive Radio (CR) paradigm.

Self-Organization

Self-Organization in Radio Networks Rationale

Cellular networks will be smaller and in greater number because:

Significant new spectrum becomes available in the high frequencies range.

Capacity growth during the life-time of cells is due to increased network density.

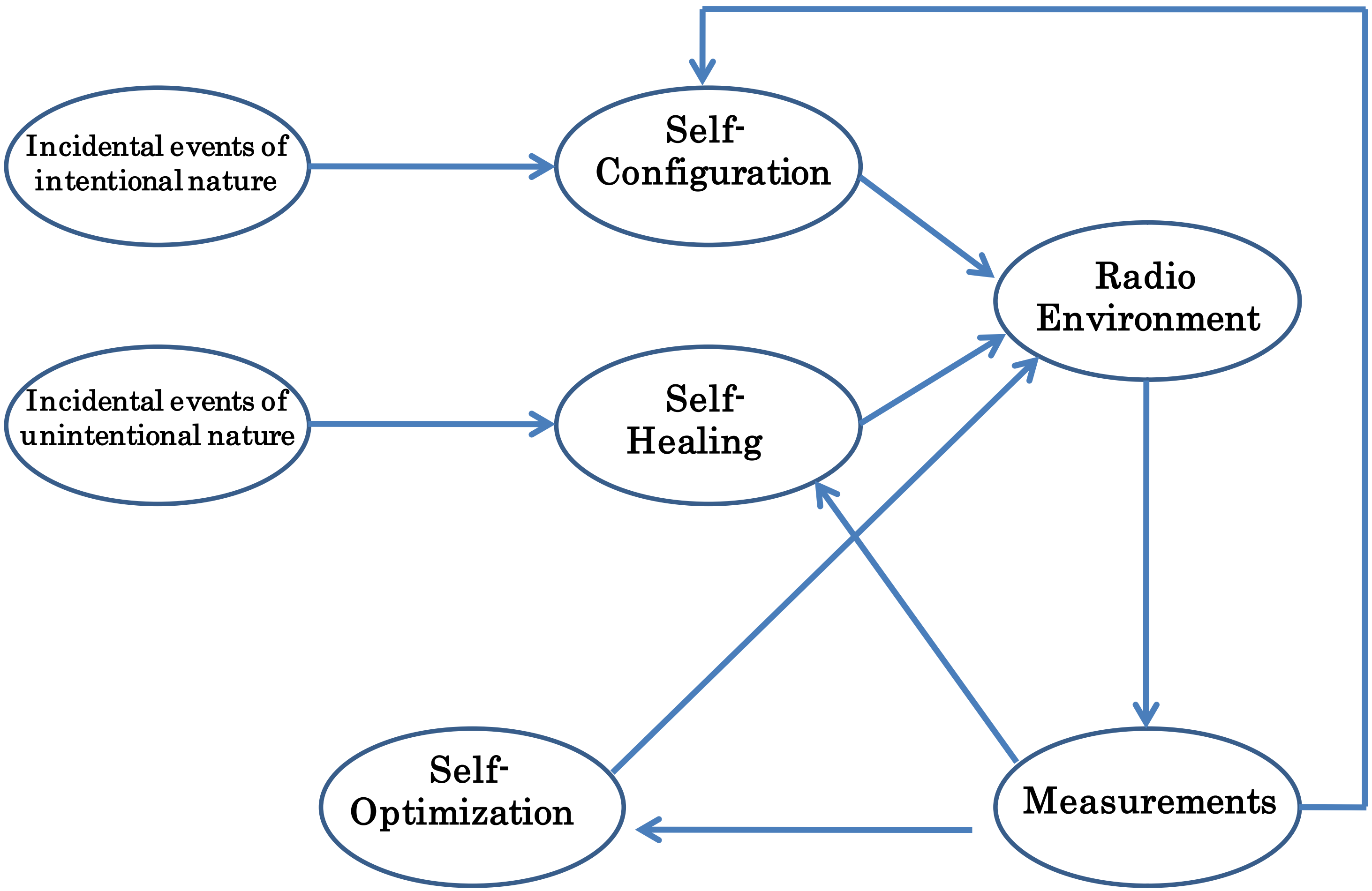
Trend to optimize towards very high peak data rates limits the range of a cell.

In this scenario the network's Operational Expenditure (OPEX) becomes the major cost.

One part of the OPEX problem is the Operation and Maintenance (OAM) cost, which is what motivates the need for SON.

Self-Organization

Self-Organization Cycle in Radio Networks

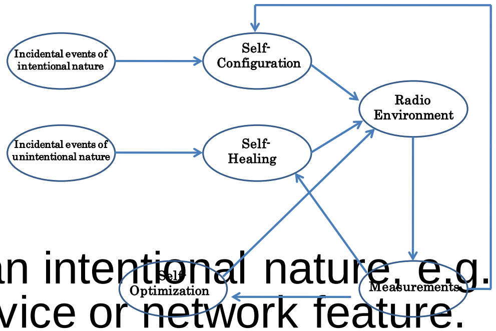


In: N.Marchetti, N.R.Prasad, J.Johansson, T.Cai, "Self-Organizing Networks: State-of-the-Art, Challenges and

Self-Organization

Self-Organization Cycle Terminology

Self-Configuration



The self-configuration is triggered by incidental events of an intentional nature, e.g. the addition of a new site or the introduction of a new service or network feature.

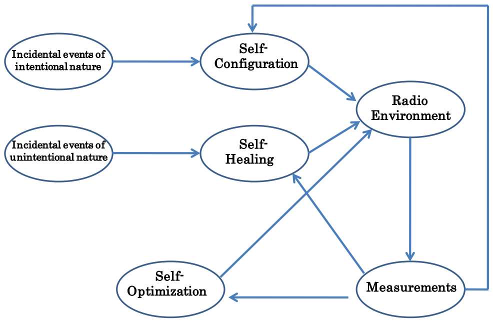
These upgrades generally require an initial (re)configuration of a number of radio parameters or resource management algorithms, e.g. pilot powers and neighbours' lists.

These parameters have to be set prior to operations and before they can be optimized as part of the continuous self-optimization process.

Self-Organization

Self-Organization Cycle Terminology

Self-Healing



Triggered by incidental events of a non-intentional nature, such as the failure of a cell or site, self-healing methods aim to resolve the loss of coverage or capacity induced by such events to the extent possible.

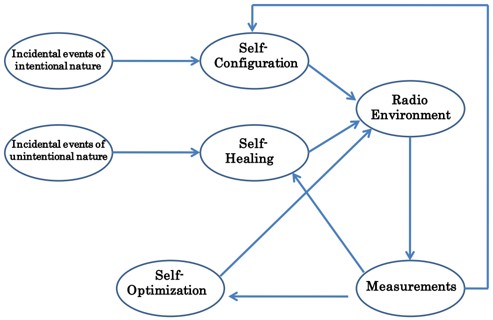
This is done by appropriately adjusting the parameters and algorithms in surrounding cells.

Once the actual failure has been repaired, all parameters are restored to their original settings.

Self-Organization

Self-Organization Cycle Terminology

Self-Optimization



In the self-optimization phase, intelligent methods apply to the processed measurements to derive an updated set of radio (resource management) parameters, including e.g. antenna parameters (tilt, azimuth), power settings (including pilot, control and traffic channels), neighbours' lists (cell Ids and associated weights), and other radio resource management parameters (admission/congestion/handover control and packet scheduling).

Self-Organization

Relation between SONs and Cognitive Radio

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The ultimate goal of communications is to achieve ubiquitous and pervasive communication with reliable universal coverage at all times.

This brings several challenges:

A large amount of communication devices contending to the same spectrum.

Most devices have limitations in the energy consumption.

Wireless might be unreliable (bigger challenges due to the medium than in wired counterpart).

From the very high heterogeneity of devices it might come incompatibility.

Self-Organization

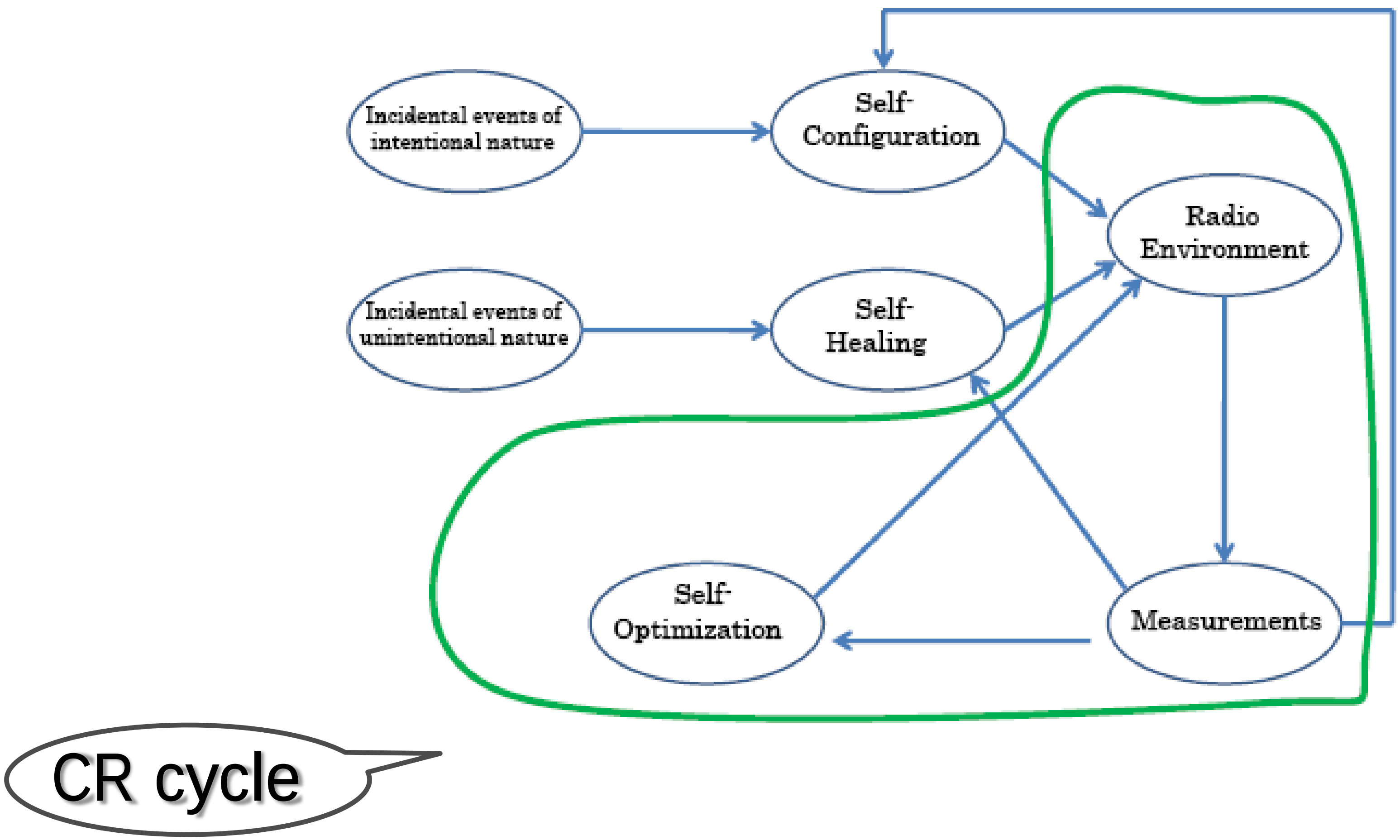
Relation between SONs and Cognitive Radio

These challenges can only be faced if a certain degree of self-organization is put into the system

Self-organized/cognitive networks will play a crucial role in identifying the needed spectrum of the proper quality for the several coexisting systems, devices and applications

Self-Organization

Relation between SONs and Cognitive Radio



In: N.Marchetti, N.R.Prasad, J.Johansson, T.Cai, "Self-Organizing Networks: State-of-the-Art, Challenges and Perspectives",8th International Conference on Communications COMM 2010, June 11, Bucharest, Romania

CRNs for AWC

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Summary of Design Challenges

• Node self-awareness and self-optimisation	• Deals with complexity in large scale networks
• Topology Control	• Improves spatial reuse, reduces complexity in routing, scalability of netwroks and algorithms
• Spectrum-aware autonomic routing	• Better resource utilisation, improved flexibility and adaptibility

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