# Cooperative Cognitive Relay Networks: Diversity and Outage Performance

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## Introduction

- Cooperative Communications
  - Wireless channel impairments and limited resources
    - ✓ Challenge on reliable wireless communications
  - Spatial diversity techniques
    - ✓ MIMO: dramatic increase in spectral efficiency without bandwidth penalty
    - ✓ Practical limitations of employing MIMO systems
  - Cooperative Relaying Techniques
    - ✓ Cooperative strategies
    - ✓ Distributed virtual antenna array
    - ✓ Robust connectivity, Improved coverage, and capacity increase.

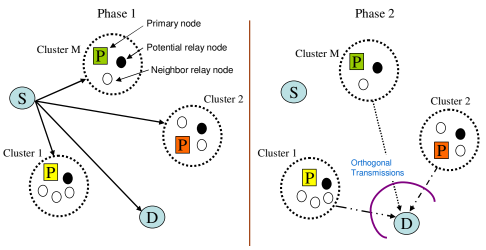
## Introduction (cont'd)

- Cognitive Radios
  - The demand for spectrum is expected to grow rapidly in the near future.
  - The Current inflexible spectrum allocation policy results in the underutilization of overall spectrum.
  - Cognitive radios as a open spectrum policy
    - ✓ Opportunistic spectrum sharing
  - Cooperative Cognitive Relay Networks
    - Inspired by the foregoing two futuristic aspects
    - Provide reliability and capacity increase as well as efficient spectrum utilization

## Objective

- Outage performance of cooperative cognitive relay networks
- High SNR approximation of outage probability to examine the diversity order
  - Improve robustness to fading
  - Reduce transmit power for the same level of performance.
- Impact of spectrum acquisition capability on the outage performance
  - Perfect Spectrum Acquisition
  - Imperfect Spectrum Acquisition
  - Cooperative Spectrum Acquisition

## System Model




- The received SNR at the relay and the destination

$$\gamma_{sr_i} = SNR|h_{r_i d}|^2,\quad \gamma_{sd} = SNR|h_{sd}|^2,\quad \gamma_{r_i d} = SNR|h_{r_i d}|^2$$

$SNR = P / N_0 W$ ($P$: transmitted power, $W$: equal BW for all licensed channels, $N_0$: AWGN variance)

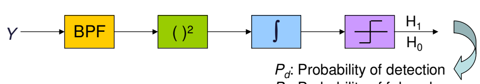
$h_* =$ fading coefficient CSCG with variance $1/\lambda_*$

## Spectrum Acquisition In Rayleigh Fading

- Primary user broadcasts a beacon ($X_b$) whenever the spectrum is available.
- Detection of unknown signal : Energy detector
  - Hypothesis testing problem

$$Y = \begin{cases} N, & H_0 \\ hX_b + N, & H_1 \end{cases}$$

$H_0$: Spectrum hole is not available, $H_1$: Spectrum hole is available
$N$: AWGN at the potential relay, $h$: fading coefficient




$P_d$: Probability of detection
$P_f$: Probability of false alarm

## Outage Performance

- Outage occurs when the mutual information ($I$) falls below a certain rate ($R$).

$$P_{out} = \sum_{R(s)} \Pr[I < R | R(s)] \Pr[R(s)]$$

- Regenerative Decode and Forward (RDF)

$$I_{RDF} = \frac{1}{M+1}\log\left(1 + SNR|h_{sd}|^2 + SNR\sum_{r_i \in R(s)} |h_{r_i d}|^2\right)$$

- Non-regenerative Decode and Forward (NDF)

$$I_{NDF} = \frac{1}{M+1}\log\left(1 + SNR|h_{sd}|^2\right) + \frac{1}{M+1}\sum_{r_i \in R(s)} \log\left(1 + SNR|h_{r_i d}|^2\right)$$

- Amplify and Forward (AF)

$$I_{AF} = \frac{1}{M+1}\log\left(1 + SNR|h_{sd}|^2 + \sum_{r_i \in R(s)} f\left(SNR|h_{sr_i}|^2, SNR|h_{r_i d}|^2\right)\right),\ \text{where } f(x,y) = xy/(x+y+1)$$

## Perfect Spectrum Acquisition

- Idealistic scenario: the potential relay nodes always acquire the spectrum holes successfully whenever they are available
  - RDF

$$P_{out} \approx \left[\frac{2^{(M+1)R}-1}{SNR}\right]^{M+1} \lambda_{sd} \sum_{R(s)} \prod_{r_i \in R(s)} \lambda_{r_i d} \prod_{r_i \notin R(s)} \lambda_{sr_i} \frac{1}{(|R(s)|+1)!}$$

  - NDF

$$P_{out} \approx \left[\frac{1}{SNR}\right]^{M+1} \left(2^{(M+1)R}-1\right)^{M} \lambda_{sd} \sum_{R(s)} \left(2^{(M+1)R}-1\right)^{-|R(s)|} \prod_{r_i \in R(s)} \lambda_{r_i d} \prod_{r_i \notin R(s)} \lambda_{sr_i} G_{|R(s)|+1}((M+1)R)$$

$$\text{, where } G_k(t) = \int_0^t G_{k-1}(t-x) 2^x \ln 2\, dx,\ k = 2,3,\ldots \text{ and } G_1(t) = 2^t - 1$$

  - AF

$$P_{out} \approx \left[\frac{2^{(M+1)R}-1}{SNR}\right]^{M+1} \lambda_{sd} \prod_{i=1}^{M} \left(\lambda_{sr_i} + \lambda_{r_i d}\right) \frac{1}{(M+1)!}$$

*Full diversity order of M+1 is achieved.*

## Imperfect Spectrum Acquisition

- Realistic scenario: the potential relay nodes may not always be able to acquire the spectrum holes successfully
  - RDF

$$P_{out} \approx \sum_{k=0}^{M} \left[\frac{2^{(M+1)R}-1}{SNR}\right]^{k+1} \binom{M}{k} P_d^k (1-P_d)^{M-k} \lambda_{sd} \sum_{R(s)} \prod_{r_i \in R(s)} \lambda_{r_i d} \prod_{r_i \in R(s)} P_d \prod_{r_i \notin R(s)} \lambda_{sr_i} \frac{1}{(|R(s)|+1)!}$$

  - NDF

$$P_{out} \approx \sum_{k=0}^{M} \left[\frac{1}{SNR}\right]^{k+1} \left(2^{(M+1)R}-1\right)^{k} \binom{M}{k} P_d^k (1-P_d)^{M-k} \lambda_{sd}$$

$$\times \sum_{R(s)} \left(2^{(M+1)R}-1\right)^{-|R(s)|} \prod_{r_i \in R(s)} \lambda_{r_i d} \prod_{r_i \in R(s)} P_d \prod_{r_i \notin R(s)} \lambda_{sr_i} G_{|R(s)|+1}((M+1)R)$$

  - AF

$$P_{out} \approx \sum_{R(s)} \left[\frac{2^{(M+1)R}-1}{SNR}\right]^{|R(s)|+1} \lambda_{sd} \prod_{r_i \in R(s)} \left(\lambda_{sr_i} + \lambda_{r_i d}\right) \prod_{r_i \in R(s)} P_d \prod_{r_i \notin R(s)} (1-P_d) \frac{1}{(|R(s)|+1)!}$$

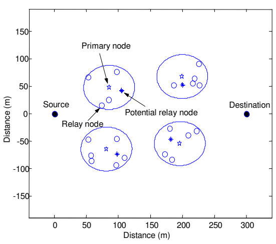
*Full diversity order of M+1 is not achieved.*

## Cooperative Spectrum Acquisition

- The imperfect spectrum acquisition does not achieve full diversity
  - Due to less than perfect spectrum acquisition performance
- Intra-cluster cooperation
  - Cooperative spectrum acquisition
  - Neighboring nodes ($N$) share spectrum acquisition information
  - Simple OR rule
- New probabilities of detection and false alarm:

$$C_d = 1 - (1-P_d)^{N+1},\quad C_f = 1 - (1-P_f)^{N+1}$$

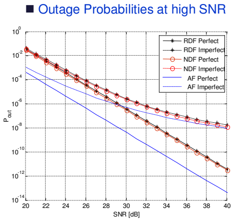
## Numerical Results



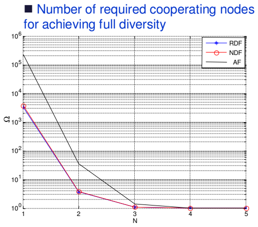

R = 1
$1/\lambda_{AB} \sim 1/d_{AB}$
($d_{AB}$ : distance from A to B)
$P_f = 10^{-2}$
$C_f = 10^{-2}$
$P_d = \min\{P_{d1}, P_{d2}, P_{d3}, P_{d4}\}$

## Numerical Results (cont'd)

- Outage Probabilities at high SNR




- Number of required cooperating nodes for achieving full diversity




- All relay transmission schemes for perfect spectrum acquisition achieve full diversity
- AF > NDF > RDF
- The required number of cooperating nodes (N): N = 3 for AF, N = 4 for RDF and NDF

## Conclusions

- Outage Performance of cooperative cognitive relay network is analyzed
- Full diversity is achieved only if the potential relay nodes successfully acquire available spectrum.
- Full diversity is not achieved if the spectrum acquisition is not guaranteed.
- Intra-cluster cooperation scheme improves the outage performance.
- Full diversity is achieved if a proper number of neighboring relay nodes in each cluster participate in intra-cluster cooperation.

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