Multicast Scheduling with Cooperation and Network Coding in Cognitive Radio Networks

(INFOCOM 2010 Paper)

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1 Introduction

2 System Model

3 Problem Formulation and Solution
- Centralized Greedy Algorithm
- Distributed Online Algorithm

4 Performance Evaluation

5 Conclusion and Discussion

Keywords:

- Cognitive radio network
- Multicast
- Cooperation
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What is Cognitive Radio Network?

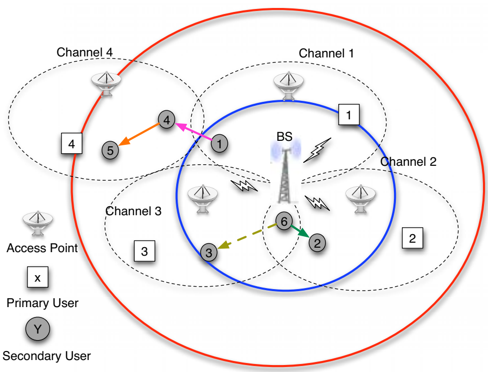

Figure: An illustrative example on multicast scheduling in CRNs.

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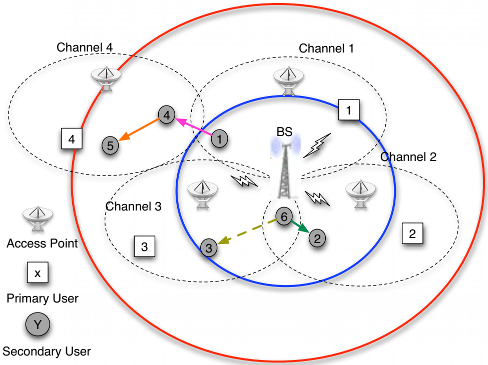

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- Access point and Primary user: Licensed channels

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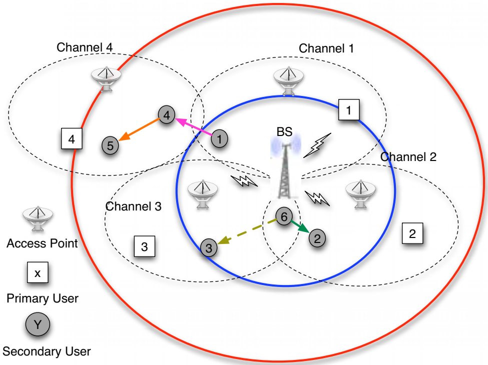

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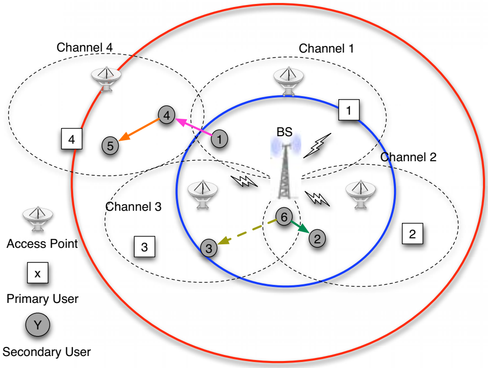

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Resource: Orthogonal channels, e.g. *FDM*, *CDM*.

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Answer: Traditional multicast algorithms assume commonly available channels.

- There may not exist commonly available channels for secondary users.
- The potential benefits provided by user and channel diversities are overlooked.

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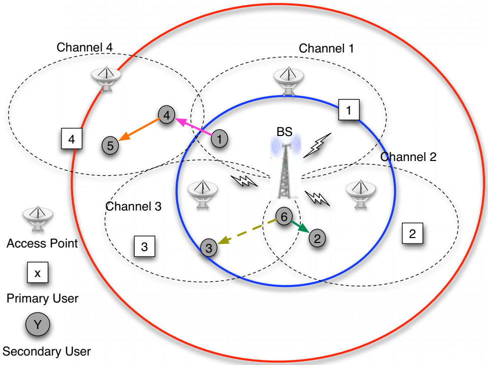
Why is single hop multicast not good?



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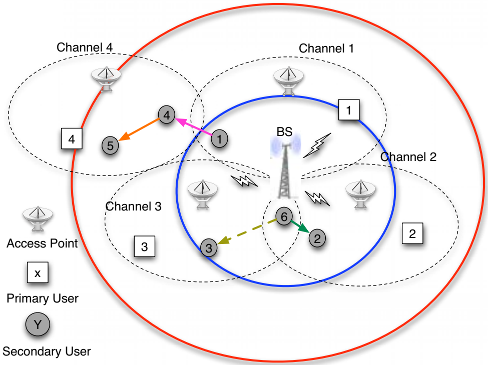

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The same reason for the need of a novel multicast algorithm.

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2. Encode the data blocks into n coded blocks with random linear coefficients.
3. Since all linearly independent blocks are equally innovative, certain number of coded blocks can recover the original packet.

The tasks:

- Power control for Base Station (BS).
- Channel assignment for Secondary Users (SU).

- C PUs and orthogonal channels, N SUs and one BS.

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- $S(t) = \{S_c(t)\}_C$: binary variables representing the channel state in each time slot t. Evolves according to a finite state ergodic Markov chain.
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- $H(t) = \{h_n^c(t)\}_{N\times C}$: Channel accessibility depending on channel state and SU location.
    - $h_n^c(t) = 1$: SU n can access channel c
    - $h_n^c(t) = 0$: Otherwise

Optimization Problem

Objective function: Maximize utility; Proportional fairness (can find a good balance between utilization and fairness)

$$\max_{P_{BS},\Theta} \sum_{n=1}^{N} \frac{U_n}{\bar{r_n}} \qquad (1)$$

U_n represents throughput on SU n;
$\bar{r_n}$ is the average throughput that SU n obtains over previous time slots;
$P_{BS} = \{P_{BS}^c\}_C$ denotes the multicast power used on each channel from BS;
$\Theta = \{\mu_{mn}^c\}_{N \times N \times C}$ is the set of feasible channel assignments.

Constraints

Constraints on power control:

$$\begin{aligned} P_{BS}^{c} &\leq P_{max}^{c} \ \forall c \\ P_{BS}^{c} \cdot g^{c} \cdot S_c &\leq \beta \ \forall c \end{aligned} \tag{2}$$

Constraints (Cont.)

Constraints on channel availability for cooperative communication.

$$\begin{aligned} &\mu_{mn}^c \le h_m^c, \mu_{mn}^c \le h_n^c \ \forall m, n, c \\ &\mu_{mn}^c \le l_m^c, \mu_{mn}^c \le l_n^c \ \forall m, n, c \end{aligned} \tag{3}$$

Constraints (Cont.)

Constraints on potential interference by cooperative communication.

$$
\begin{aligned}
&0 \leq \sum_{m=1}^{N} \mu_{mn}^{c} \leq 1 \ \forall n, c \\
&0 \leq \sum_{c=1}^{C} \mu_{mn}^{c} \leq 1 \ \forall m, n \\
&0 \leq \sum_{m=1}^{N} \mu_{mn}^{c} + \sum_{m'=1}^{N} \mu_{nm'}^{c} \leq 1 \ \forall n, c
\end{aligned}
\tag{4}
$$

Constraints (Cont.)

Constraints on utility calculation.

$$U_n = \sum_{c=1}^{C} BW \cdot \log_2(1 + \frac{P_{BS}^c \cdot g_n^c}{N_n^c}) + \sum_{c=1}^{C} \sum_{m=1}^{N} \mu_{mn}^c \omega_{mn}^c$$
$$\omega_{mn}^c = \min\{\omega_{max}, \max\{0, \frac{B_m - B_n}{T}\}\} \qquad (5)$$

BW and N_n^c denote channel bandwidth and noise respectively; ω_{mn}^c represents the achievable cooperative transmission rate from SU m to SU n on channel c with upper bound ω_{max}; it is also limited by amount of innovative data that SU m is able to contributed to n: $B_m - B_n$.

A centralized greedy algorithm can be derived using *branch-and-bound* algorithm.

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Buffer dynamics

$$B_n(t+1) = \max\{B_n(t) - R_n(t), 0\} + M_n(t) + \sum_{c=1}^{C}\sum_{m=1}^{N} \mu_{mn}^{c}(t) S_n^c(t) \omega_{mn}^{c}(t) \tag{6}$$

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- $R_n(t)$ is the rate that SU n takes data off from the buffer at time slot t bounded as $\min\{B_n(t), R_{max}\}$
- $M_n(t)$ is the multicast throughput obtained directly from BS at time slot t for SU n.

Average throughput of SU n

$$r_n = \lim_{t\to\infty} \frac{1}{t} \sum_{\tau=0}^{t-1} R_n(\tau) \tag{7}$$

Collisions by cooperative transmissions

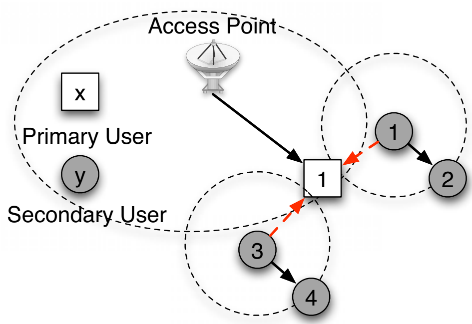

Figure: Cooperative communication may generate interference to PUs.

Collisions by cooperative transmissions (Cont.)

Total number of collisions caused by cooperative transmission for each PU:

$$E_c(t) = \sum_{m=1}^{N} \sum_{n=1}^{N} \mu_{mn}^c(t) I_m^c(t)(1 - S_c(t)) \tag{8}$$

Here, $I_m^c(t)$ is the binary variable indicating whether the cooperative communication issued by SU m may generate interference to PU c at time slot t.

Collisions by cooperative transmissions (Cont.)

Time average rate of interference for PU c:

$$e_c = \lim_{t \to \infty} \frac{1}{t} \sum_{\tau=0}^{t-1} E_c(\tau) \tag{9}$$

Collisions by cooperative transmissions (Cont.)

Interference queue dynamics:

$$X_c(t+1) = \max\{X_c(t) - \rho_c, 0\} + E_c(t) \tag{10}$$

Here, ρ_c is the time average interference tolerant rate for channel PU c.

Optimal online scheduling policies

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- Power control policy: BS chooses multicast power as the solution of the following problem

$$\begin{aligned} \max \quad & \sum_{n=1}^{N} R_n(t) M_n(t) \\ s.t. \quad & (2) \end{aligned}$$

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- Channel allocation policy: Channel resources are allocated as the solution of the following

$$\begin{array}{ll} \max & \sum_{n,m,c} \mu_{mn}^{c}(t)(\omega_{mn}^{c}(t) B_n(t) P_c(t) - X_c(t) I_m^c(t)(1 - P_c(t))) \\ s.t. & (3) - (5) \end{array}$$

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Stochastic Lyapunov Optimization is applied to solve this problem.

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- NOCoop: Power control at BS but without cooperative communication among SUs
- NOPower: With no power control nor cooperative communication

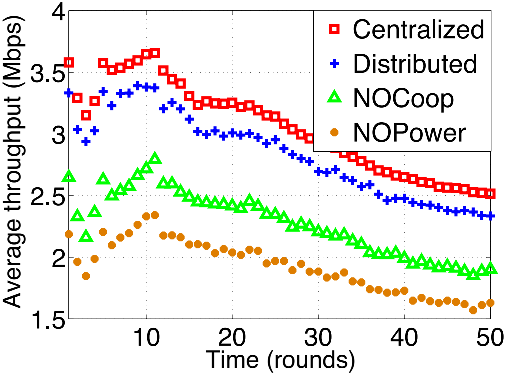

Figure: Average throughput performance of all protocols in realistic CRN scenarios.

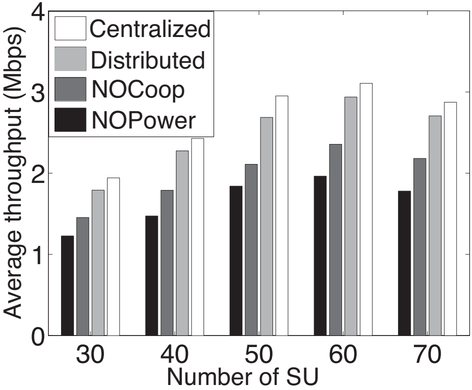

Figure: Throughput performance of all protocols with different numbers of SUs, which represent the degree of possible cooperation among SUs.

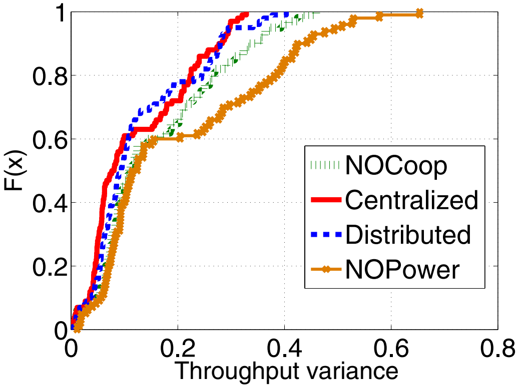

Figure: CDF of all SUs with respect to throughput variance, which indicates fairness performance.

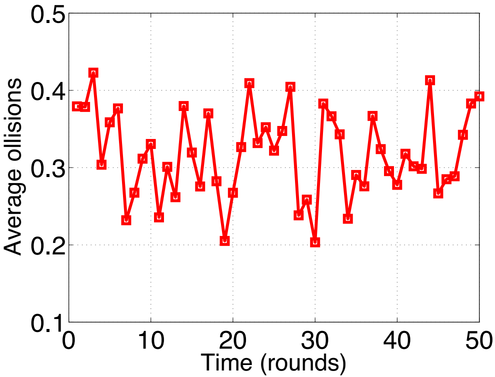

Figure: Evaluation of interference on PUs, which remains stable and bounded in our protocols.

Contribution

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Discussion

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1. Protocol interference model is utilized. What about the difference to system design and performance under physical interference model?
2. Both algorithms are derived with optimization tools and only multicast is addressed. How about extend the problem into unicast, anycast, broadcast, convergecast? Also, we can try graph-theory on the problems.

Thank You!