Utility-Maximizing Data Dissemination in Socially Selfish Cognitive Radio Networks

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- Licensed spectrum, *e.g.*, reserved as military, TV and paging frequencies; Under-utilized!
- Unlicensed spectrum, *e.g.*, shared by computer networking, sensor networks, RFID and ultra-wideband devices. Congested!

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- Sense the spectrum availability;
- Let the secondary (unlicensed) user to get the licensed spectrum when the primary (licensed) users are idle;
- Increase the efficiency of spectrum.

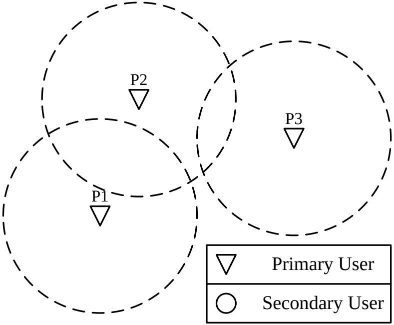
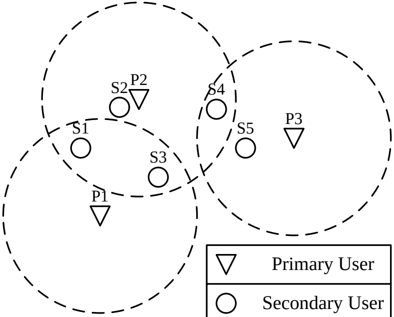


Figure: Example of a Cognitive Radio Network.



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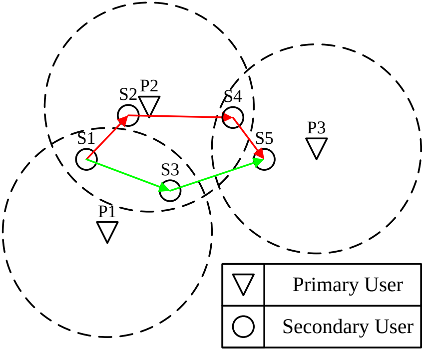
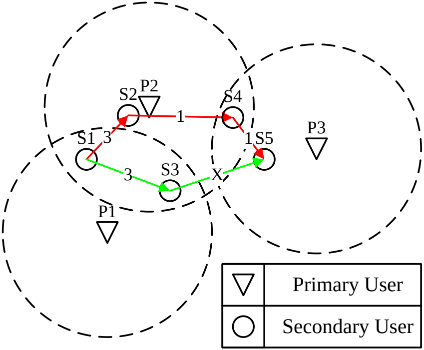


Node #	Available Channel
S1	1,2,3
S2	1,2,3
S3	1,2,3
S4	1,2,3
S5	1,2,3

Figure: All primary users are idle.



Node #	Available Channel
S1	3
S2	1,3
S3	3
S4	1
S5	1,2

Figure: All primary users are active.

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Cross-layer dynamic control is required.

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- Transport layer: end-to-end rate control;

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- Transport layer: end-to-end rate control;
- Network layer: routing;

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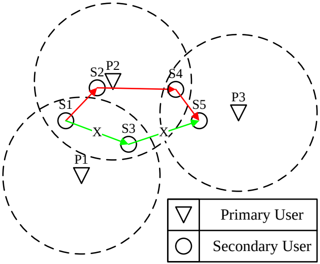
How to maximize the overall average throughput utility over long term?

Cross-layer dynamic control is required.

- Transport layer: end-to-end rate control;
- Network layer: routing;
- MAC layer: channel allocation and link scheduling.

- In emerging network applications, *e.g.*, civilian networks, there are social ties among users.
- Users tend to help the ones with social ties while decline the strangers.



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- Not a study on incentive mechanism.

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- $\mathcal{M}$: Set of unicast sessions, total number of M;
- s_m: Source of session $m \in \mathcal{M}$; d_m: Destination of session $m \in \mathcal{M}$;
- E: Set of links among secondary users; $e_{ij} \in E$: Directed link from node i to j.

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- Primary interference: each user can either transmit or receive data on one channel at each time.

Practical concern on transport layer

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- Given with $A_m(t) \in [0, A_{max}^{(m)}]$: arbitrary data arrival rate of session m in time slot t; $A_{max}^{(m)}$: maximum arrival rate of session m;

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End-to-end rate control,

- Given with $A_m(t) \in [0, A_{max}^{(m)}]$: arbitrary data arrival rate of session m in time slot t; $A_{max}^{(m)}$: maximum arrival rate of session m;
- Decide $r_m(t) \in [0, A_m(t)]$: admissible data rate of session m in time slot t; for congestion control and network stability.

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Assumption: one unit of data can be transmitted from node i to node j in each time slot.

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Queueing law:

$$\begin{aligned} Q_n^{(m)}(t+1) = & Q_n^{(m)}(t) - \sum_{e_{nj} \in E} \mu_{nj}^{(m)}(t) + \sum_{e_{in} \in E} \mu_{in}^{(m)}(t) \\ & + \mathbf{1}_{\{n=s_m\}} r_m(t), \end{aligned} \quad (1)$$

where

$$\mathbf{1}_{\{n=s_m\}} = \begin{cases} 1 & \text{if } n = s_m, \\ 0 & \text{otherwise.} \end{cases}$$

Practical concern on MAC layer

Channel allocation and link scheduling,

$$\alpha_{nj}^{(c)}(t) = \begin{cases} 1 & \text{if } e_{nj} \text{ is scheduled on channel } c \text{ in time slot } t, \\ 0 & \text{otherwise.} \end{cases}$$

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- Capacity constraint: overall routed data units over e_{ni} for all sessions equals overall link capacity of e_{ni} over all channels,

$$\sum_{c \in \mathcal{C}} \alpha_{nj}^{(c)}(t) = \sum_{m \in \mathcal{M}} \mu_{nj}^{(m)}(t), \forall e_{nj} \in E, \tag{2}$$

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- Interference constraints.

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$\rho_n^{(m)} = h(\rho_{n,s_m}, \rho_{n,d_m})$: a function of the social ties between user n and the source/destination of session m.

Social preference: buffer space

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- $q_n^{(m)}$: buffer size for data queue $Q_n^{(m)}$ of session m on user n; a function of $\rho_n^{(m)}$.

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- $z_n^{(m)}$: preset average relaying rate of session m on user n; a function of $\rho_n^{(m)}$.

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- $z_n^{(m)}$: preset average relaying rate of session m on user n; a function of $\rho_n^{(m)}$.
- Actual average rate relayed by node n for session m should be no larger than $z_n^{(m)}$:

$$\overline{\sum_{e_{nj} \in E} \mu_{nj}^{(m)}(\tau)} \leq z_n^{(m)},$$
$$\forall n \in V_S, m \in \mathcal{M}, n \neq s_m, n \neq d_m. \qquad (3)$$

where $\overline{(\cdot)}$ denotes the average over long term.

Definition (Queue and Network Stability)

A queue Q is strongly stable (or stable for short) if and only if

$$\lim_{t \to \infty} \sup \frac{1}{t} \sum_{\tau=0}^{t-1} \mathbb{E}(Q(\tau)) < \infty,$$

where $Q(\tau)$ is the queue size at time slot τ and $\mathbb{E}(\cdot)$ is the expectation.

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A network is strongly stable (or stable for short) if and only if all queues in the network are strongly stable.

Utility Maximization problem

Objective: maximize the overall utility with guarantee of network stability and social preference of the users.

$$\max \quad \sum_{m \in \mathcal{M}} U(\bar{r}_m) \tag{4}$$

$$s.t. \quad \bar{\mathbf{r}} \in \Lambda, \tag{5}$$

$$0 \leq r_m(t) \leq A_m(t), \ \forall m \in \mathcal{M}, t = 1, 2, \ldots \tag{6}$$

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- Λ: the *capacity region* of the network; the set of all $\bar{\mathbf{r}}$, for each of which there exists a feasible routing and channel allocation algorithm to stabilize the network.

Theorem (Necessity for Queue Stability)

For any queue Q with the following queuing law,

$$Q(t+1) = Q(t) - b(t) + a(t),$$

where $a(t)$ and $b(t)$ are the queue incoming rate and outgoing rate in time slot t, respectively, the following results hold:

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- Use Lyapunov optimization theory for
  - Dynamic control;
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- Use queue stability to ensure the inequality constraints on average values, *e.g.*, the social preference on average relaying rate.

Virtual queues: transport layer

At the transport layer of each source node s_m,

$$Y_m(t+1) = \max\{Y_m(t) - r_m(t) + \eta_m(t), 0\}, \quad (7)$$

under the constraints

$$0 \leq r_m(t) \leq A_m(t), 0 \leq \eta_m(t) \leq A_{max}^{(m)},$$

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- $Y_m(t)$ as the budget for data admission.

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The network layer of node n for each data session m it relays,

$$G_n^{(m)}(t+1) = \max\{G_n^{(m)}(t) + \sum_{e_{nj} \in E} \mu_{nj}^{(m)}(t) - z_n^{(m)}, 0\}. \tag{8}$$

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Application of Lyapunov optimization

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- Define our own Lyapunov function:

$$L(\mathbf{\Theta}(t)) = \frac{1}{2}\sum_{m\in\mathcal{M}}\sum_{n\neq d_m}\frac{q_{s_m}^{(m)}(Q_n^{(m)}(t))^2}{q_n^{(m)}} + \frac{1}{2}\sum_{m\in\mathcal{M}}(Y_m(t))^2 + \frac{1}{2}\sum_{m\in\mathcal{M}}\sum_{n\neq s_m, n\neq d_m}(G_n^{(m)}(t))^2. \tag{9}$$

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- One-slot Lyapunov drift:

$$\Delta(\mathbf{\Theta}(t)) = L(\mathbf{\Theta}(t+1)) - L(\mathbf{\Theta}(t)). \quad (10)$$

Application of Lyapunov optimization (Cont.)

Drift-plus-penalty framework:

$$\Delta(\boldsymbol{\Theta}(t)) - V \sum_{m \in \mathcal{M}} U(\eta_m(t)) \leq B - \Psi_1(t) - \Psi_2(t) - \Psi_3(t). \tag{11}$$

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- $\Psi_3(t)$: an expression only related with $\mu_{nj}^{(m)}(t)$.

End-to-End Congestion Control at Each Source

Each source node s_m decides,

$$r_m(t) = \begin{cases} A_m(t) & \text{if } Y_m(t) > Q_{s_m}^{(m)}(t) \\ 0 & \text{otherwise} \end{cases}; \quad (12)$$

$$\eta_m(t) = \max\{\min\{U'^{-1}(\frac{Y_m(t)}{V}), A_{max}^{(m)}\}, 0\}, \quad (13)$$

where $U'^{-1}(\cdot)$ is the inverse function of $U'(\cdot)$, the first order derivative of $U(\cdot)$.

Joint Routing and Channel Allocation at Each Relay

$\forall e_{ni} \in E$, calculate the weight for routing session m over link e_{ni}, *i.e.*, $\mu_{ni}^{(m)}(t) = 1$,

$$w_{nj}^{(m)}(t) = \frac{q_{s_m}^{(m)}}{q_n^{(m)}} Q_n^{(m)}(t) - \frac{q_{s_m}^{(m)}}{q_j^{(m)}} Q_j^{(m)}(t) - \mathbf{1}_{\{n \neq s_m\}} G_n^{(m)}(t), \ \forall m \in \mathcal{M},$$

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Joint Routing and Channel Allocation at Each Relay

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Joint Routing and Channel Allocation at Each Relay (Cont.)

$\forall e_{ni} \in E$, calculate the weight for link activation, *i.e.*, $\exists c \in \mathcal{C}, \alpha_{ni}^{(c)}(t) = 1$,

$$w_{ni}^{\hat{m}_{nj}}, \text{ with } \hat{m}_{nj} = \arg\max_{m}\{w_{nj}^{(m)}(t)\}.$$

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Derive channel allocation variable $\alpha_{nj}^{(c)}, \forall e_{ni} \in E, c \in \mathcal{C}$, by solving problem

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$$s.t. \quad \text{No interference.}$$

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$$s.t. \quad \text{No interference.}$$

Prefer links with the largest weight $w_{nj}^{(\hat{m}_{nj})}(t)$.

Joint Routing and Channel Allocation at Each Relay (Cont.)

Routing decisions are made as follows,

$$\mu_{nj}^{(m)}(t) = \begin{cases} \sum_{c \in \mathcal{C}} \alpha_{nj}^{(c)}(t) & \text{if } m = \hat{m}_{nj} \\ 0 & \text{otherwise} \end{cases}, \forall e_{ni} \in E, m \in \mathcal{M}.$$

Rationale of the joint routing and channel allocation algorithm:

Rationale of the joint routing and channel allocation algorithm: Prioritize transmissions from a relatively more congested node (high $Q_n^{(m)}(t)/q_n^{(m)}$) with low relay-capacity deficit (low $G_n^{(m)}(t)$), to a less congested node (low $Q_j^{(m)}(t)/q_j^{(m)}$).

Finite Buffer Size

Unique contribution of this paper[1],

[1] L.B. Le, E. Modiano, and N.B. Shroff. *Optimal control of wireless networks with finite buffers.* In Proc. of IEEE INFOCOM'10, 2010.

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- $Y_m(t) \leq VU'(0) + A_{max}^{(m)}$;

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Comparison with [1],

- This work: finite buffer at all nodes, v.s., [1]: unbounded buffer at source;
- This work: distributed decision with local information, v.s., [1]: need queue size at source.

[1] L.B. Le, E. Modiano, and N.B. Shroff. *Optimal control of wireless networks with finite buffers.* In Proc. of IEEE INFOCOM'10, 2010.

Utility Optimality and Network Stability

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- Each queue in the network is stable;
- Overall utility with our Algorithm can be arbitrarily close to the maximum utility $\sum_{m\in\mathcal{M}} U(\bar{r}_m^*)$, if
  - $q_n^{(m)}$ is proportional to $q_{s_m}^{(m)} = VU'(0) + 2A_{max}^{(m)} + 1$;
  - $V \to \infty$.

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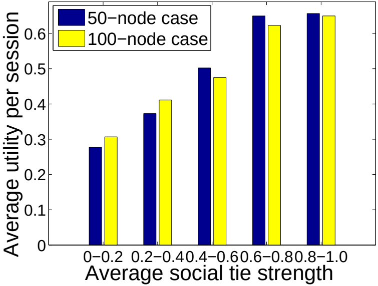
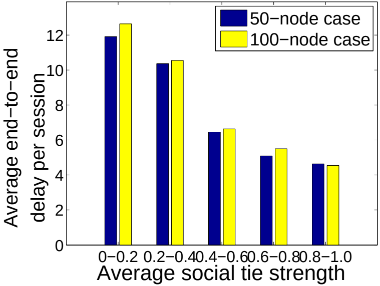
- $q_n^{(m)} \propto (1/\rho_n^{(m)})$;
- $V = 2000$.

Impact of Social Selfishness: different social tie strengths



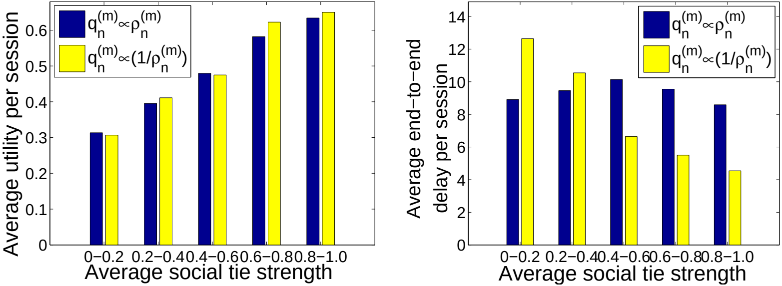
(a) Impact on Utility



(b) Impact on End-to-End Delay

Figure: Performance of sessions with different social tie strengths with relays.

Impact of Social Selfishness: different buffer size differentiation methods



(a) Impact on Utility (b) Impact on End-to-End Delay

Figure: Performance with different buffer size differentiation methods.

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- Joint end-to-end rate control, routing and channel allocation protocol achieving network stability and utility optimality.
- Finite buffer at each node.

Thank You!

Q&A