COGNITIVE TRANSCEIVERS FOR WIRELESS RELAYING SYSTEMS

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ABSTRACT:
In this paper we investigate possible solutions to the problems of the increasing interference and decreasing QoS in future wireless networks, by studying wireless cooperative diversity systems under a novel point-of-view, in order to fully exploit their benefits. To this end, cognitive transceivers need to be developed within a novel framework, which will merge the technologies of cognitive radio and cooperative diversity at the PHY-layer.

Key words: Cooperative systems, cognitive systems.

I. INTRODUCTION

The increasing need for reliable communication anytime anywhere is expected to lead to a tremendous growth in the number of users in wireless communication networks, bringing about major technical problems such as the significant increase of the interference level and the decrease of the per-user available bandwidth. Additionally, these problems are expected to deteriorate due to the continuously increasing demand for wireless multimedia and web-based applications, which require efficient data rates and high level of Quality of Service (QoS). Furthermore, the evolution of real-time mobile multimedia communication underlines the necessity for energy-efficient strategies, since the terminals involved are mainly mobile, i. e., battery-powered.

The above issues have raised serious concerns that no existing multiple access technique would be able to cope with the challenges promised by future wireless

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networks. Although some research efforts have been directed towards such a solution, they mainly focus on investigating higher parts of the frequency spectrum, or on improving existing techniques by using novel resource allocation algorithms. To this end, the concept of *wireless relaying* transmissions was recently proposed as an alternative method for combating fading, by utilizing a set of independent terminals that act as relays. These systems, that actually form distributed Multiple-Input Multiple-Output (MIMO) setups, are usually referred to as *cooperative diversity systems*, since they attain the beneficial effects of diversity in fading channels by forming virtual antenna arrays, i. e., arrays whose elements are not co-located but carried by individual, spatially distributed terminals. Such terminals may be either fixed (infrastructure-based relays) or mobile. Nonetheless, although cooperative diversity has been thought of as an efficient method for enhancing the system's QoS and coverage, its promising potential to tackle the aforementioned problems has not been exploited yet.

In this work, we aim at fully exploiting the benefits of wireless relaying systems by designing them within a novel framework. To be more precise, the distributed nature of wireless relaying systems can be utilized so that *the apparent disadvantage of the increasing number of users would turn into an advantage.* This stems from the fact that the relays involved could actually represent the *degrees of freedom of a dynamic system,* allowing for an opportunistic allocation of the available resources. We emphasize that wireless relaying systems can offer high diversity gains that entail a considerable reduction on the per-user transmitting power; *this leads to a significant reduction on the total interference level, resulting finally in a capacity increase*. However, there is a key issue that prevents the realization of this vision today. This is the limited capabilities of the existing transceivers to intelligently observe the operating environment and thus make fast logic decisions, which aim at optimizing the system's performance. In other words, a possible implementation of the cooperative diversity concept under the existing transceiver's design could lead to the opposite results (e. g., interference increase from multiple re-transmissions), since it would actually resemble the attempt to make a logical conversation by using only the words „yes" and „no".

Towards this end, we support that in order this novel concept to be realized, *the transceivers involved need to be cognitive*, or equivalently, *the physical layer (PHY-layer) technologies of cognitive radio and cooperative diversity need to be merged*. This would enable wireless relaying systems to intelligently adapt several of their features to time-variant environments and applications, contributing thus substantially to the alleviation of the spectral inefficiency problem that cooperative transmissions suffer from [1]-[3]. Towards this direction, cognitive transceivers will be able to identify the so-called spectrum holes (i. e., licensed band sectors that are temporarily idle [4]), and „comprehensively *converse*" with each other in order to optimally manage the available resources. For instance, one interesting perspective that seems to follow this novel approach is the formation of *„virtual cells-in the-cell",* where neighboring cognitive transceivers intelligently form groups with specific characteristics (e. g., the number of idle and active terminals or the time for which the terminal are active or idle), in order to be typically isolated from other

virtual cells- in the cell, resulting in interference reduction, bandwidth reuse capabilities and better exploitation of the wireless medium.

Apparently, a comprehensive research on cognitive wireless relaying systems, involves a cross-layer cognition analysis. This work, however, will mainly focus on the PHY-layer (i. e., cognitive transceivers for wireless relaying systems-CONVERSE) due to the direct relationship of the cooperative diversity concept with the wireless medium (e. g. small and large scale fading), the optimum exploitation of which has a significantly positive impact on system's performance.

To sum up, the main objective of this work is to *investigate possible solutions to the problems of interference increasing and QoS decreasing in future wireless networks, by studying wireless cooperative diversity systems under a novel point-of-view, in order to fully exploit their benefits. To this end, cognitive transceivers need to be developed within a novel framework, which will merge the technologies of cognitive radio and cooperative diversity at the PHY-layer.*

The research on this new perspective is expected to be long-term, involving the combined research on several fundamental areas, such as channel modeling, spectrum acquisition, optimum transceiver design, implementation of well-known diversity techniques in a distributed fashion, etc.

II. BASIC CONCEPT

In order to attain the main objective of this work referred to above, the sub-objectives that need to be met are the following (Figure 1):

A. *Optimal transceiver design; optimal relay-selection and power allocation techniques*

Optimizing the transceivers involved, in terms of modulation, coding and diversity strategies employed, constitutes a vital part of this work, significantly affecting the resulting performance. Moreover, the degrees of freedom endowed with cooperative diversity can be appropriately utilized *by using optimal relay-selection and power allocation methods*. Such techniques aim at optimizing the use of relays (under a software-based cognitive concept), either by selecting only a subset out of the set of the available ones (according to certain criteria), or by adapting their transmission power in order to minimize the interference and power consumption, towards the optimum performance. An energy-based relay assignment must have both a large-scale and an individual perspective, e. g., aiming at minimizing the total energy consumption while satisfying the terminals' needs, on an individual basis. Additionally, distributed space-time coding techniques in the presence of co-channel interference will be analyzed and thereby assessed (under a cognitive perspective as well).

B. Channel modeling

To the best of our knowledge, a complete statistical analysis of the relaying channel has not been conducted yet, when both a mobile-mobile and a mobile-fixed channel are considered, rendering it an important goal for their analysis. Additionally, the need for an accurate channel modeling is also followed from the fact that in cognitive systems the communication environment must be statistically known, in order to achieve an intelligent adaptation (see also below the ensuing „adaptation and learning" sub-objective).

C. Adaptation and learning

The transceivers involved must have the ability to adapt several of their features to channel variations and each time application demands. Such features include transmitting power, bandwidth and modulation used, as well as selection of the available relays, in conjunction with their type (e. g. fixed or mobile, regenerative or non-regenerative etc). We note, that the *adaptation of the relaying systems' special features* actually consists the main part of this objective. Moreover, it is our aim to make the CONVERSE terminals capable of recording the user's moves and habits (as much as this is possible), allowing thus for a better self-adaptation through learning.

D. Spectrum acquisition

Another issue of great importance in this work is the spectrum acquisition techniques involved, i. e., techniques for identifying the spectrum holes (i. e., licensed band sectors that are temporarily idle). Apparently, such acquisition needs to be rapid and accurate, since otherwise it may lead to an inefficient use of the available spectrum or to a high level of interference. We emphasize that in order to guarantee an accurate spectrum acquisition, it is necessary that channel path-loss and shadowing effects are taken into account. Such techniques have not been developed yet; to this end, *relaying transmissions offer an efficient method for tackling the problem of hidden terminals.*

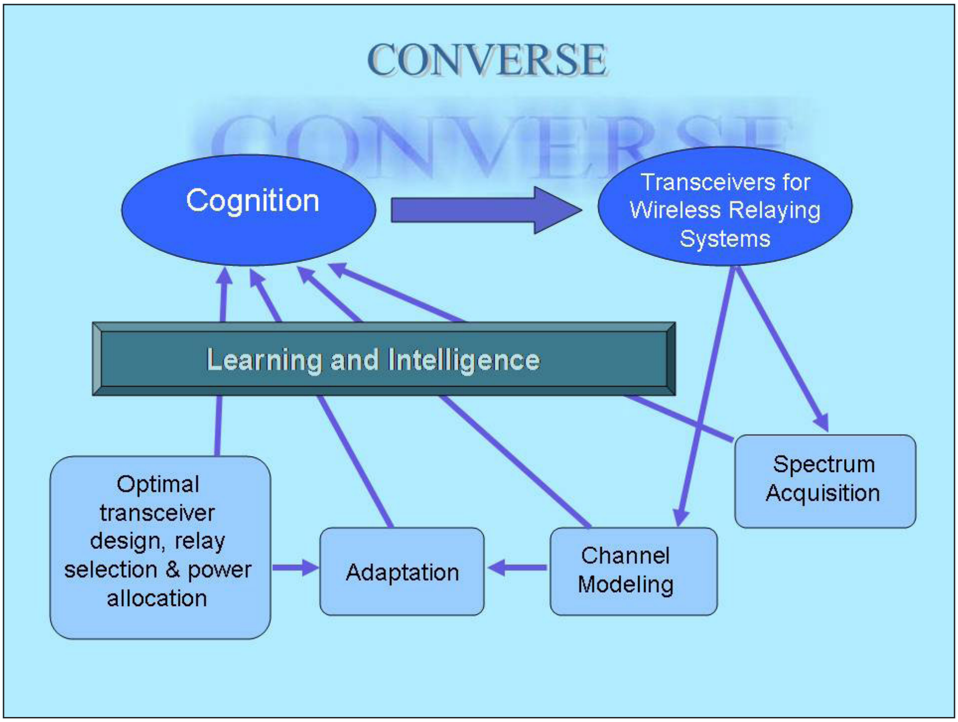

Fig. 1. CONVERSE. Merging Wireless relaying systems with cognitive technology.

III. IMPLEMENTATION

Below, we summarize the key elements, necessary for implementing the proposed system, i. e., the steps need to be followed in order to meet the sub-objectives described above.

A. Optimal transceiver design; optimal relay-selection and power allocation techniques

Optimizing the transceivers' functionality, as well as the relays' activation and transmitting power, requires exhaustive theoretical analysis that involves several fundamental research areas such as diversity techniques, modulation and coding, space-time coding, optimization theory etc. Certain performance metrics (like outage probability, bit error probability and energy consumption) will be expressed as functions of controllable parameters (for instance, the relays' transmitting power), allowing for a direct transceiver calibration. We emphasize that, contrary to existing works on cooperative diversity, interference will be also included in the corresponding analysis.

B. Channel modeling

In order to attain an accurate modeling of the wireless relaying channel, both sampling and statistical analysis of the derived results are required. The sampling part consists of exhaustive channel measurements in various environments, such as indoor, outdoor, urban, suburban etc, including both the mobile-fixed and the mobile-mobile channel. The theoretical part undertakes a statistical extension of the above results to relaying channel, i. e., the virtual source-relay-destination one. Correlation of the fading channels will be also taken into account, by employing advanced statistical techniques (e. g., the stochastic geometry-based approach). Both large-scale (shadowing) and small-scale fading realizations will be concerned, with emphasis on the latter due to the more complex fading mechanisms involved.

C. Adaptation and learning

Apparently, the transceivers' adaptation to the application's demands requires low complexity techniques that will provide a quick foreknowledge of the imminent performance given the terminals' channel state knowledge; this may refer to either knowledge of the long-term channel, (i. e., knowledge of average channel gains), or the short-term one. Therefore, performance expressions that allow for a quick and easy process (e. g., closed-form ones) will comprise one of the main parts of this sub-objective. The learning part will focus on a statistical processing of the terminals' behavior history (e. g., a data-burst or mobility record).

D. Spectrum acquisition techniques

The spectrum scanning techniques will aim at obtaining a quick and accurate spectrum overview, periodically updated at a rate that reaches a happy medium between reliable acquisition and complexity involved. To this end, spectrum acquisition in this work will be relay-assisted, resulting in a better spectrum overview throughout the whole communication range. In general, spectrum acquisition will be energy-based, i. e., a band sector will be considered idle (and thus free of use) if the energy on that band is below a given threshold. The impact of imperfect or outdated spectrum acquisition on the interference level will be also measured and thereafter parameterized.

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Wireless Communications

Present, Future and Research Challenges

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Outline

- ✓ The Wireless Life-Style
- ✓ MIMO
- ✓ Cooperative Systems
- ✓ Cognitive Radio
- ✓ Cognitive transceivers for wireless relaying systems
- ✓ Summary

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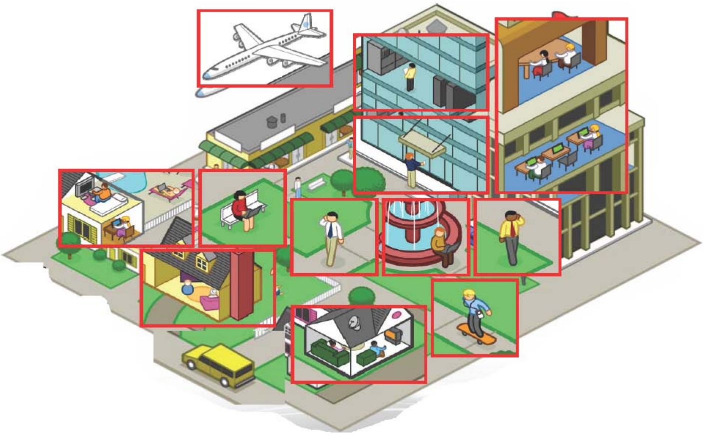
The Wireless Life-Style
Seamless, Reliable, High-performance



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The Wireless Life-Style
Everything in one device

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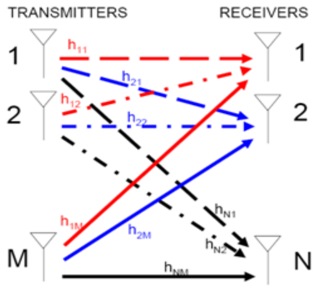
Multiple Input Multiple Output (MIMO)



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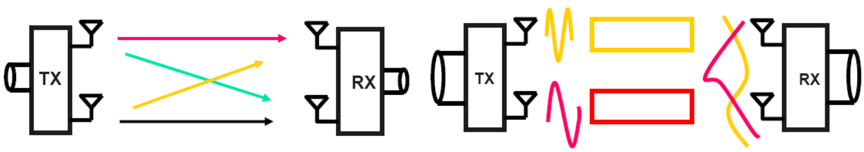
MIMO

Spatial Multiplexing and Space-Time Coding

- ✓ MIMO provides additional capacity.
- ✓ This capacity can be used as:
  - ❑ **Spatial Multiplexing**
    - Data rate increases by channel demultiplexing
    - Data streams are independent
    - BER remains the same
  - ❑ **Space-Time Coding**
    - Data rate remains the same but BER is improved
  - ❑ Combinations are possible (Diversity-Multiplexing Trade-off)



Spatial Diversity: Increased SNR

Spatial Multiplexing: Increased rate

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MIMO
Reduced Power Consumption

- ✓ MIMO Enables Data Bursting
  - ❑ Burst Data at High-speed, then Shut Down Radios
- ✓ MIMO Provides Diversity Gain
  - ❑ With 4 Antennas (2x2 or 4x1), Required Power Reduced by 6 dB
  - ❑ Provides Robustness
    - Fewer Retransmission
      - ➢ Less Power/Packet
      - ➢ Less Interference to Other Users

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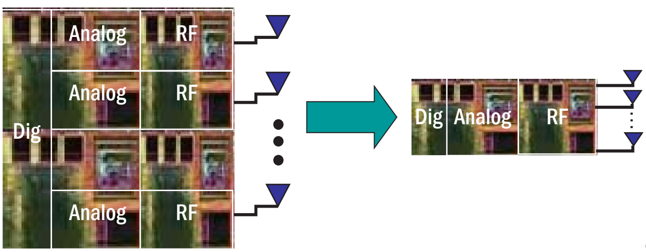
MIMO
Chipsets

- ✓ Typically each antenna requires RF and analog receive chain
  - ❑ Increased cost, size, and power
- ✓ Technology evolving to reduce size/power for digital
  - ❑ Little impact on RF/analog circuitry
- ✓ Technology breakthroughs needed to provide same reductions for analog and RF circuitry
  - ❑ Small multi-band antenna designs also critical



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MIMO
Standards

- ✓ MIMO techniques are beginning to make an appearance in standards.
  - ❑ WiMAX (802.16d)
  - ❑ Mobile WiMAX (802.16e)
  - ❑ Next generation Wi-Fi (802.11n)
    - Enhancements to OFDM PHY
      - ➢ Enables 2 x 2 MIMO operation in 20 MHz to achieve 100 Mbps throughput
      - ➢ Up to 4 x 4 MIMO to achieve 500+ Mbps
    - Bandwidth extension option
      - ➢ User channel doubling (40 MHz) to further increase data rate
  - ❑ 3GPP (UMTS).
    - Space-Time Transmit Diversity (STTD)

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MIMO
Research Challenges

- ✓ Better chipset design
- ✓ *The MIMO cube*: A compact MIMO with 12 antennas at the edges of the cube [Getu & Andersen,2005]
- ✓ Quasi-orthogonal space-time coding
- ✓ Operation with “Best Antenna Subset Selection”

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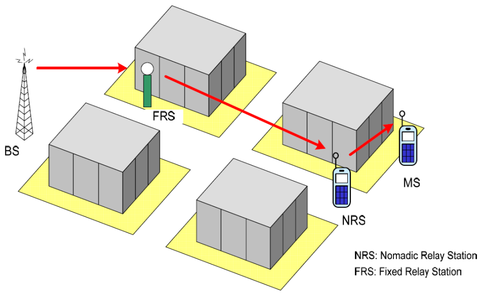
MIMO
Summary

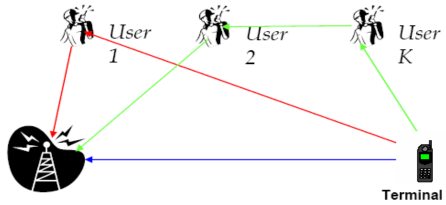
- ✓ Intensive academic interest in MIMO started about 12 years ago
- ✓ MIMO systems gain most capacity benefit in multi-path scattering environments (e.g. indoor or dense urban)
- ✓ MIMO capacity can be used for spatial multiplexing or space-time coding
- ✓ Versions of Orthogonal STBC are widespread through-out standards
- ✓ Some experimental systems have shown good results in lab/office environments
- ✓ Some WCDMA network simulations (Ericsson) have shown reasonably promising results. Other less optimistic (Nokia)
- ✓ Commercial MIMO chipsets available now

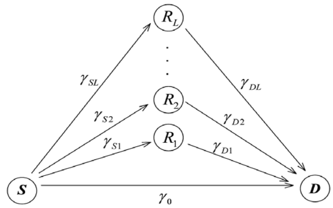
Cooperative Communications
The Distributed MIMO Concept

- ✓ **Question**: Is there any way to face the limits of the MIMO system's configuration?
- ✓ **Alternatively**: Could we translate the well-known receiver (or the transmitter) diversity techniques, under a distributed perspective?
- ✓ **Answer**: The distributed MIMO concept

Cooperative Communications
The Distributed MIMO Concept







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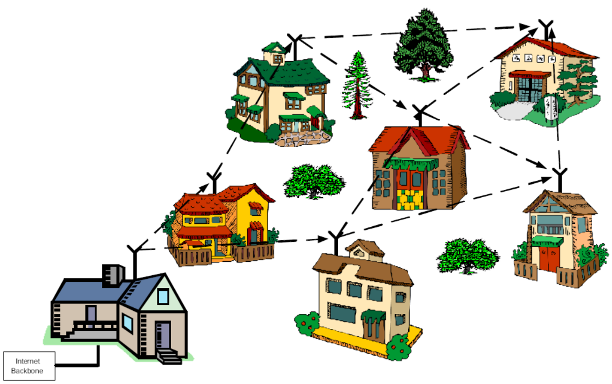
Cooperative Communications
Applications: In-Home Broadband Access

- ✓ Nokia has proposed to deliver high-speed data to sparse residential areas by means of roof-top relaying systems.



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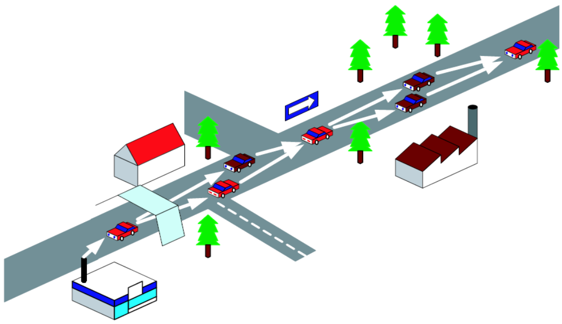
Cooperative Communications

Applications:Vehicle-to-Vehicle Communication

- ✓ Future vehicles will allow for automated steering within a group of cars, in-vehicle internet access, inter-vehicle communication, etc.
- ✓ The increasing density of vehicles allows the deployment of distributed relaying vehicle systems which can support above systems with low probability of outage.



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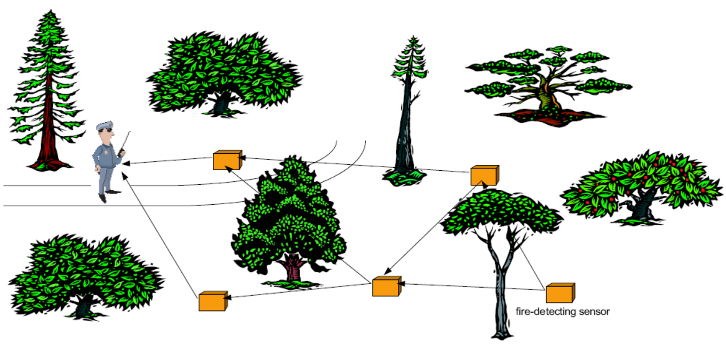
Cooperative Communications

Applications: Sensor Networks

- ✓ Large scale sensor networks are only recently emerging with a large spectrum of applications.
- ✓ Distributed relaying will be shown to decrease the power consumption per relaying sensor node.



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Cooperative Communications
Research Challenges

- ✓ Channel Modeling
  - ❑ First & second order statistics of the relaying fading channel
  - ❑ To find simple and tight approximations for the statistics of the dual-hop (or multi-hop) channel, which will help in the performance analysis.
- ✓ Link Capacity
  - ❑ "Capacity' with constraints, e.g. imperfect CSI, delay limits, etc.
- ✓ Distributed synchronization
- ✓ Choice of relaying & cooperation (AF/DF/hybrid?)
- ✓ Coding/modulation strategies

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Cooperative Communications
More Research Challenges

- ✓ Distributed transmit antenna selection
  - ❑ A subset of the available relays that is going to participate in the cooperative process needs to be appropriately selected according to certain criteria-constraints
- ✓ Simpler cooperative schemes (e.g distributed switched diversity)
- ✓ PHY-Layer Fairness
  - ❑ Cooperative diversity involves usage of the remaining cooperating users's energy, which they involuntarily waste for the sake of a partner.
  - ❑ There is a need for design from a fairness point of view.
  - ❑ The concept of fairness at the PHY-layer aims at equally allocating the total consumed energy among the relays.
- ✓ Switching rate of cooperative links in time varying channels
  - ❑ Implementing selective cooperative relaying in time-varying channels may cause frequent relay switching that deteriorates the overall performance

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Cooperative Communications

✓ The nature teaches…

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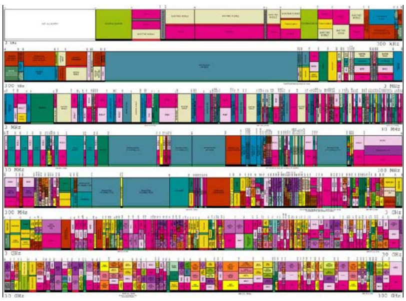
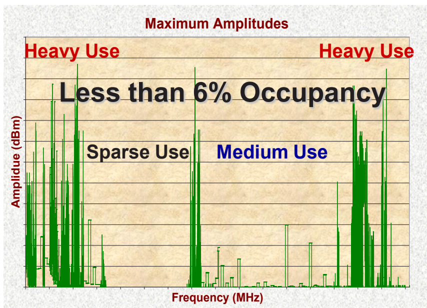
Cognitive Radio

Motivation

✓ Existing spectrum policy forces spectrum to behave like a fragmented disk

✓ FCC measurement shows that occupancy of approximately 700 MHz of spectrum below 1 GHz is less than 6~10%





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Cognitive radio
Spectrum Sharing

- ✓ Existing techniques for spectrum sharing:
  - ❑ Unlicensed bands (WiFi 802.11 a/b/g)
  - ❑ Underlay licensed bands (UWB)
  - ❑ Opportunistic sharing
- ✓ Drawbacks of existing techniques:
  - ❑ No knowledge or sense of spectrum availability
  - ❑ Limited adaptability to spectral environment
  - ❑ Fixed parameters: BW, Fc, packet lengths, synchronization, coding, protocols, …
- ✓ New radio design philosophy: all parameters are adaptive
  - ❑ Cognitive Radio Technology

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What is Cognitive Radio?

- ✓ Evolution of the SDR
- ✓ Cognitive radio properties
  - ❑ RF technology that "listens" to huge swaths of spectrum
  - ❑ Knowledge of primary users' spectrum usage as a function of location and time
- ✓ Cognitive radio requirements
  - ❑ co-exists with legacy wireless systems
  - ❑ uses their spectrum resources
  - ❑ does not interfere with them

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Cognitive Radio
Conclusions and Research challenges

- ✓ Derive system specification from measurements
- ✓ Develop and implement algorithms for:
  - ❑ Sensing environment
  - ❑ Dynamic frequency selection and adaptive modulation
  - ❑ Transmit power control
  - ❑ Interference cancellation
  - ❑ Spectrum rental strategies
- ✓ Test algorithms in realistic wireless scenarios

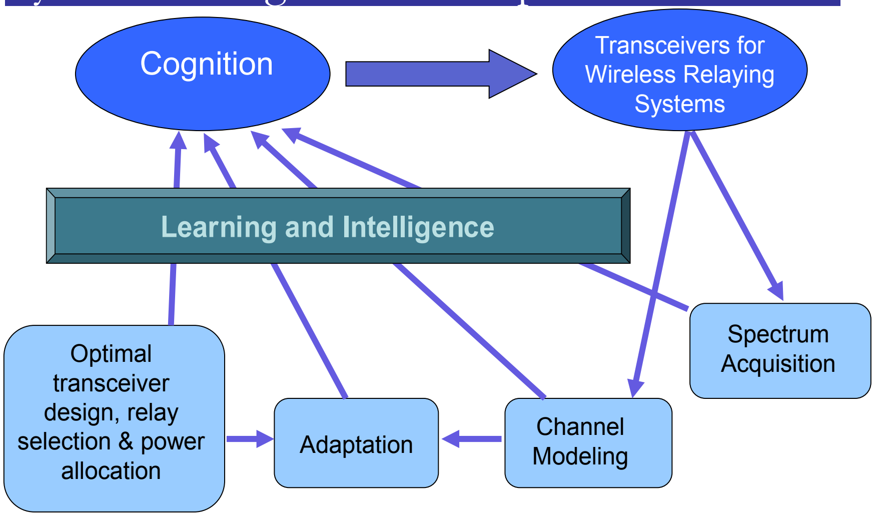
Cognitive Transceivers for Wireless Relaying Systems

- ✓ **Questions**:
  - ❑ Could we face the core problems of future wireless communications systems, *the interference increasing and QoS decreasing*, by looking at the wireless cooperative systems under an alternative point-of-view?
  - ❑ Does the distributed nature of wireless relaying systems can be utilized so that the apparent disadvantage of the increasing number of users would turn into an advantage?
- ✓ **Answer**:
  - ❑ The answer is YES if the transceivers involved are cognitive, or equivalently, **the PHY-layer technologies of cognitive radio and cooperative diversity are merged**.
    - This would enable wireless relaying systems to intelligently adapt several of their features to time-variant environments and applications.
- ✓ The research on this new perspective is expected to be long-term, involving the combined research on several fundamental areas, such as channel modeling, spectrum acquisition, optimum transceiver design, implementation of well-known diversity techniques in a distributed fashion, etc.

Cognitive transceivers for wireless relaying systems: More thoughts…

- ✓ The relays involved in a wireless relaying system, could actually represent the degrees of freedom of a dynamic system, allowing for an opportunistic allocation of the available resources.
- ✓ Wireless relaying systems can offer high diversity gains that entail a considerable reduction on the per-user transmitting power; this leads to a significant reduction on the total interference level, resulting finally in a capacity increase.
- ✓ Cognitive transceivers will be able to identify the so-called spectrum holes and "comprehensively converse" with each other in order to optimally manage the available resources.

Cognitive transceivers for wireless relaying systems: The general concept



Lecture Summary

- ✓ In future networks, one device will enable a seamless wireless lifestyle.
- ✓ High-performance reliable wireless networks will be available indoors and outdoors.
- ✓ MIMO will be in all wireless systems
- ✓ Cooperative communications (Distributed MIMO) will offer MIMO performance in practice.
- ✓ Merging of cognitive radio and cooperative communications seems to be the revolutionary concept.

- ✓ Thanks for your attention

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