Basics of Cognitive Radio Networks with examples of CR-oriented protocol design

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Corso di Reti Avanzate – a.a. 2012-2013

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Spectrum occupancy with current technologies

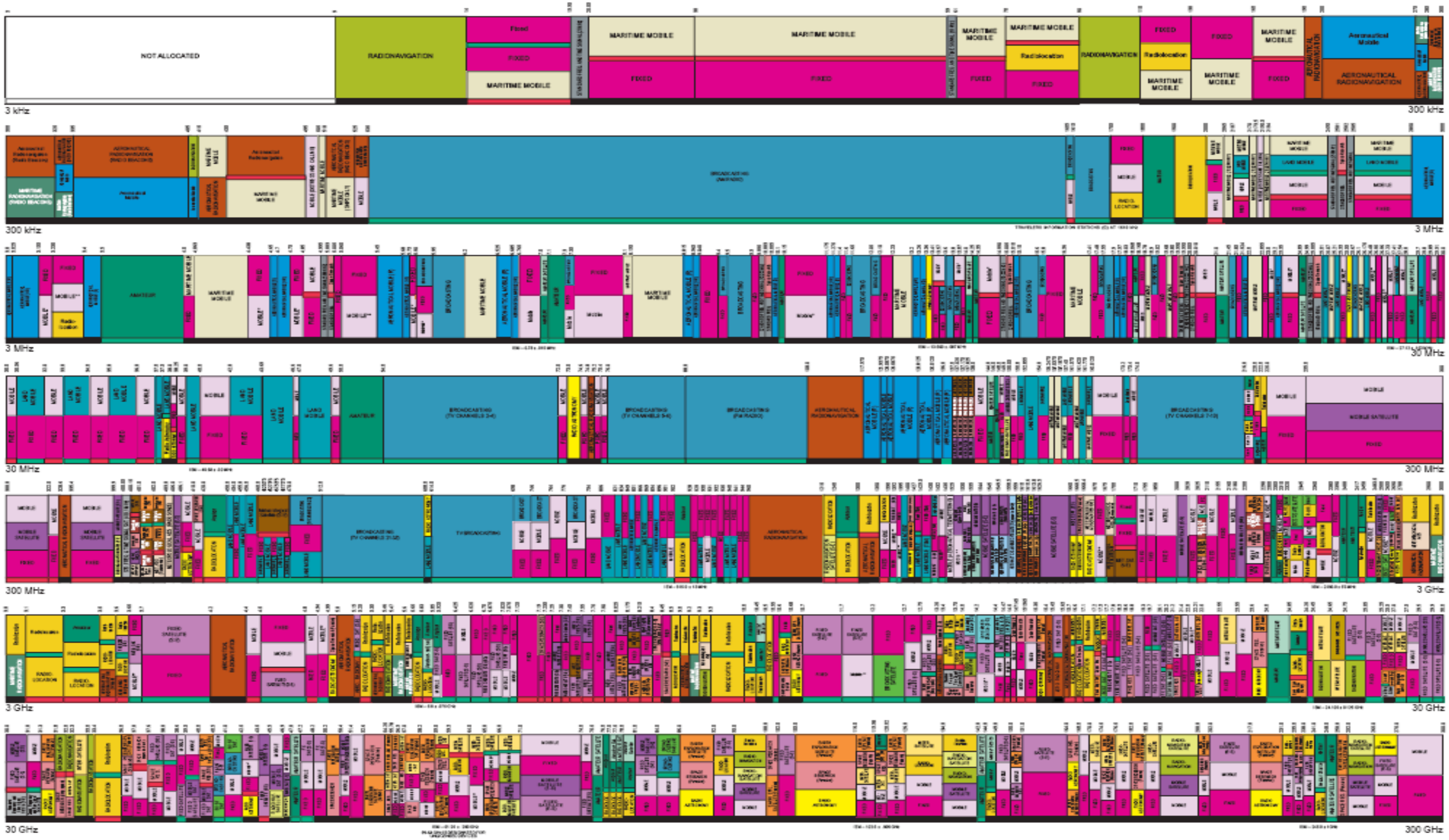
- Current wireless networks, operating in either licensed or unlicensed bands, almost occupy the entire available spectrum for nowadays commercial communication technologies.

- Yet the demand for spectrum is constantly increasing, pushed by the availability of new services, either entirely new, or formerly thought for wired networks.

- It is a fact, however, that in most licensed bands, the actual percentage of spectrum usage is under 50%, or in some cases, in the order of 10%

Spectrum occupancy with current technologies

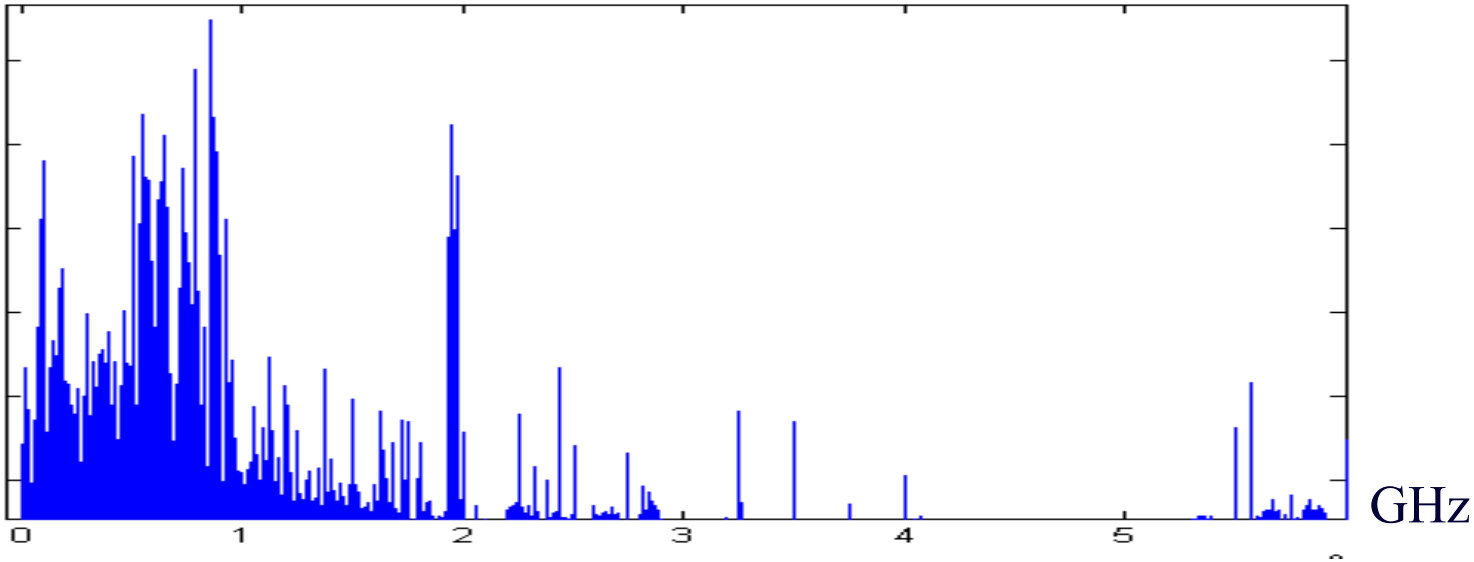
Fixed Spectrum Assignment:



Spectrum occupancy with current technologies

Effective bandwidth usage:

PSD (Power Spectrum Density)



Freq (GHz)	0~1	1~2	2~3	3~4	4~5	5~6
Utilization(%)	54.4	35.1	7.6	0.25	0.128	4.6

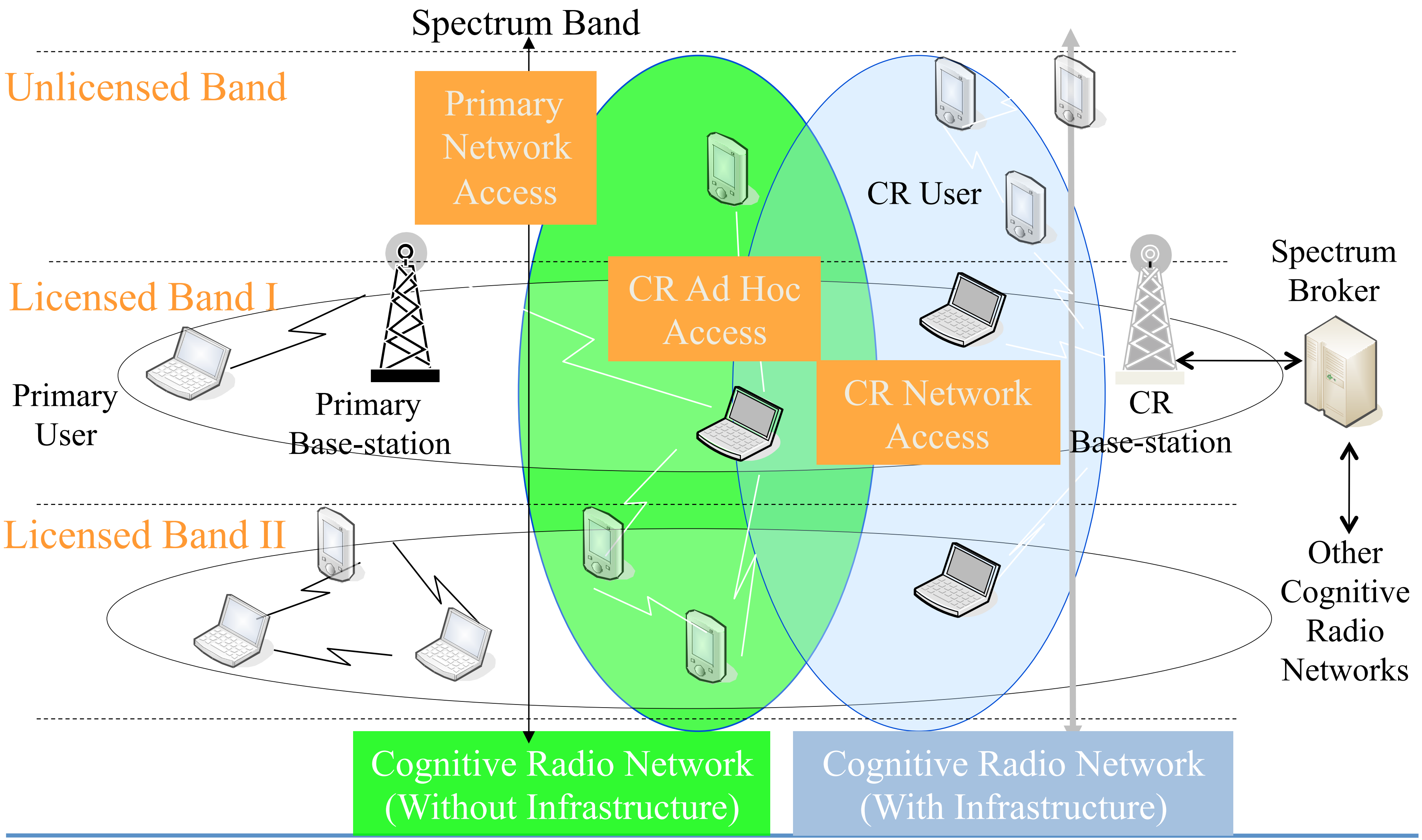
Cognitive Radio Networks

Question: Is there a way to improve the spectrum usage, both in licensed and unlicensed bands (irrespective of the different networks and technologies that already operate in those bands)?

- A possible answer is given by **Cognitive Radio** ("A radio or system that senses and is aware of its operational environment and can dynamically and autonomously adjust its radio operating parameters accordingly." [*ITU (Wp8A working document)'05*]), and **Cognitive Radio Networks**.

- One flavor of Cognitive Radio Networks is represented by ***Dynamic and Opportunistic Spectrum Access networks.*** Such networks have the capability to use or share the spectrum in an opportunistic manner.

Cognitive Radio Networks



Sketch of main functionalities

What are the main functionalities that a cognitive network should implement and that are not implemented by conventional networks/ users?

- Identify current opportunities for spectrum (or channels) utilization
  - Spectrum Sensing
  - Spectrum Decision
  - Spectrum Sharing

- Be able to vacate that spectrum (or channel) if a licensed user wants to use that resource.
  - Spectrum mobility

Sketch of main functionalities

Identification of opportunities, also termed "spectrum holes," for channel use from the cognitive network.

- *Spectrum sensing* – The capability of a cognitive terminal (or of a set of cognitive terminals) to monitor the spectrum bands and the distinct channels in which the cognitive network is supposed to operate, to detect the presence of primary users in each channel, and the overall primary users activity in each (sub)-band. Spectrum sensing can be, depending on the scenario, distributed or centralized, cooperative or non-cooperative.

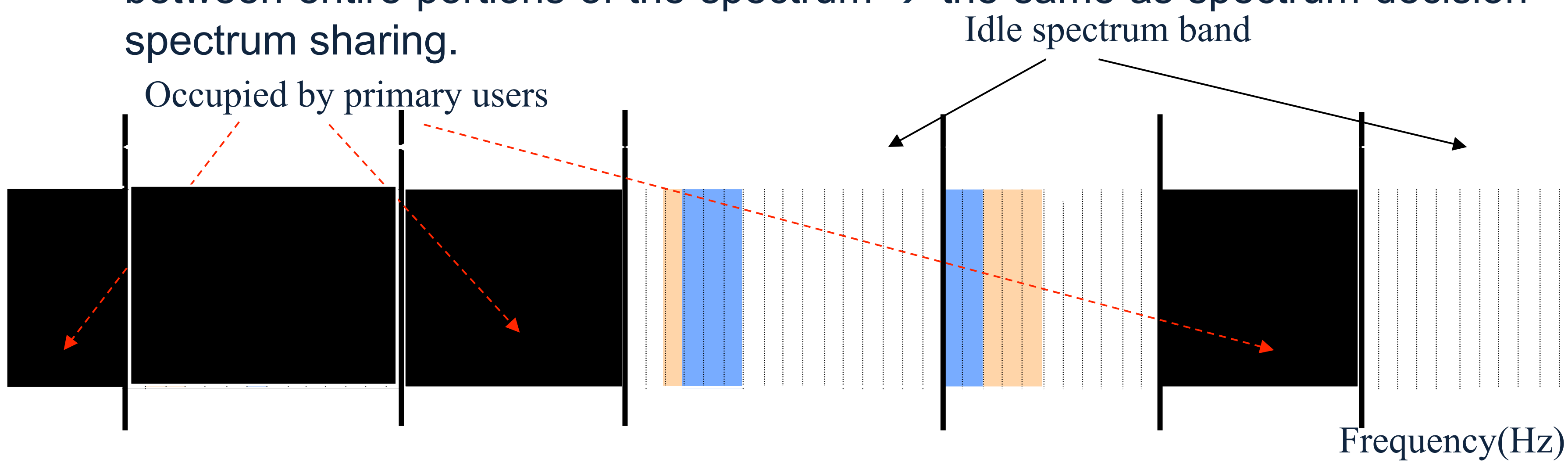
- *Spectrum decision* – Given the set of candidate available bands, obtained through sensing and long–term statistics, cognitive users determine the best spectrum band to use. The choice can be driven not only from channel quality, but also from internal or external policies.

- *Spectrum sharing* - Multiple CR users try to access the spectrum CR network access should be coordinated in order to prevent multiple users colliding in overlapping portions of the spectrum.

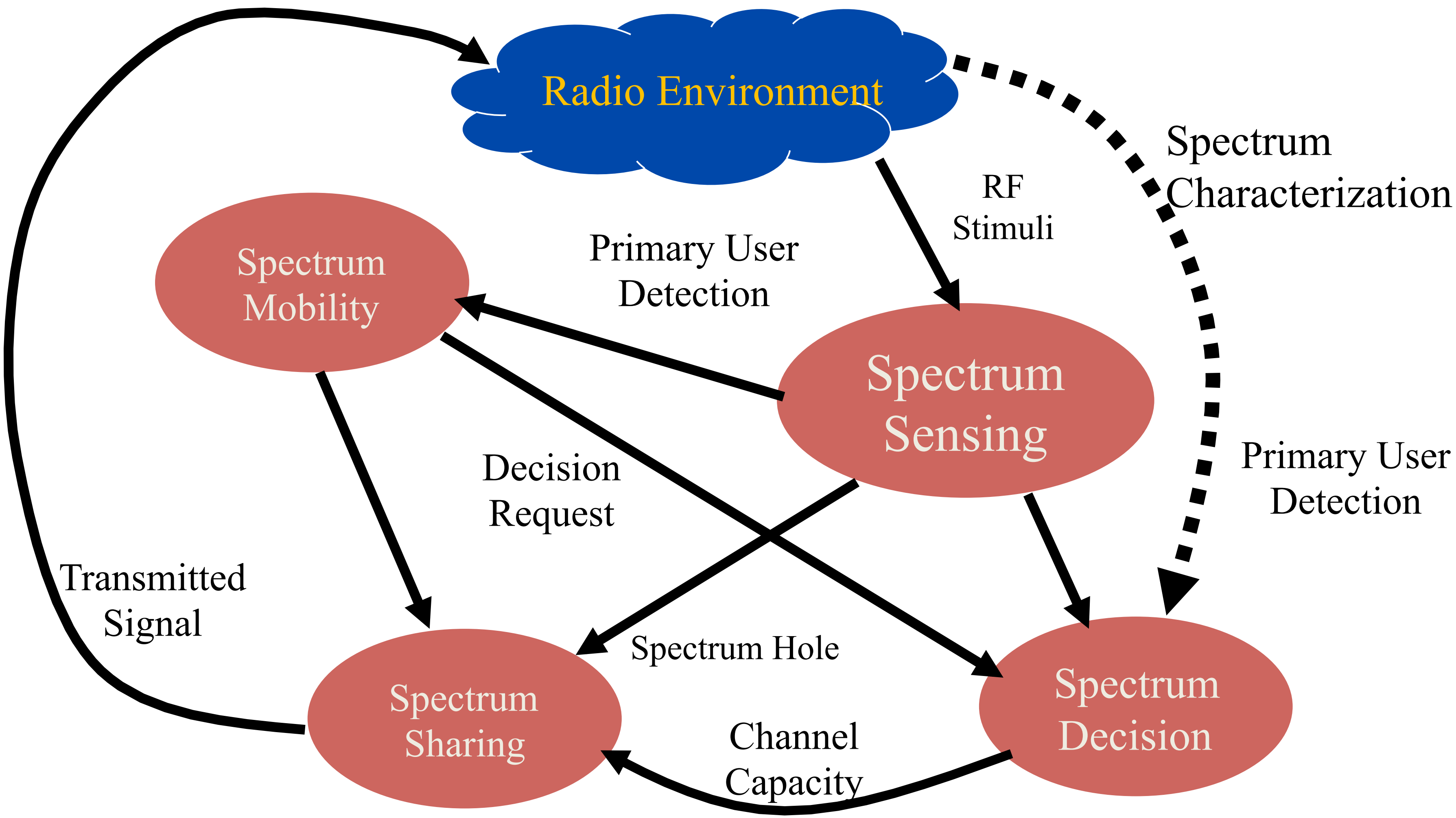
Sketch of main functionalities

Capability to vacate a spectrum (or channel) currently used by a cognitive terminal if a licensed user wants to use that resource.

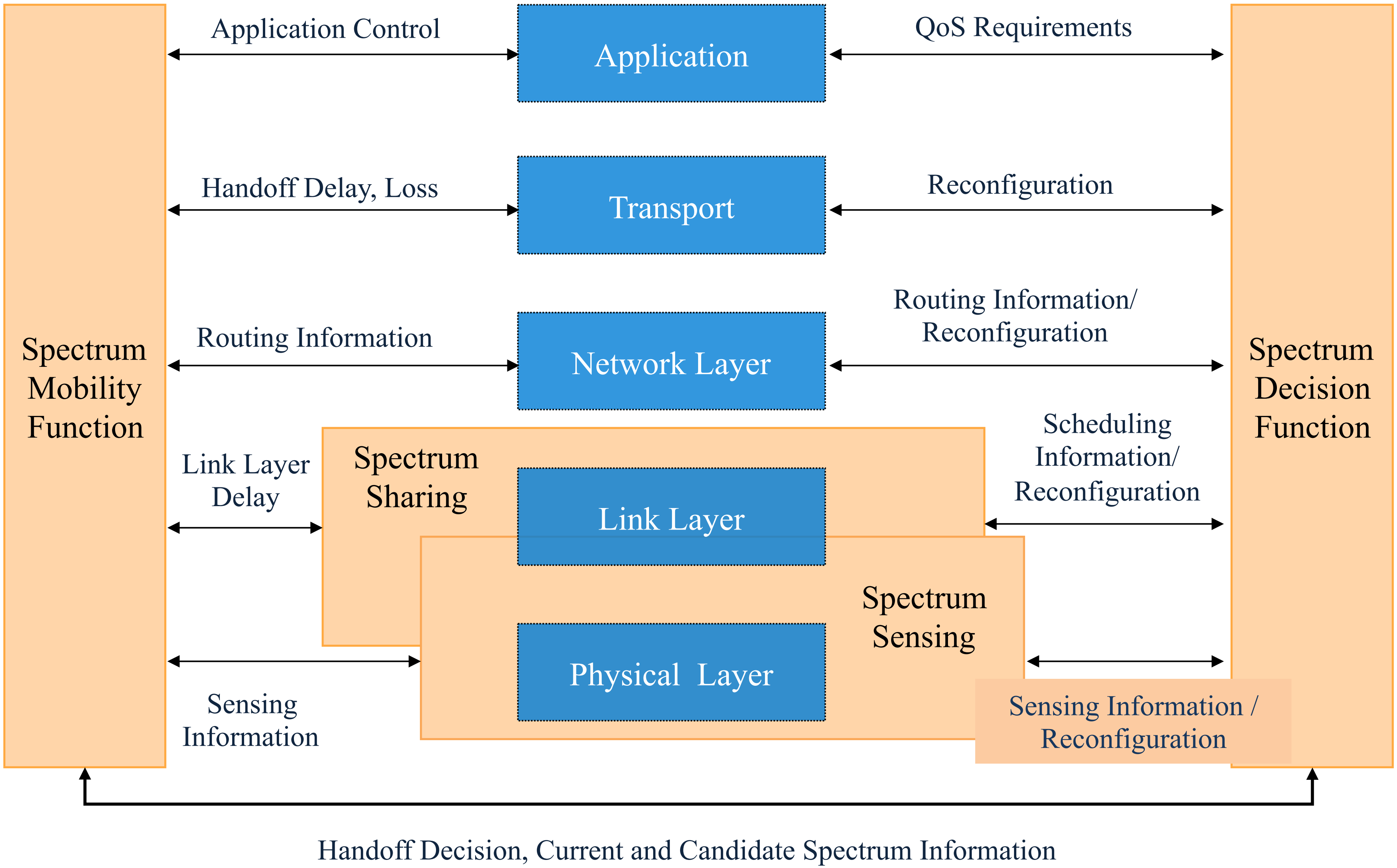
- *Spectrum mobility* – When a channel, or an entire band, that is being currently used from the cognitive radio network is accessed by a licensed (or high priority) user, that resource must be vacated from the CRs "on the fly" and in the shortest possible time. This should be done preserving the connectivity of cognitive users → spectrum handoff.
- *Different levels of granularity* - The above procedure could be implemented at the channel level within the same band, or at band level, i.e. between entire portions of the spectrum → the same as spectrum decision – spectrum sharing.



Cognitive cycle



Impact on the protocol stack



Reconfigurability

- Spectrum decision, sharing, and mobility, require a high level of **reconfigurability** of the radio interface of cognitive users. They should be able to co-exist with different wireless communication technology.
- It is advisable for the cognitive network transmission technology to have a high degree of self-reconfiguration.

Reconfigurable parameters:

- Operating Frequency
- Modulation
- Transmission Power
- Communication Technology

➡ Air interfaces developed following a unified framework, e.g., for different access schemes (TDMA, CDMA, OFDMA), have the potential to obtain a high degree of self-reconfigurability at a lower cost with respect to a system that implements, in parallel, different radio interfaces designed for used with a single transmission technology.

Spectrum Sensing

- The operational band of a cognitive network is composed by several system bands of traditional wireless networks, each band is composed of many channels
- Spectrum sensing characterizes, in real time, the spectrum usage from licensed or high priority networks/users both at the channel level and at the band level.
- Its outcomes serve as an input to spectrum decision and sharing modules.
- Different techniques involving different knowledge of the primary technology, known or estimated.
- If the band of interest is too wide, monitoring the whole set of channels with a battery powered device could be impossible: solutions for observing different subsets of channels at different nodes could be necessary – also related to the primary users activity.

Spectrum Sensing

Different approaches:

- Centralized vs decentralized: with a decentralized approach sensing and sharing are performed at a local level: in principle it is simpler, but not always applicable, e.g. for spectrum decision it is better to collect and process information at a sink node.

- Cooperative or non-cooperative: Cooperative sensing and decision on channel occupancy yield best performance in terms of accuracy, but they demand for exchange of measured data, or local decision, among nodes, which is band-, and time-consuming, hence it could be impractical if the scenario demands for a quick system response.

- Reactive or proactive: With a cooperative approach, depending on the cognitive network traffic load, sensing functions either can be activated only when a users requests for a transmission, or can be performed independently, in such a way that the system gives a quicker respons when a user makes a request to transmit.

Spectrum decision

- The entire spectrum where cognitive users operate can be very wide, and involving different system bands with different technologies.
- Depending on the selected scenario, it could be impractical, or even impossible, for a single user to handle spectrum access and mobility over the entire available spectrum
- An external controller could be demanded to choose the band for CRs to operate, then inside that band, access and mobility are performed at a local level.
- This choice is usually performed on the basis of long-term statistics, where available capacity is the most important, but not the only one, aspect to take into account.
- In particular, other factors, such as QoS requirements of the cognitive network, or economical considerations, come into play in this step.

Spectrum decision with different CR networks

If multiple CR networks, with possibly different kind of services, operate in the same area and in the same spectrum, the problem of coexistence among them, and with licensed networks, arises.

- One way to face this problem is the presence of a *spectrum broker, i.e.,* a central network entity that plays a role in sharing the spectrum resources among different CR networks.
- It can be connected to each network and can serve as a spectrum information manager to enable co-existence of multiple CR networks.

Spectrum sharing

- Deals with on-the-fly channel assignment to different CR users.
- The primary function is to take into account the presence of licensed or high priority users operating on the same set of channels.
- A channel for a CR users has not necessarily the same badwidth of a channel for primary users
- Based on the sensing results performed at the channel level, it identifies an appropriate subset of channels to use.
- Contention among different CR users can be solved either in a coordinated manner, or with a random access protocol.

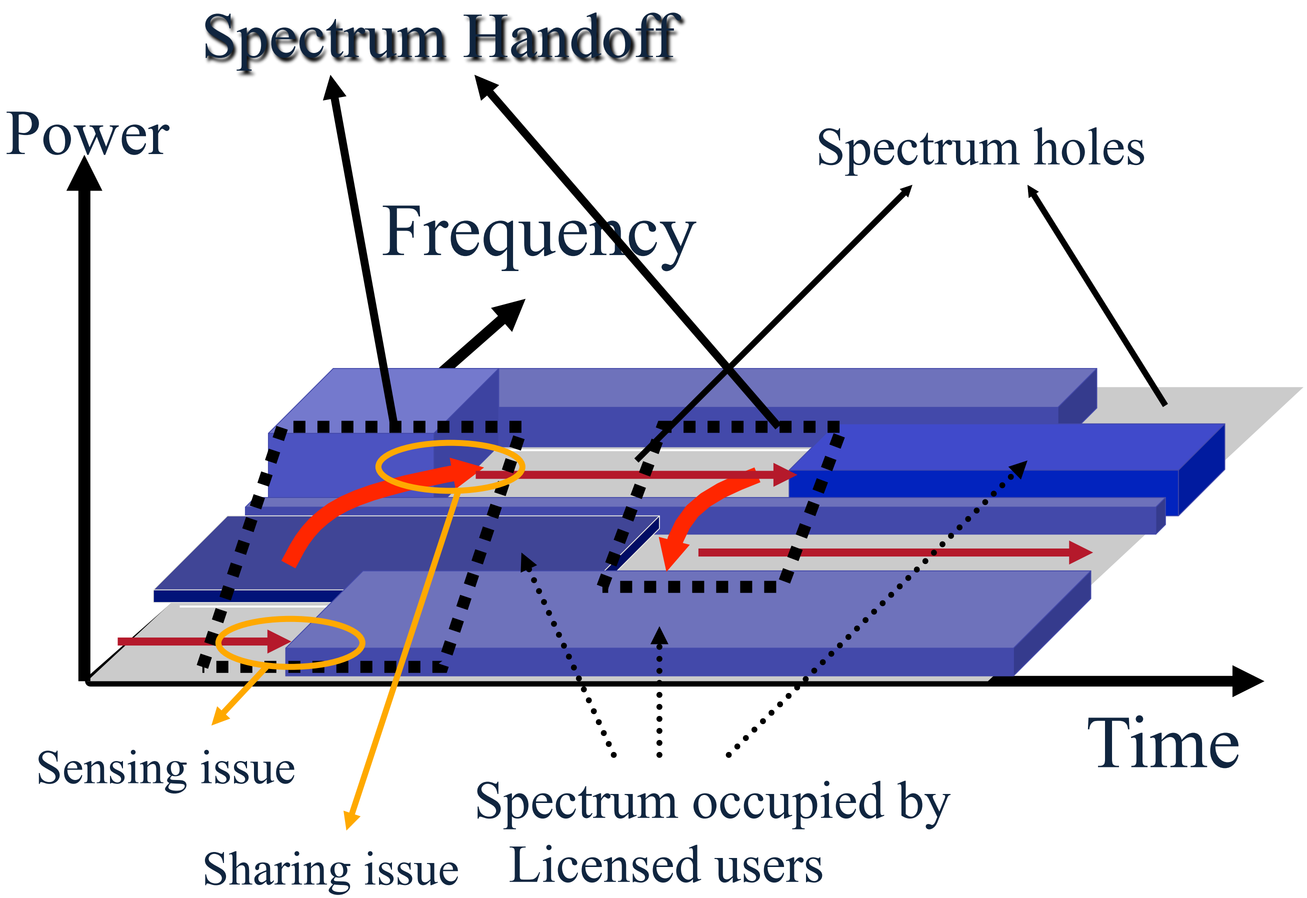
Spectrum sharing

- At this level, the degree of self-reconfigurability of air interfaces plays a major role.
- Existing solution in the literature provide means for reducing interference caused to primary users, and among CR users, in a completely decentralized way.
- Decentralized design often use Game Theory as a basic tool.
- Accurate modeling of licensed users activity is a key point in the design of efficient spectrum sharing protocols.
- Jointly optimized spectrum sensing-sharing are a possible solution when a single node can monitor and/or access only a subset of the available channels

Spectrum mobility and handoff

Spectrum handoff is a multi-step process, including:

- PU Detection
  (Sensing issue)
- PU Notification
- Channel Switching
  (Hardware issue)
- Resuming communication
  (Sharing issue)



Decoupling sensing and actuation: Motivation

- Motivation
  - Power consumption, observable bandwidth
    - Given a sensing technology, the time and power required for sensing a channel, or a set of channels, is proportional to the overall channel bandwidth

      ⇨ It could be impractical, due to strict time constraints and excessive power consumption, to let a cognitive users sense the whole spectrum.

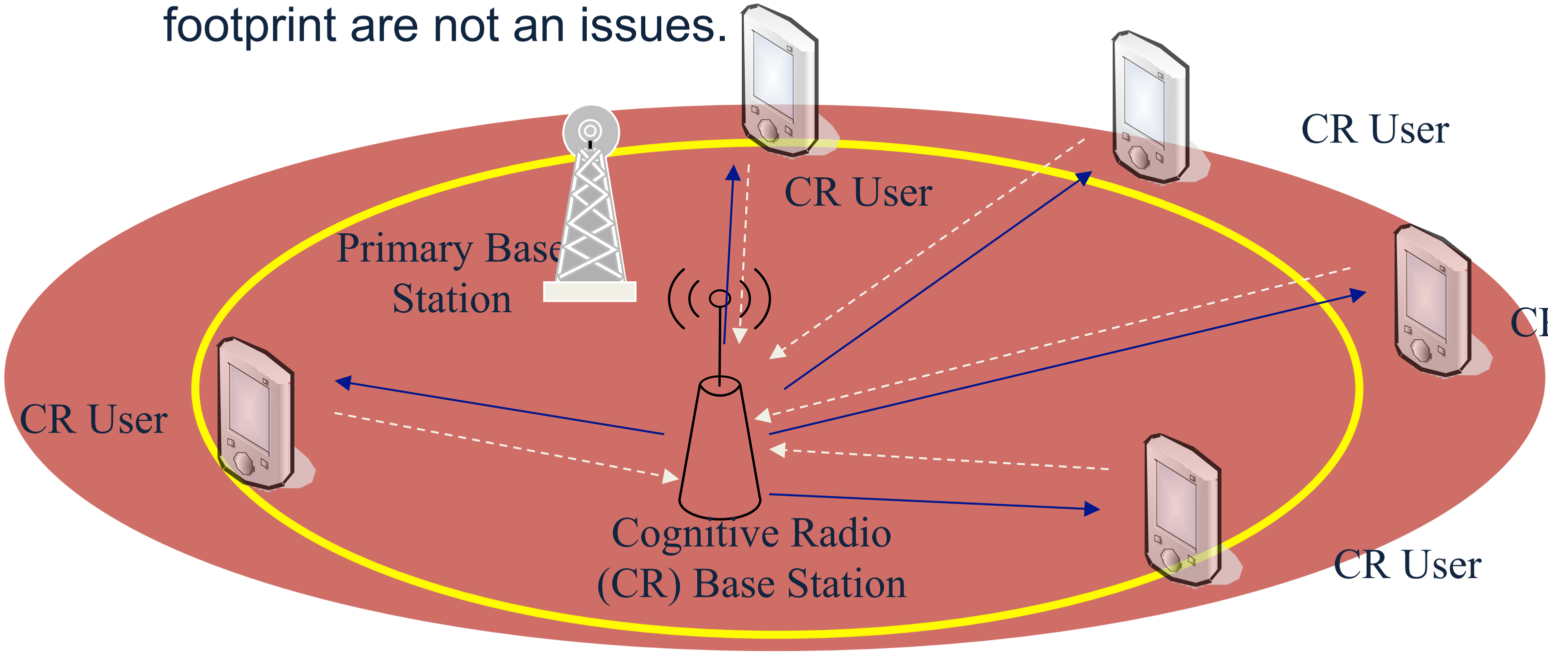
    - On the other hand, sensing a larger amount of spectrum clearly allows for a larger number of transmission opportunities, or spectrum holes.

Decoupling sensing and actuation: Motivation

- Motivation
  - Geographic related problems

    we must make a distinction between two possible scenarios:

    a) The coverage radius of cognitive terminals is comparable with the coverage radius of primary users, and the service area of the primary network. E.g.: an indoor wireless LAN with a single AP cohexisting with bluetooth devices. → With this scenario, hidden terminals and radio footprint are not an issues.

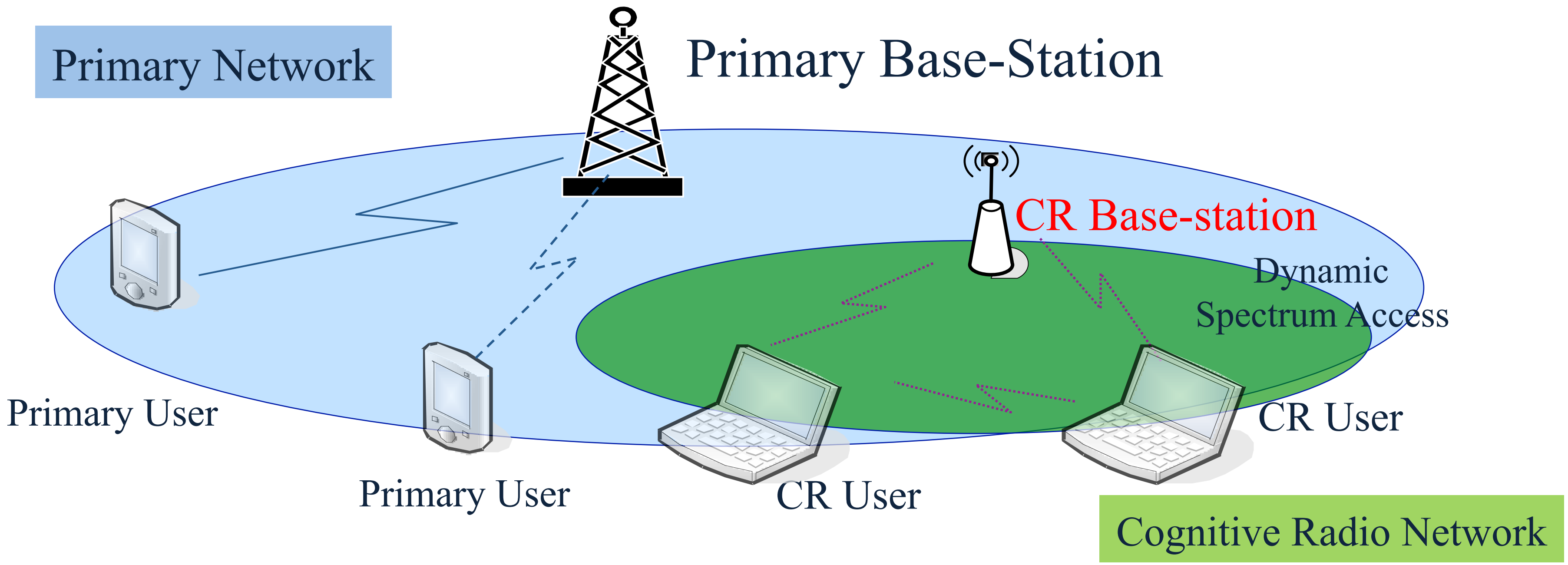


Decoupling sensing and actuation: Motivation

- Motivation
  - Geographic related problems

    we must make a distinction between two possible scenarios:

    b) The service area of the primary network is much larger than the coverage radii, e.g., a cellular network as a licensed network and a WLAN as a cognitive network.



Decoupling sensing and actuation: how to do it

Proposed solution:

Given the problem of monitoring a large spectrum, and in particular in scenario b), a separate ***sensor network*** dedicated to spectrum sensing can be deployed in parallel with the primary and cognitive networks.

- The problems of hidden terminals, especially in the case of unknown positioned primary receivers, would be solved, since the sensor network could provide information on the spectrum occupancy to the CR network not only at a given spot, but on the entire radio footprint of the transmitter, thus allowing for minimal interference with licensed users.
- Furthermore, sensors would provide a finer spatial resolution on spectrum occupancy, and, most important, can be grid-powered, i.e. with the capability to employ more sophisticated sensing algorithms and to monitor larger bands.

Sensor network for spectrum sensing

Furthermore:

- the sensor network can serve different cognitive networks, with different requirements, thus optimizing the efforts dedicated to spectrum sensing.
- It could be part of the infrastructure of a spectrum broker

Challenges:

- Sensor network dimensioning
- Sensor network architecture design
  - Decentralized-vs-centralized
  - Cooperative or non-cooperative algorithms
  - Proactive or reactive
  - Protocol design for
    - inter-sensor communication
    - interface with CR networks

Conclusion (Part 1)

- Cognitive radio can be an effective way to improve efficiency in the spectrum usage with respect to nowadays standards.
- Architecture and protocol stack design are affected at different layer by the presence of additional network functionalities to manage dynamic and opportunistic spectrum access and spectrum mobility.
- There is a variety of possible scenarios, that may lead to a variety of solutions.
- The presence of a third part entity, called spectrum broker, is an option when considering the coexistence of more than one CR network
- Furthermore, the presence of a separate sensor network for spectrum sensing functions

Joint MAC and Routing Protocol Designs in Cognitive Radio Ad Hoc Networks (CRAHNs) Based on Interference Maps

A Decentralized routing, MAC, and scheduling protocol for CRAHNs

Problem setup:

- A CRAHN coexists with a Primary Network which operates on a set of N parallel frequency channels
- The Pnet gerates random traffic on the licensed channels
- In the CRAHN, there is a set of end-to-end multihop flows. Each node can realy traffic for multiple flows, besides those originating at it.
- Time is organized in periods. In each period, secondary nodes pick one of their outgoing links a (also specifying a channel) and transmit data on that link. Channel access is regulated through a CSMA algorithm.
- The selection is performed relying on a set of link availability parameters that are fed periodically to the seconday nodes
- Flows always have data to transmit (saturation regime).

Goal: to maximize the secondary throughput under the **constraint** that the outgoing link selection is performed in a decentralized manner, exchanging only local information.

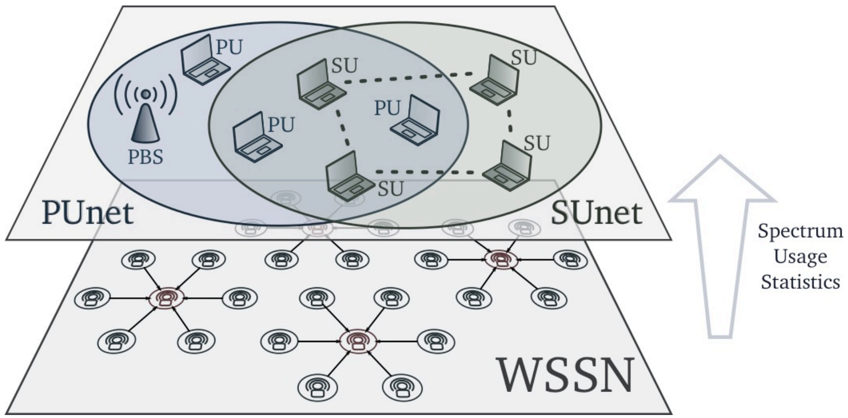
A Decentralized routing, MAC, and scheduling protocol for CRAHNs

- We assume that the network connectivity graph is given, i.e., we are not pursuing topology optimization, power control issues, etc…
- For simplicity, we assume that each channel has the same capacity.

The protocol should select the channels not in use, or less used, by the Pnet. How to do it?

- Provide a means for each node to obtain the channel availability parameters on each outgoing link

- Seek the optimal rule for Snet nodes to decide which link to schedule for transmission, and on which channel, in each period.



Network Utility Maximization Problem (NUM)

- A utility function is defined which assigns a utility to each value of the data rate which the network grants to each flow

- The global utility is the sum of the utilities for each flow

- A NUM problem represents the search of the optimal system parameter settings (basically, the selection of the links on which to transmit) to achieve maximum utility for a given set of assumptions.

$$U(x) = \sum_{f \in \mathcal{F}} U_f(x_f)$$

Where f idicates a flow and x_f its rate

A Decentralized routing, MAC, and scheduling protocol for CRAHNs

Protocol description

- At the beginning of epoch j, for each flow f, the source node s(f) recomputes the outgoing traffic rate x_f as the maximizer of the function $U_f(x_f) - q_{s(f)f}x_f$ in the interval $[0, x_M]$, where $q_{s(f)f}$ is the normalized queue length of flow f at its origin.

- Each node schedules for each of its links (n,m) the transmission the link belonging to the flow with maximal differential backpressure on the link.

$$f^*_{nm} = \operatorname{argmax}_{f \in F} \left(q^{(j)}_{nf} - q^{(j)}_{mf} \right)$$

Protocol description continued

- MAC: packets of different links are transmitted by each node through a CSMA protocol:
  - the channel to use for each packet is selected randomly using a probability vector $(p_{n,m,1},\ldots,p_{n,m,N})$.
  - the backoff intervals are the inverse of quantities R_{nm}

Both $(p_{n,m,1},\ldots,p_{n,m,N})$ and R_{nm} are computed for each epoch taking into account the differential queue length and the channel availability**, which is acquired through spectrum monitoring.**

Finally, an RTS-CTS mechanism is implemented to avoid collisions due to hidden terminal problems or propagation delays.

A Decentralized routing, MAC, and scheduling protocol for CRAHNs

- **Primary protection**: it is obtained through the CSMA mechanism and through the selection of the less used channels

- **Secondary flows throughput:** the proposed protocol has been proved to achieve maximum throughput under the assumptions of negligible propagation delays and absence of collisions

- **Practical considerations:** nevertherless, after a careful parameter selection and the implementation of the RTS-CTS mechanism, it achives very good performance.

A Decentralized routing, MAC, and scheduling protocol for CRAHNs

- **How to obtain channel availability information for each link:** This is achieved through spectrum monitoring, i.e., collection of short-term channel occupancy statistics.

- Spectrum sensing can be done
  - Locally by Snet nodes
  - Cooperatively by Snet nodes
  - Cooperatively by a dedicated network of nodes which provides and updates an interference map, and feeds it to Snet nodes

  -> tradeoff between spatial accuracy and time resolution of the statistics

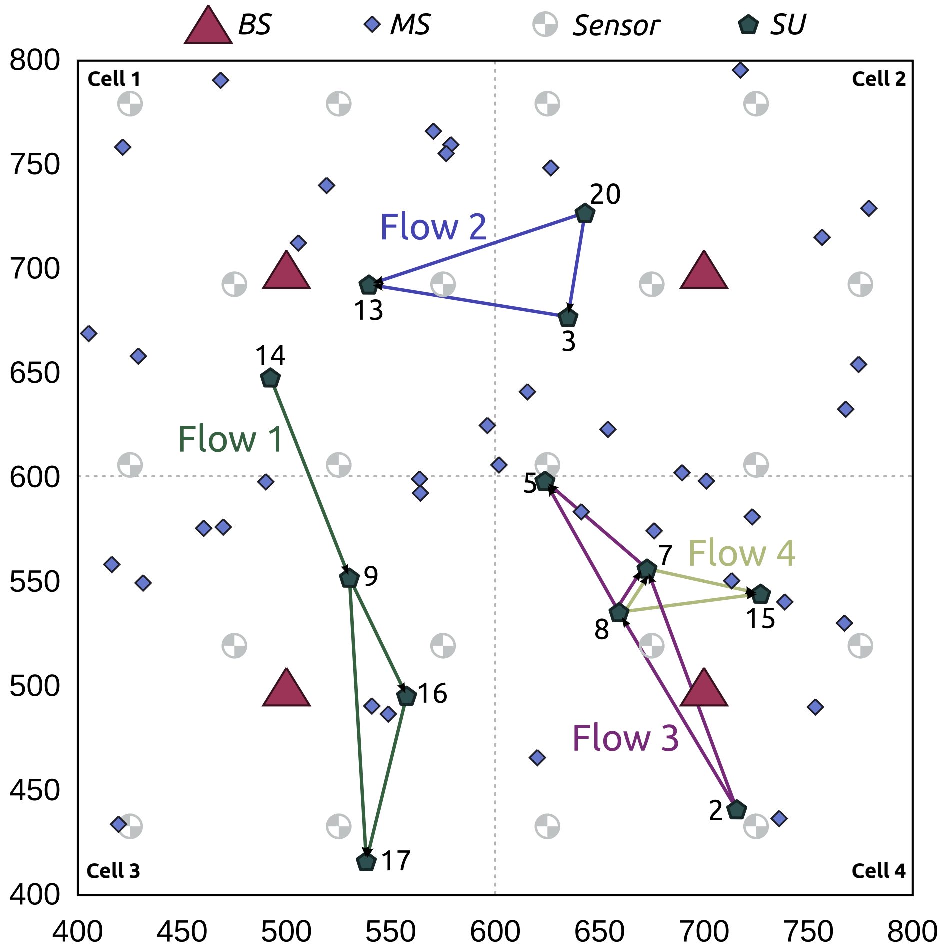
A Decentralized routing, MAC, and scheduling protocol for CRAHNs

Simulation environment

Built using the ns2-Miracle framework

Includes Pnet (as a cellular network), CRAHN Snet, and a network for spectrum monitoring.

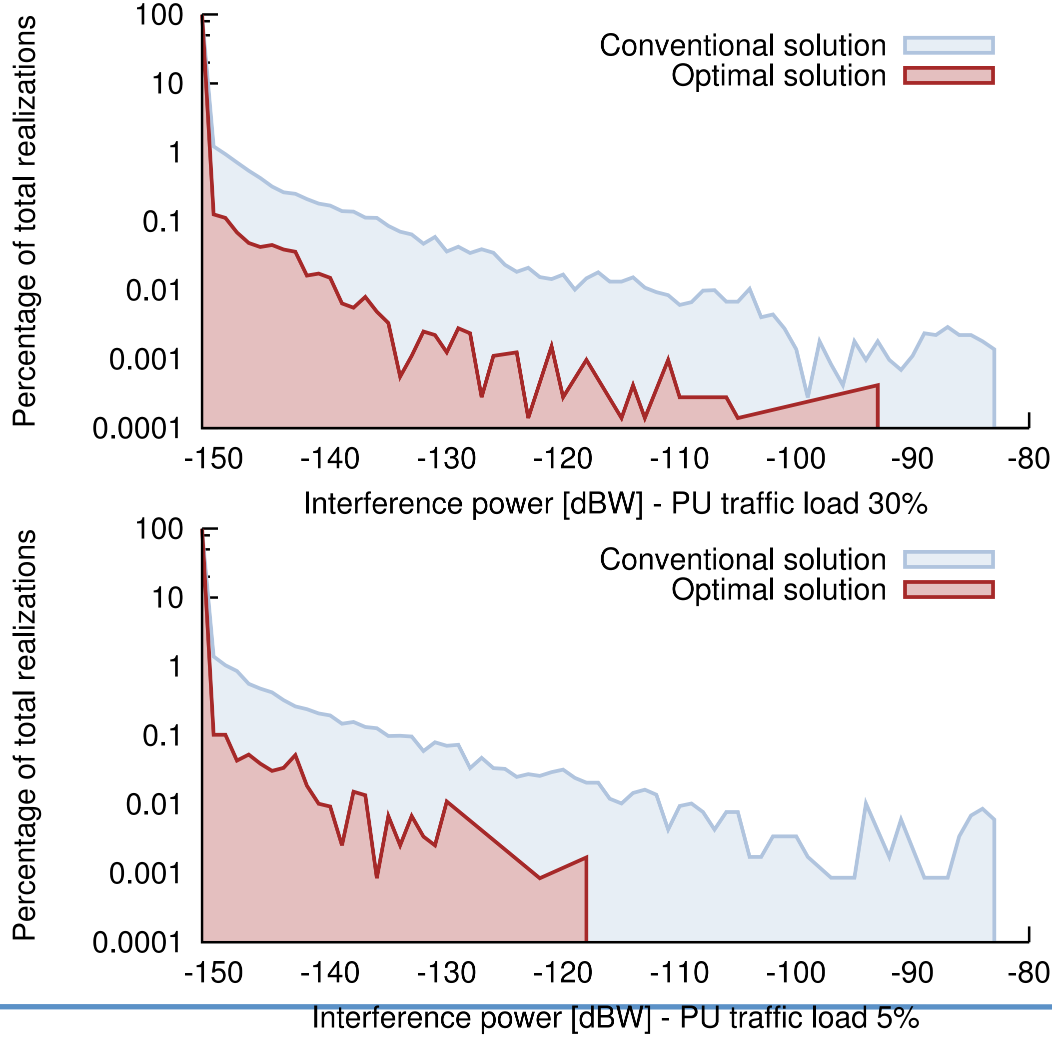
Includes both communication and control aspects.



A Decentralized routing, MAC, and scheduling protocol for CRAHNs

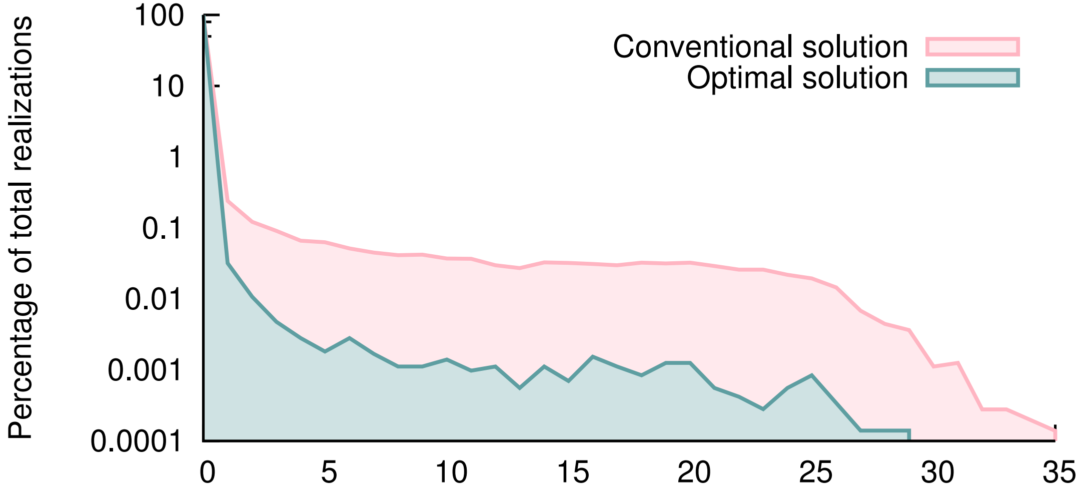
Performance evaluation (comparison with a predefined routing scheme with random channel selection)

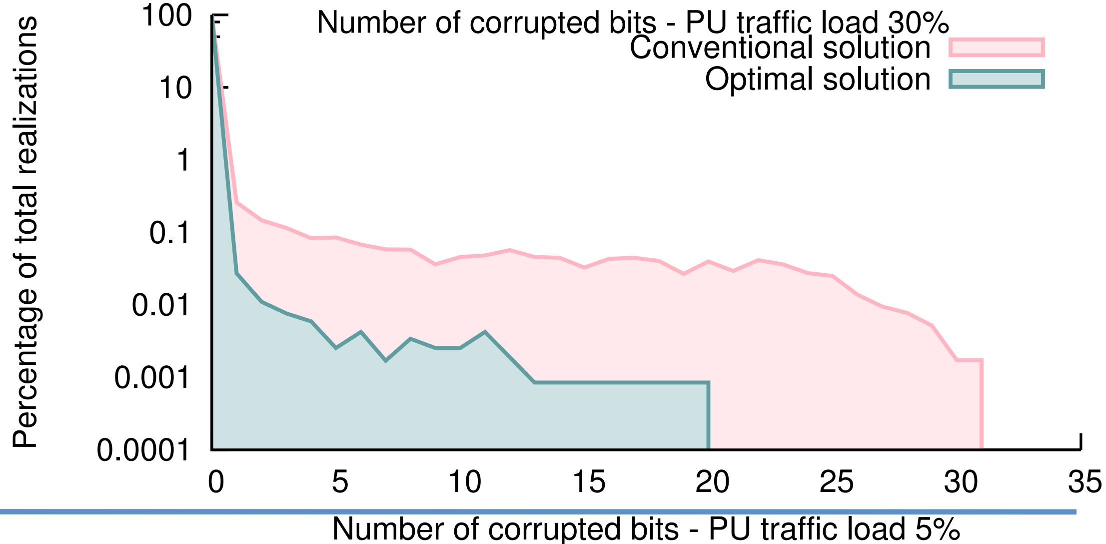
Interference caused at primary receivers under different Pnet traffic load (30% and 5% of the total capacity, respectively)



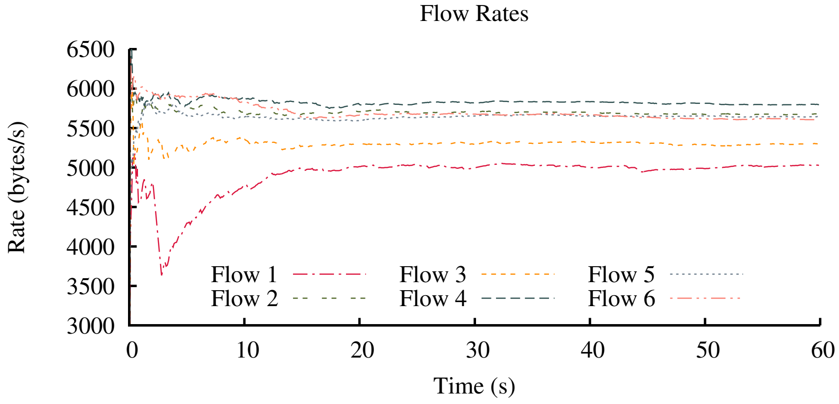
Performance evaluation (comparison with a predefined routing scheme with random channel selection)

Number of corrupted bits (for primary packet of)

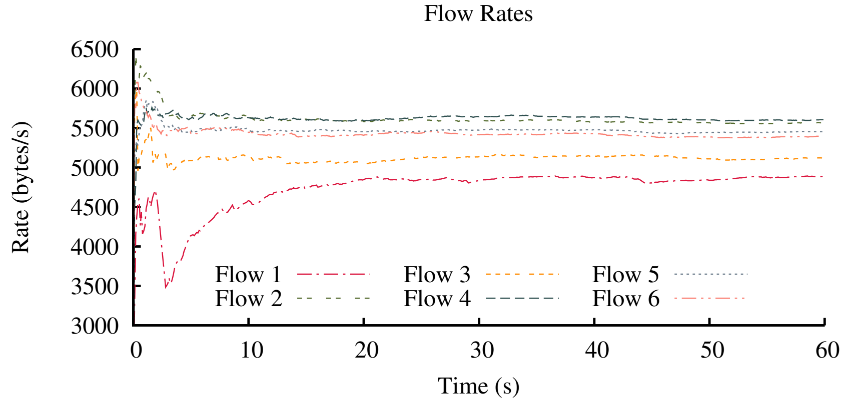




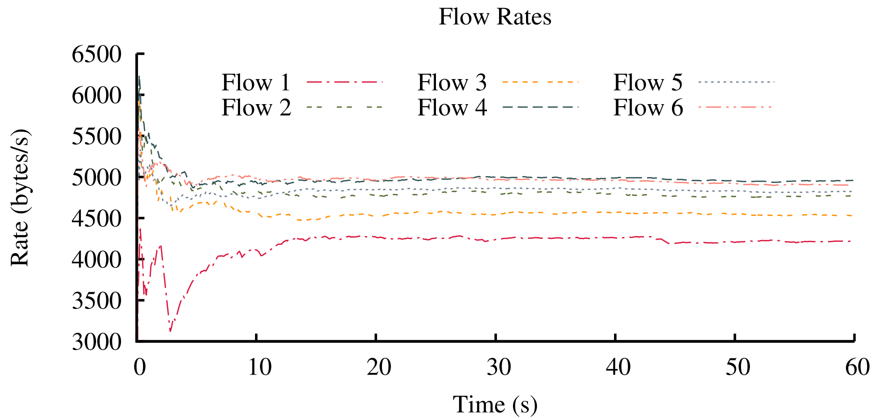
Performance evaluation: CRAHN flow rates



(a) No Pnet traffic



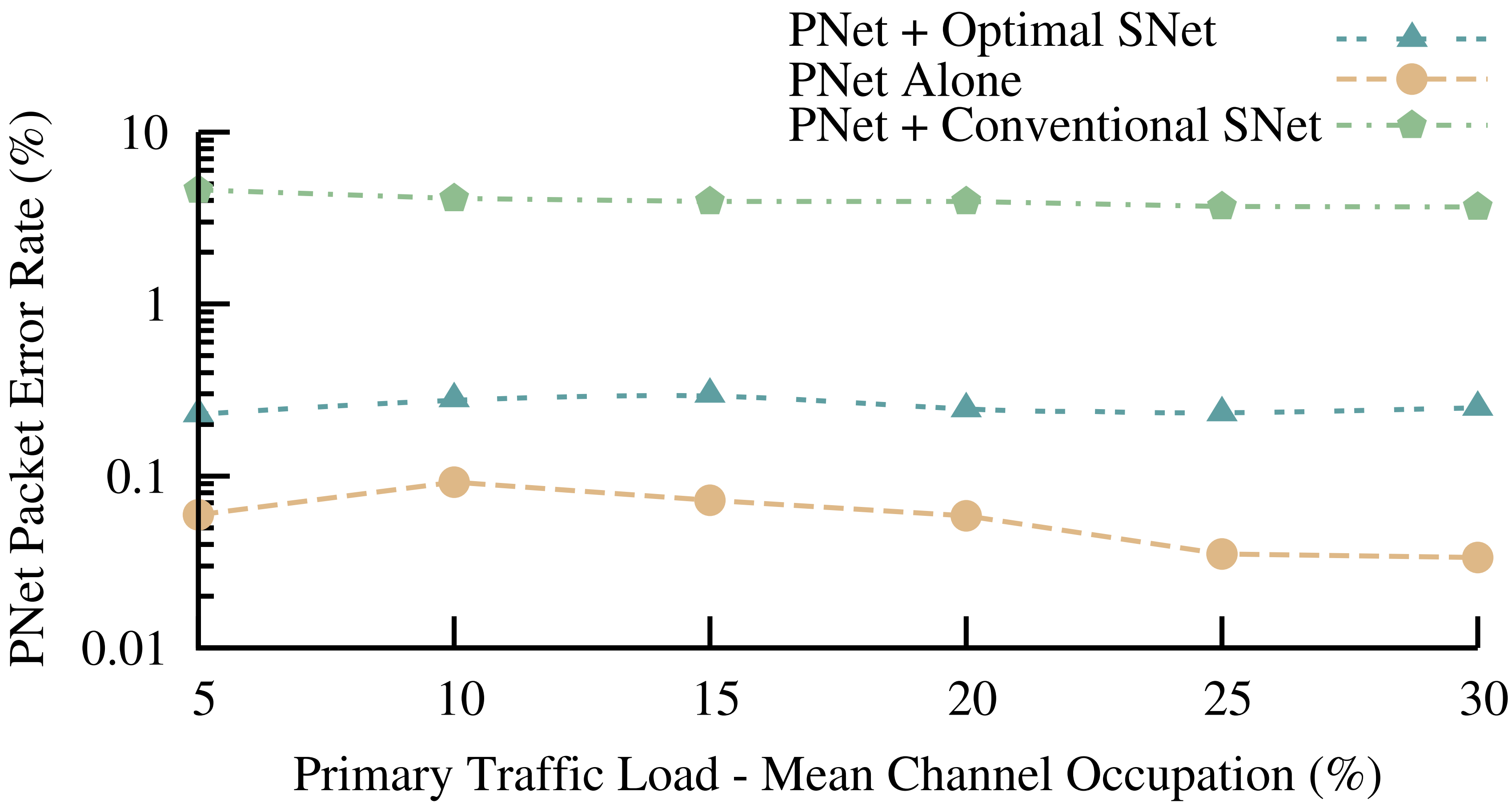
(b) 5% Pnet traffic



(c) 30% Pnet traffic

A Decentralized routing, MAC, and scheduling protocol for CRAHNs

Performance evaluation: impact on the Pnet packet error rate



IEEE MASS 2012

Las Vegas, Nevada, USA
October 2012

Goodput Maximization in Opportunistic Spectrum Access Radio Links with Imperfect Spectrum Sensing and FEC-based Packet Protection

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Overview

- Motivation: MAC and Link-level adaptation in opportunistic channel access (OSA) networks
- Goodput maximization
  - Perceived PU activity
  - SU packet transmission rate
  - SU Packet Error Rate
- Results
- Conclusion

MAC and Link Level adaptation in OSA networks

In conventional Wireless Networks:

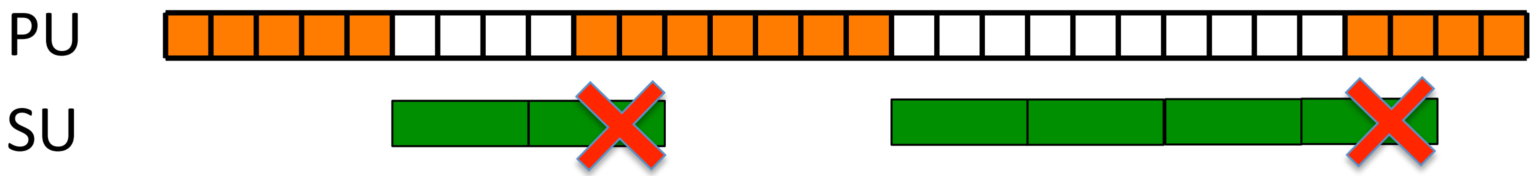
- Channel variations due to fading/mobility
- Multi User Interference: may be combated with CA, orthogonal channel access) …emphasis on maximizing *own* performance
- Service type

In OSA networks:

- Channel availability due to Primary Users (PU) channel use
  - Need to limit interference towards PU, preserving *its* performance
  - PU channel use modeled as a stochastic process with its own characteristics and time scales
  - SUs rely on spectrum sensing to detect PUs

MAC and Link Level adaptation in OSA networks

- PUs leaves unused resources to SUs in an unpredictable way (at least deterministically)
- SU should use the resources in a way that maximizes its throughput while avoidig using the same resources as Pus
- Packet: an atomic unit that can be decoded if and only if received entirely. ***Overhead + Payload***



- In conventional networks: packet size is limited by coding delay, link stability, and MU considerations
- In OSA: the presence of the PU has to be taken into account

MAC and Link Level adaptation in OSA networks

SU packet overhead:

1. Headers: non-application SDU data (IP addresses, MAC, ecc…)
2. FEC redundancy
3. Spectrum sensing

➢ Items 2 and 3 involve a tradeoff:

- ❑ Reduction of the payload, but…
- ❑ Decrease of the packet error probability
  - 2. -> more bit errors are corrected
  - 3. -> less miss detections/false alarms in the sensing phase

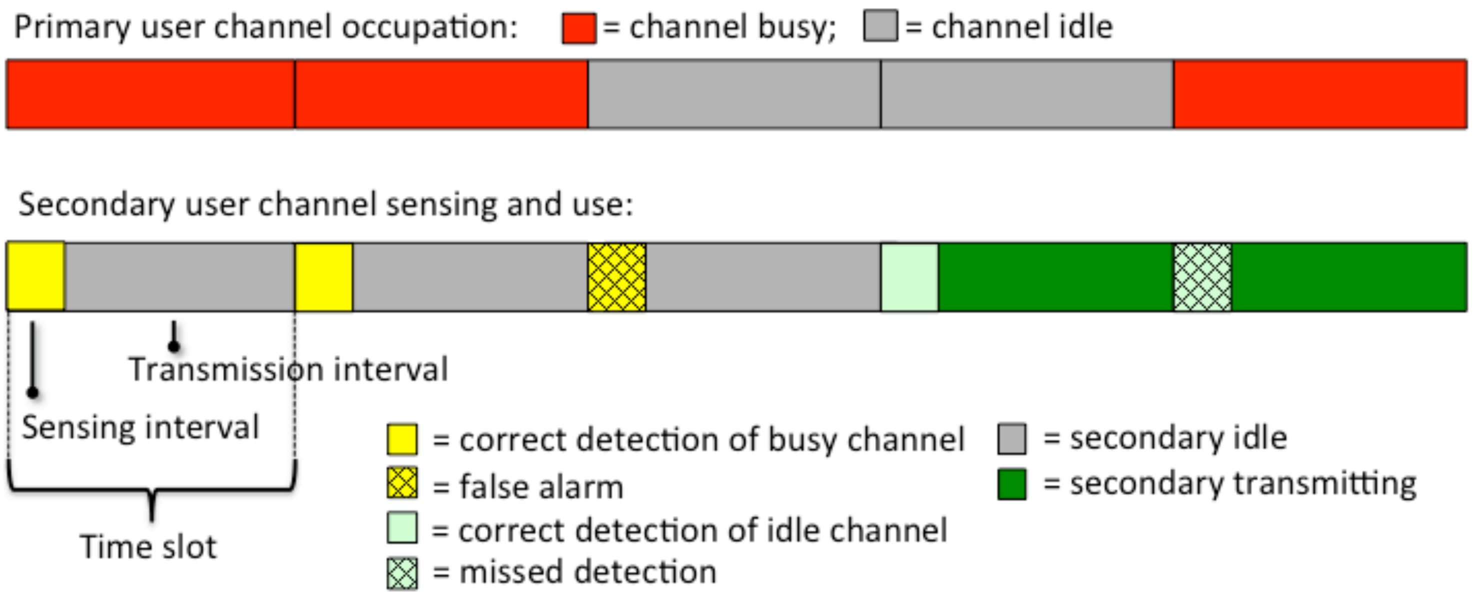
➢ FEC and PS may require to be jointly optimized for goodput maximization

➢ PU channel use statistics play a role

MAC and Link Level adaptation in OSA networks

Our assumptions:

- SU slots: sensig + data transmission
  - If during the sensing PU activity is detected, the packet trasmission is aborted
- Slotted channel access even for PU
- SU packets formed by *M* time-slots



Goodput maximization

$$\text{GOODPUT} = R_{TX} * (1\text{-PER}) * (1\text{-OH})$$

R_{TX} : SU packet transmission rate: how often SU manages to transmit in *M* consecutive slots

*It depends on the **perceived** PU traffic*

OH: overhead: includes headers, spectrum sensing resource reservation, FEC redundancy

PER: Packet error rate. Depends on the FEC and on the ***posterior probability that the sequence of transmission interval the channel was indeed not used by the PU***

$$\tilde{p}\left(\boldsymbol{s}_0\right) = \frac{p\left(\boldsymbol{x} = \boldsymbol{s}_0,\, \boldsymbol{y} = \boldsymbol{s}_0\right)}{p\left(\boldsymbol{y} = \boldsymbol{s}_0\right)}$$

Goodput maximization

$$GOODPUT = R_{TX} * (1\text{-}PER) * (1\text{-}OH)$$

Goal: find out the best FEC code and packet size in given channel conditions (SNR) and PU traffic statistics

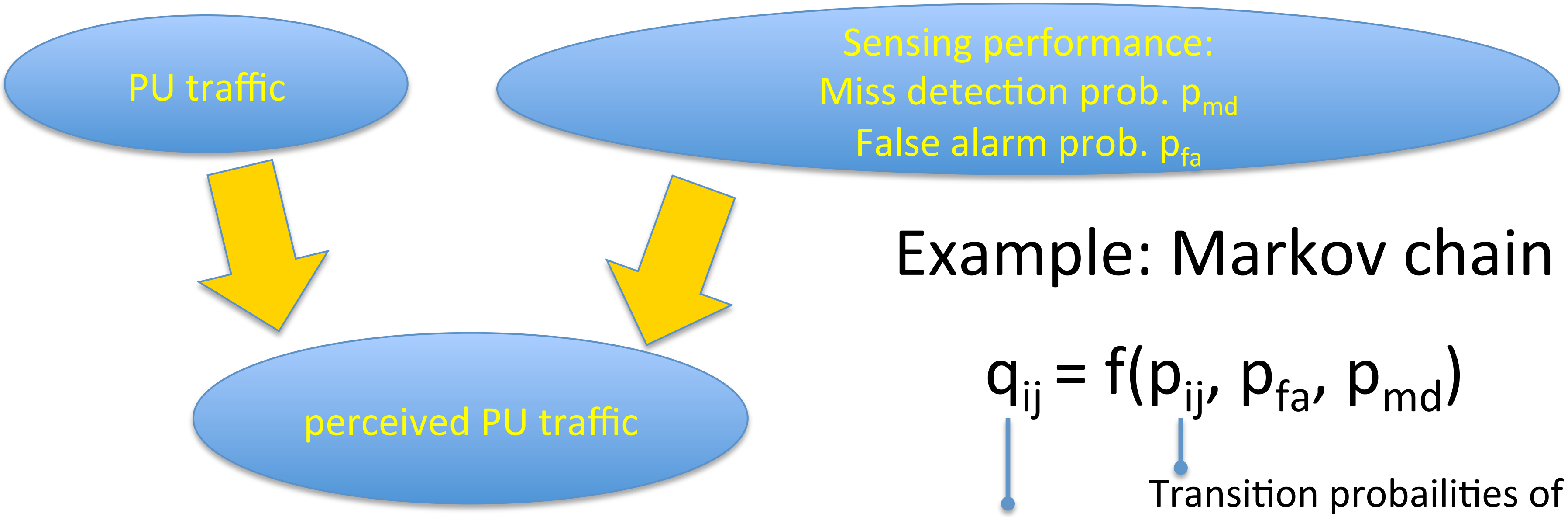
(with given spectrum sensing performance)

Goodput maximization

$$GOODPUT = R_{TX} * (1\text{-}PER) * (1\text{-}OH)$$

- Computation of the transmission rate R_{TX}

- SUs observe the channel through imperfect spectrum sensing



Example: Markov chain

$$q_{ij} = f(p_{ij}, p_{fa}, p_{md})$$

Transition probabilities of the observed states

Transition probabilities of the actual states

Goodput maximization

$$\text{GOODPUT} = R_{TX} * (1\text{-PER}) * (1\text{-OH})$$

- Computation of the transmission rate R_{TX}

- How much often does the SUs observes a sequence of *M* consecutive idle slots?

$$R_{Tx} = \frac{q_{01} q_{10} \left(1 - q_{01}\right)^{M-1}}{1 - \left(1 - q_{01}\right)^{M}} \frac{1}{q_{01} + q_{10}}$$

- Remember that this result embeds both PU traffic statistics and sensing performance $q_{ij} = f(p_{ij}, p_{fa}, p_{md})$

Goodput maximization

GOODPUT = R_{TX} * (1-PER) * (1-OH)

- Computation of the Packet Error Rate

- Cosider a class of convolutional codes, i.e. an encoder which retains the same structure for different packet lengths

  Nominal performance (valid in the absence of miss-detections!)

$$\bar{P}_e = \bar{P}_e\left(K, M, \mathcal{P}_{rx}/\sigma^2\right)$$

Coding rate SNR

- Exact PER should consider all the possible sequences of correct idle-detections and miss-detections

$$\boxed{P_e\left(K, M\right) = \sum_{i=0}^{2^M-1} P_e\left(\boldsymbol{s}_i\right)\tilde{p}\left(\boldsymbol{s}_i\right)}$$

Goodput maximization

GOODPUT = R_{TX} * (1-PER) * (1-OH)

- Computation of the Packet Error Rate

- Upper and lower bounds on the exact PER

$$P_e(\boldsymbol{s}_0) < P_e(K, M) < P_e(\boldsymbol{s}_0)\,\tilde{p}(\boldsymbol{s}_0) + (1 - \tilde{p}(\boldsymbol{s}_0))$$

where $\tilde{p}(\boldsymbol{s}_0) = \dfrac{p(\boldsymbol{x} = \boldsymbol{s}_0,\, \boldsymbol{y} = \boldsymbol{s}_0)}{p(\boldsymbol{y} = \boldsymbol{s}_0)}$,

and it can be showed that: $p(\boldsymbol{x} = \boldsymbol{s}_0,\, \boldsymbol{y} = \boldsymbol{s}_0) = p_0 p_{00}^{M-1} (1 - p_{fa})^M$.

$$p(\boldsymbol{y} = \boldsymbol{s}_0) = p_0 (1 - p_{fa}) \sum_{i=0}^{(2^{M-1}-1)} \prod_{k=2}^{M} p_{s_{k-1}^{(i)} s_k^{(i)}} \phi\left(s_k^{(i)}\right) + p_1 p_{md} \sum_{i=2^{M-1}}^{(2^M-1)} \prod_{k=2}^{M} p_{s_{k-1}^{(i)} s_k^{(i)}} \phi\left(s_k^{(i)}\right).$$

Goodput maximization

$$GOODPUT = R_{TX} * (1\text{-}PER) * (1\text{-}OH)$$

- Computation of the overhead:
  - Headers represent a fixed amount of overhead, independent of the packet size
  - Sensing OH and redundancy represent a fixed percentage of the packet length.

Goodput maximization

GOODPUT = R_{TX} * (1-PER) * (1-OH)

- Upper and lower bounds on the achievable goodput (i.e. in a SU traffic saturation regime)

$$R_{Tx}\left(1-\hat{P}_e\left(K,M\right)\right)b_m \leq G_{bits} < R_{Tx}\left(1-P_e\left(\boldsymbol{s}_0\right)\right)b_m$$

with $\hat{P}_e\left(K,M\right) = P_e\left(\boldsymbol{s}_0\right)\tilde{p}\left(\boldsymbol{s}_0\right)+\left(1-\tilde{p}\left(\boldsymbol{s}_0\right)\right)$

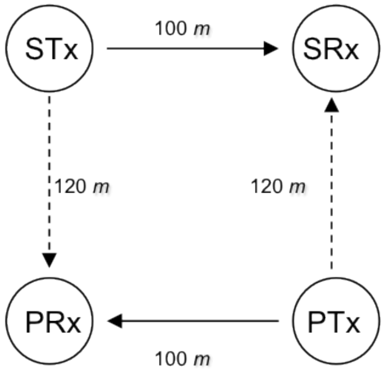
- Can we use these results to infer optimal packet size and FEC coding rate *K*?

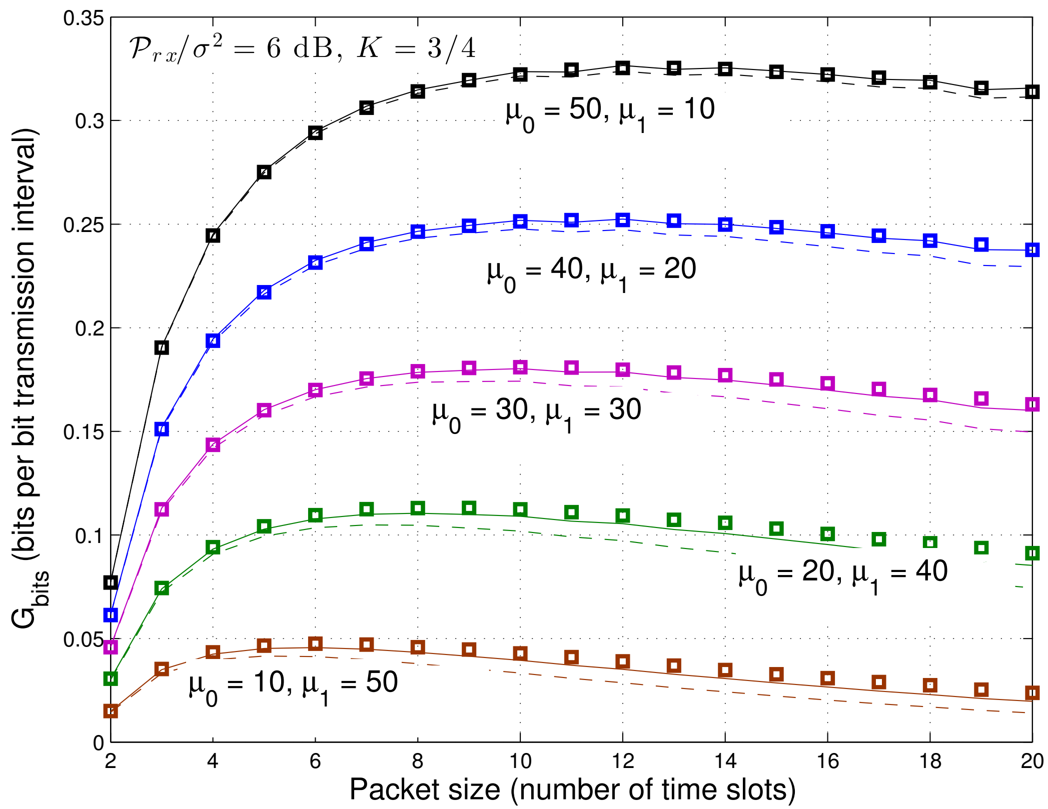
Results

- The upper and lower bounds can be used provided that p_{md} and p_{fa} are small numbers (<< 1).

Goodput for different PU traffic load. @SNR = 6dB

Solid lines = upper bound
dashed lines = lower bound
markers = simulations



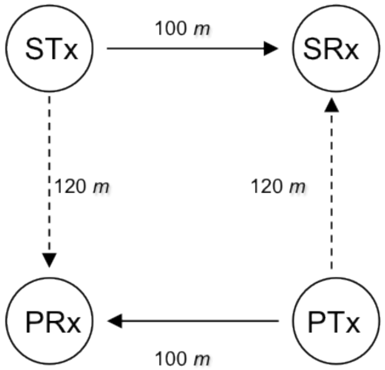


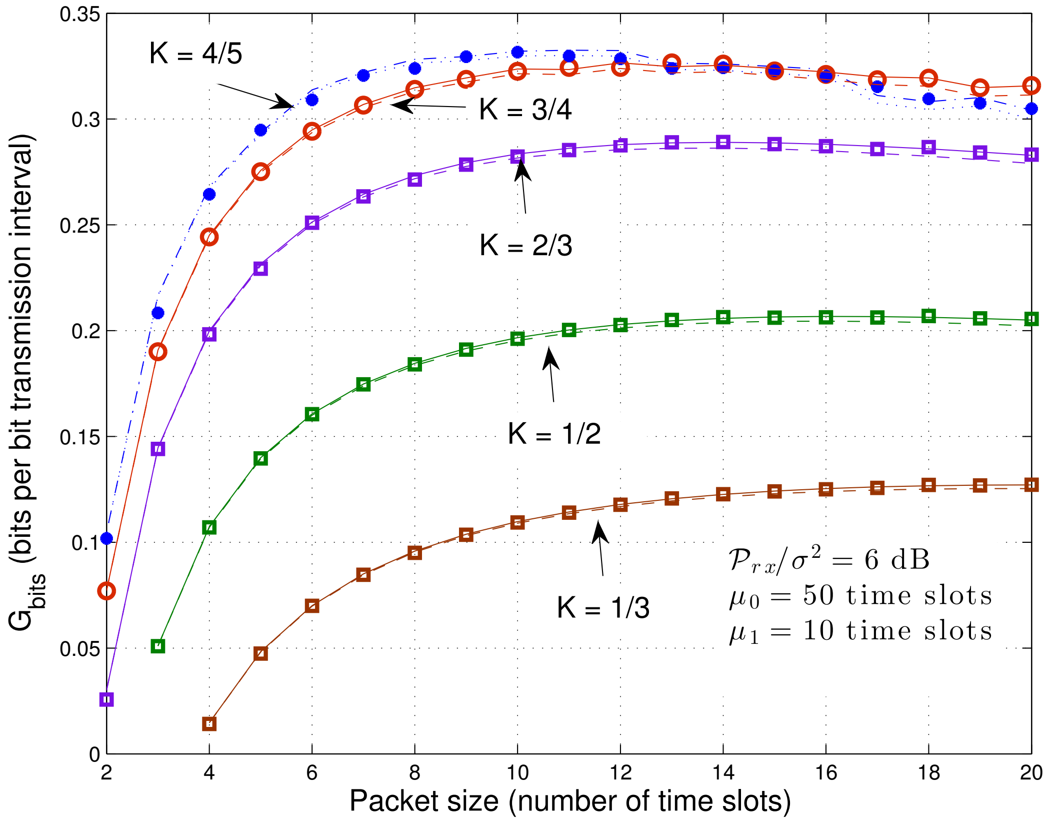
Results

- The upper and lower bounds can be used provided that p_{md} and p_{fa} are small numbers (<< 1).

Goodput for different coding rates. @SNR = 6dB

Solid lines = upper bound
dashed lines = lower bound
markers = simulations



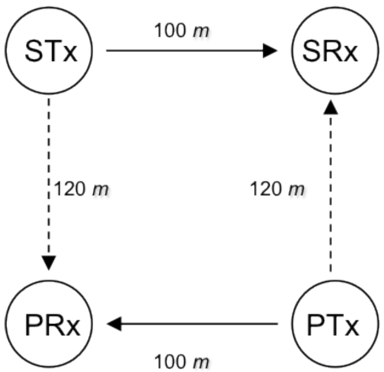


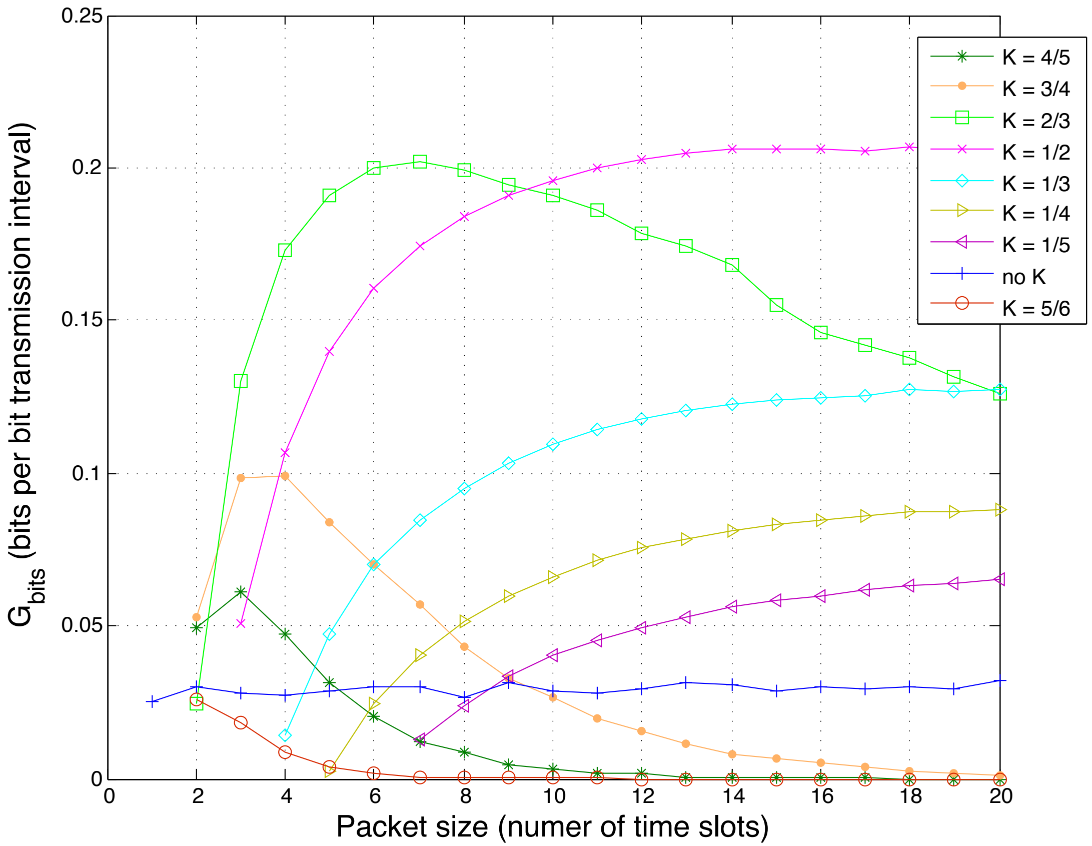
Results

➢ The upper and lower bounds can be used provided that p_{md} and p_{fa} are small numbers (<< 1).

Goodput for different coding rates. @SNR = 3dB

Solid lines = upper bound
dashed lines = lower bound
markers = simulations



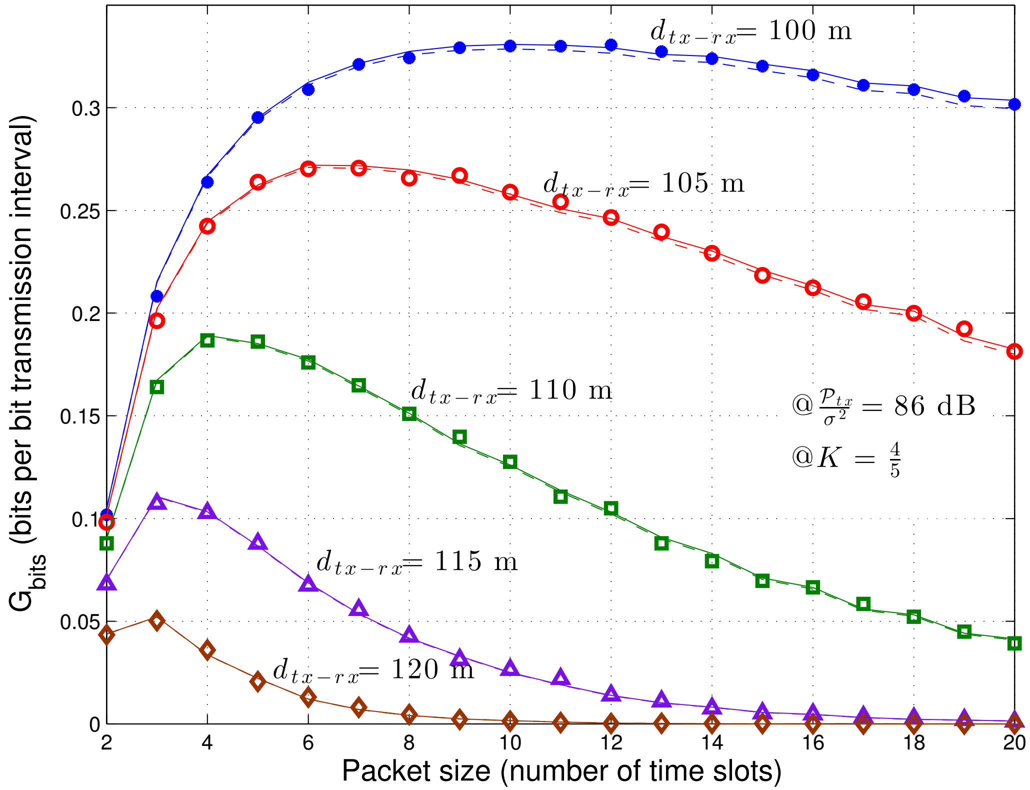


Results

- The upper and lower bounds can be used provided that p_{md} and p_{fa} are small numbers (<< 1).

Goodput for different Tx-Rx distances. @SNR = 6dB

Solid lines = upper bound
dashed lines = lower bound
markers = simulations



Conclusion

- ✓ Considered the problem of adapting the parameters of the data link and MAC layers to changing conditions in an CR-OSA scenario
- ✓ Taken into account OSA specific aspects such as PU traffic presence, spectrum sensing performance
- ✓ Closed form results for PER and Goodput (upper and lower bounds)
- ✓ Showed that Packet Size and Coding rate should be optimized jointly based on received power and PU traffic statistics