Advanced Computer Networks
SS 2016

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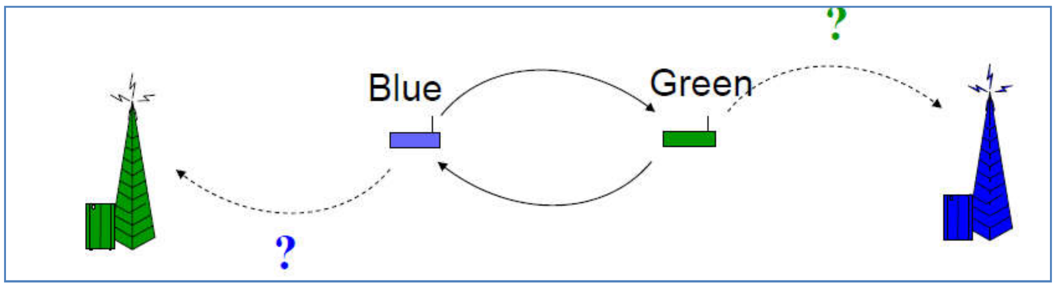
Outline of Wireless Block

- Game theory and its applications
  - Game theory basics and concepts
  - Distributed Spectrum Sharing Application
- Social Group Maximization Framework
  - Introduction to the framework
  - Wireless Network Applications
- Mobile Data Offloading
  - Basics and ideas
  - Optimized Offloading Decision

Packet Forwarder's dilemma



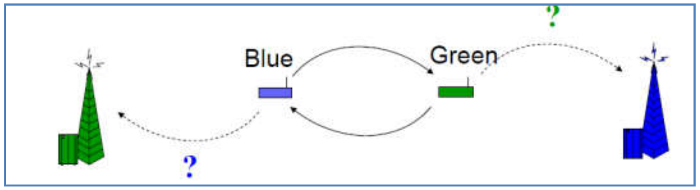
Forwarding has an energy cost of *c* *(c<< 1)*
Successfully delivered packet: benefit of 1 for packet owner

If Green **drops** and Blue **forwards**: (1,-c)
If Green forwards and Blue drops: (-c,1)
If both forward: (1-c,1-c)
If both drop: (0,0)

Each user is trying to selfishly maximize it's individual net gain

What can we predict?

Packet Forwarder's dilemma

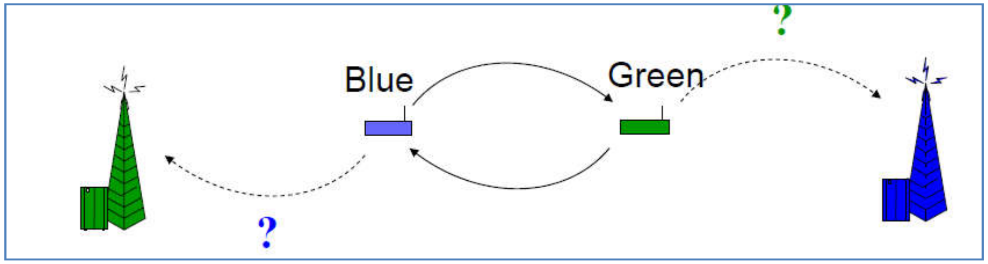


Game:

Players: Green, Blue
Actions: Forward (F), Drop (D)
Payoffs: (1-c,1-c), (0,0), (-c,1), (1,-c)

Blue \ Green	Forward	Drop
Forward	(1-c, 1-c)	(-c, 1)
Drop	(1, -c)	(0, 0)

Packet Forwarder's dilemma



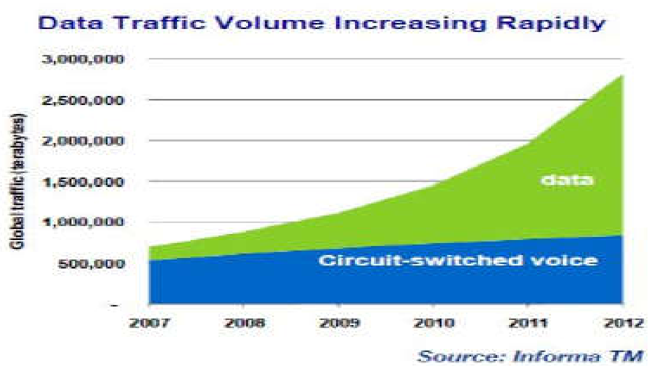
Blue \ Green	Forward	Drop
Forward	(1-c, 1-c)	(-c, 1)
Drop	(1, -c)	(0, 0)

NE of the game

Sometimes being fully rational/selfish may lead to tragedy of commons!

Social Group Utility Maximization: From Non-Cooperative to Socially-Aware

Growing Wireless Data Traffic



Apple FaceTime

Phone calls like you have never seen before !

Significant gap between demand and wireless capacity …

- Cellular traffic has been growing exponentially, e.g., 230% increase in 2011.
  - Average smartphone data usage tripled in 2011;
  - These sharp increases are projected to continue in foreseeable future
- In July 2011, Credit Suisse reported that wireless base stations in US were operating at 80% of their maximum capacity during busy periods.

Major Advances in Wireless Communications

- MIMO (multi-antenna technology)
- OFDM (OFDMA)
- Turbo coding, LDPC
- Cooperative relaying

(in 3G/4G)

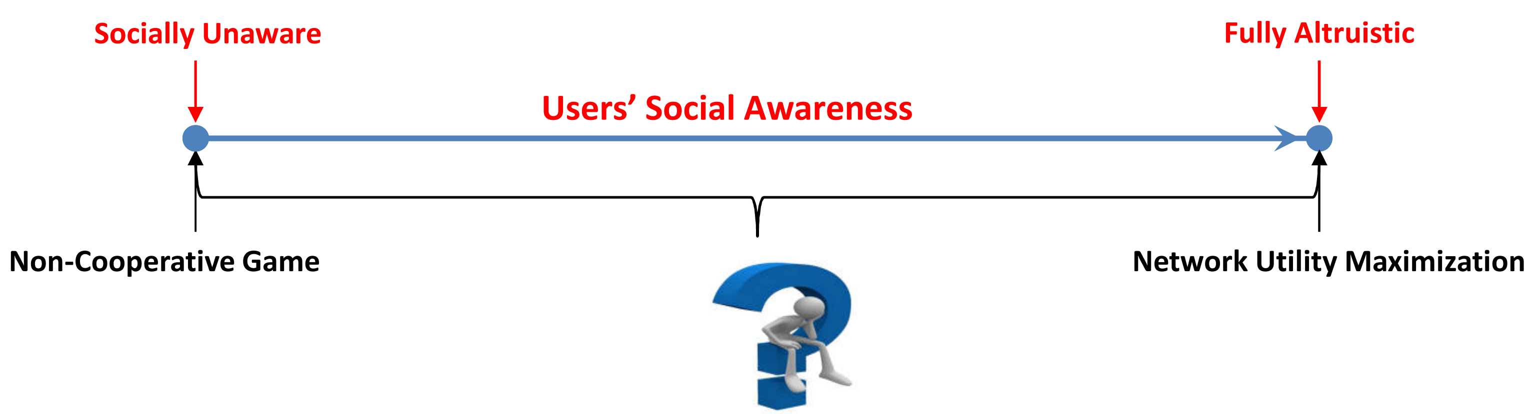
- Channel-aware scheduling (in 4G)
- Wireless network coding
- Cognitive radio networks
- …

- Research trends: towards exploiting interplay across technology, economics, social networks …
- This part: a new paradigm on mobile social networking, making use of interplay between mobile communication and social structure

From Non-cooperative Game to Network Utility Maximization

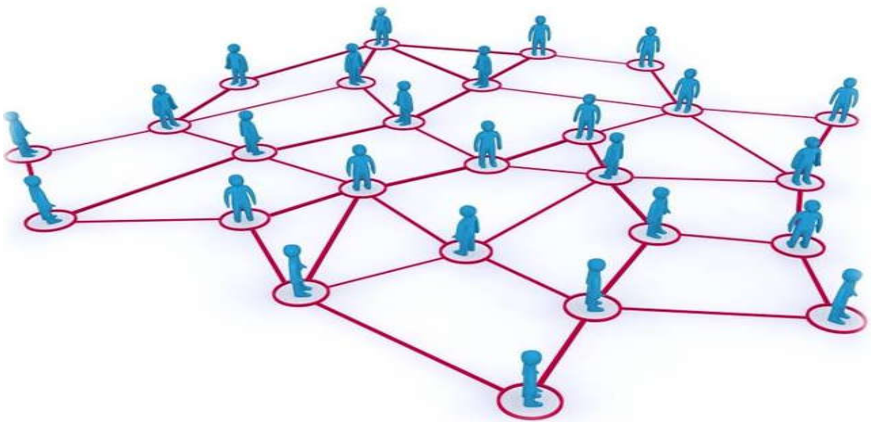
- Non-cooperative game (NCG)
  - Each user is fully rational (selfish), aiming to maximize its individual utility
  - Widely applied to model strategic interaction among network entities
- Network utility maximization (NUM)
  - Users are altruistic, aiming at social welfare maximization
  - Extensively studied for network resource allocation
- NCG and NUM are two extreme cases: socially oblivious or fully social-ware

Question: What is between these two extremes?



Mobile Social Networking

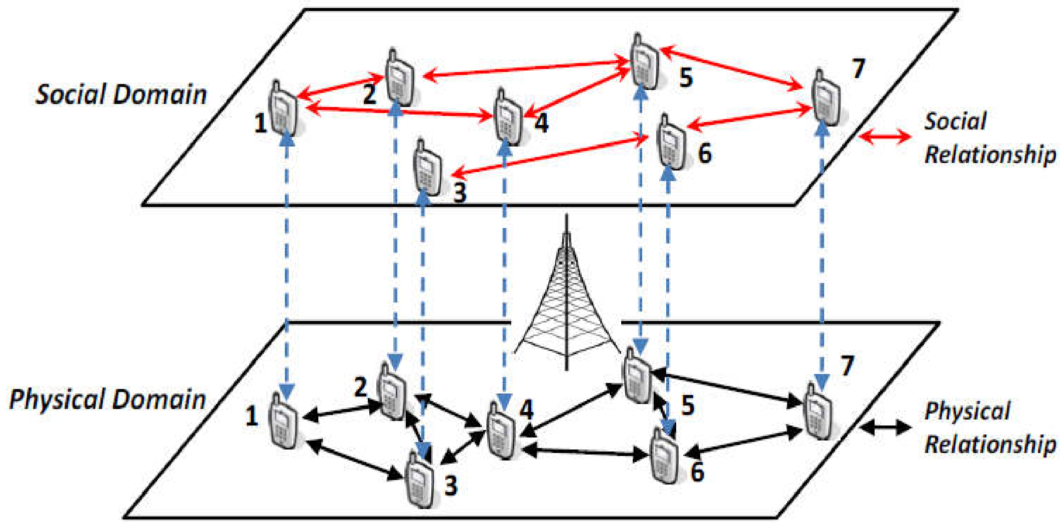
- A new paradigm for mobile social networking; offer rich flexibility in modeling the continuum between NCG and NUM
  - Hand-held mobile devices are operated by human beings
  - People have diverse social relationships and care about their social neighbors at different levels (e.g., family, friends, acquaintances)
  - Explosive growth of online social networks opens up a new avenue to integrate social interactions for cooperative network design



Outline of Wireless II

- Social Group Utility Maximization Framework
- Random Access Control under SGUM
- Database-assisted Spectrum Access under SGUM

Social Network Overlays Mobile Network



- Physical-social coupling among mobile devices
  - Physical domain: physical coupling subject to physical relationship
  - Social domain: social coupling due to social ties among users

Physical Graph Model

- A set of wireless users N={1,2,…,n}
- Feasible strategy set X_i : User-specific, due to heterogeneous physical constraints, e.g., channel selection, power level selection
- Physical graph G^p={N,E^p}
  - Two users are connected by a physical edge if they have physical coupling
  - Capture the physical relationships among the users, e.g., interference
  - N_i^p: the set of users having physical coupling with user i
- Individual user utility $U_i(x)$
  - User's payoff under strategy profile x , e.g., achieved data rate or QoS requirement satisfaction
  - Depend on the underlying physical graph, e.g., interference graph

Social Graph Model

- Exploit social tie for enhancing mobile networking
  - Knowledge of human social ties can be leveraged, e.g., kinship, friendship, or colleague relationship

- Social graph G^s={N,E^s}
  - Two users are connected by a social edge if they have social tie
  - Capture the social coupling among the users
  - N_i^s: user i's social group, i.e., the set of users having social ties with it
  - a_{ij}: strength of the social tie from user i to user j with $0 \leq a_{ij} \leq 1$

- Social group utility

$$S_i(x) = \underbrace{U_i(x)}_{\text{User i's utility}} + \underbrace{\sum_{j \in N_i^s} a_{ij} \; U_j(x)}_{\text{weighted sum of utilities of social neighbors of user i}}$$

  - Each user is social aware and cares about users having social tie with it

Social Group Utility Maximization Game

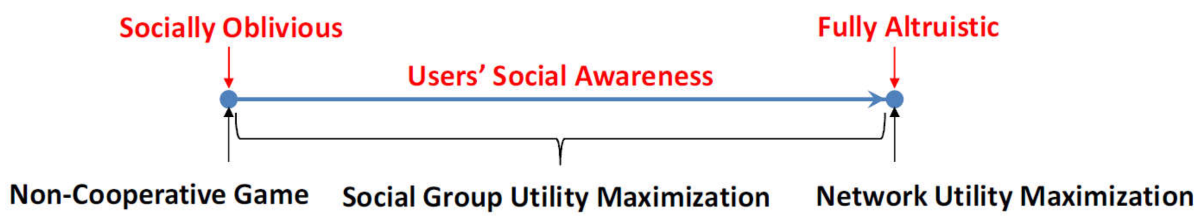
- Distributed decision making among users
  - Each user aims to maximize its own social group utility
- Social group utility maximization (SGUM) game
  - N → player set
  - X_i → strategy space of player i
  - $S_i(x)$ → payoff function of player i
- Social-aware Nash equilibrium (SNE)

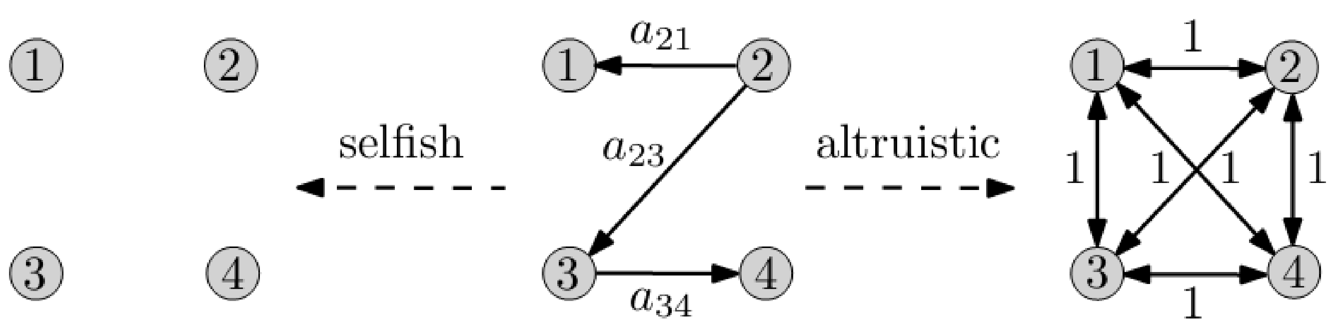
$$x_i^{SNE} = \underset{x_i \in X_i}{\operatorname{argmax}}\, S_i(x_i, x_{-i}^{SNE}), \forall i \in N$$

  - $(x_1^{SNE}, \dots, x_n^{SNE})$ is a SNE if no user can improve its social group utility by unilaterally changing its strategy

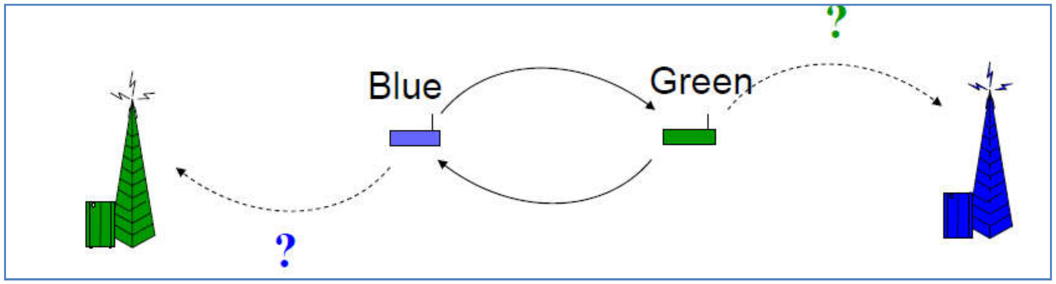
Social Group Utility Maximization Game

- SGUM provides rich modeling flexibility
  - If no social tie exists (i.e., $a_{ij} = 0, \forall i, j$), SGUM degenerates to NCG as $S_i(x_i, \boldsymbol{x}_{-i}) = u_i(x_i, \boldsymbol{x}_{-i})$
  - If all social ties have the maximum strength (i.e., $a_{ij} = 1, \forall i, j$), SGUM becomes NUM as $S_i(x_i, \boldsymbol{x}_{-i}) = \sum_{j=1}^{n} u_j(x_j, \boldsymbol{x}_{-j})$
  - Span the continuum space between NCG and NUM





Packet Forwarder's dilemma: Revisited



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If Green **drops** and Blue **forwards**: (1,-c)
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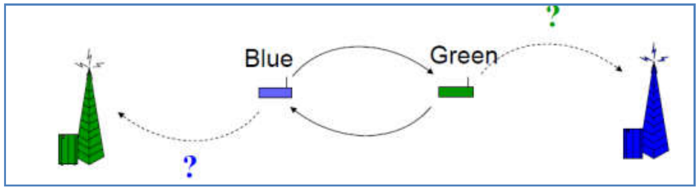
Suppose Blue and Green have a social tie of w

Packet Forwarder's dilemma: Revisited



Blue \ Green	Forward	Drop
Forward	1+w-c-wc, 1+w-c-wc	w-c, 1-wc
Drop	1-wc, w-c	0, 0

If w>c, then (Forward, Forward) is social-aware NE!

A little social trust leads to efficient outcome!

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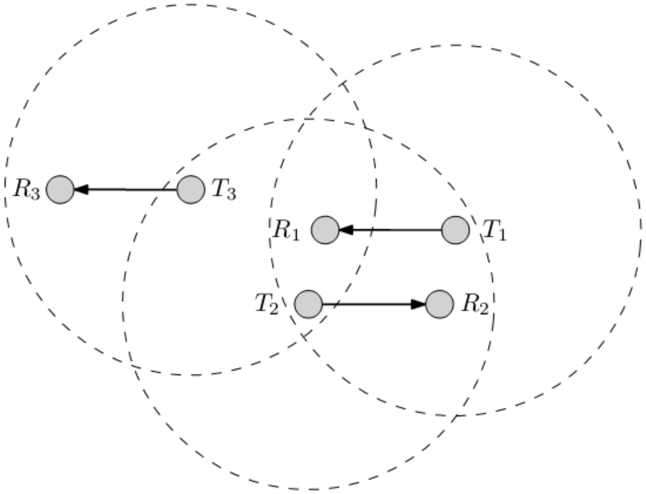
- Social Group Utility Maximization Framework
- Random Access Control under SGUM
- Database-assisted Spectrum Access under SGUM

Random Access Control

- Protocol interference model
  - Each user i is a link consisting of a transmitter T_i and a receiver R_i
  - T_i causes interference to R_j if R_j is in the interference range of T_i
  - $\boldsymbol{I}_i^+$: set of the receivers that T_i causes interference to
  - $\boldsymbol{I}_i^-$: set of the transmitters that causes interference to R_i
- Random access control
- Each user i chooses access probability q_i to contend for data transmission
  - If multiple users contend, a collision occurs and no user can grab the transmission opportunity
  - b_i: successful contention probability of user i

$$b_i(q_i, \boldsymbol{q}_{-i}) = q_i \prod_{j \in \boldsymbol{I}_i^-} (1 - q_j)$$



Random Access Control Game under SGUM

- Random access control game under SGUM: $G^R \triangleq \{\mathcal{N}, \{q_i\}, \{U_i\}\}$
  - Individual utility of user i: $U_i(q_i, \boldsymbol{q}_{-i}) = \log[\theta_i b_i(q_i, \boldsymbol{q}_{-i})] - c_i q_i$
  - θ_i: user i's achieved data rate of utilizing the transmission opportunity
  - Log utility function: widely used to model utility of wireless users
  - c_i: user i's for channel contention, e.g., energy consumption
  - Social group utility of user i:

$$S_i(q_i, \boldsymbol{q}_{-i}) = U_i(q_i, \boldsymbol{q}_{-i}) + \sum_{j \in N_i^s} a_{ij} U_j(q_i, \boldsymbol{q}_{-i})$$

Random Access Control Game under SGUM

THEOREM: There exists a unique SNE $(q_1^{SNE}, \ldots, q_N^{SNE})$ in the random access control game under SGUM, and the access probability q_i^{SNE} is

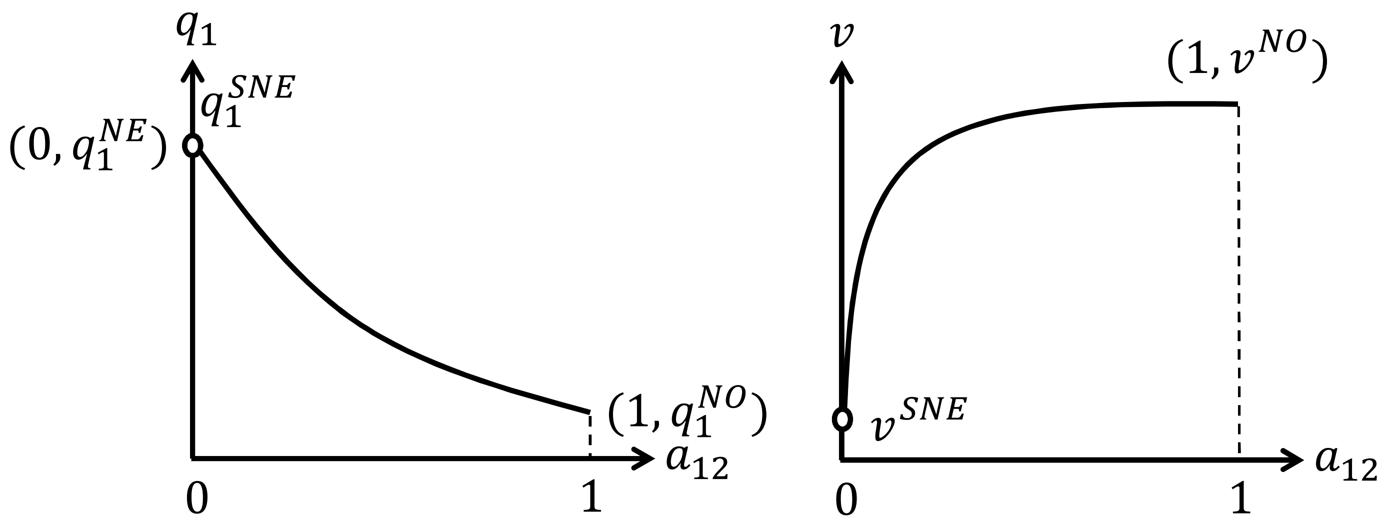
$$\frac{\sum_{j \in \boldsymbol{I}_i^+} a_{ij} + 1 + c_i - \sqrt{(\sum_{j \in \boldsymbol{I}_i^+} a_{ij} + 1 + c_i)^2 - 4c_i}}{2c_i},$$

- Each user's SNE strategy q_i^{SNE} decreases when its social ties with others increase
- When more friends are near by, user acts more altruistically

THEOREM : The total network utility $v = \sum_{i \in \mathcal{N}} U_i(q_i, q_{-i})$ at the SNE is increasing in $a_{ij}, \forall j \in \boldsymbol{I}_i^+, \forall i \in \mathcal{N}$, and reaches maximum when $a_{ij} = 1, \forall j \in \boldsymbol{I}_i^+, \forall i \in \mathcal{N}$.

Random Access Control Game under SGUM

- Intuition: As the social tie strengths increase from 0s to 1s, the SNE strategy of each user migrates from the NE strategy of a NCG to the optimal strategy for NUM ⇒ SGUM spans the continuum space between NCG and NUM



- An example of two-user game with $a_{21} = 1$

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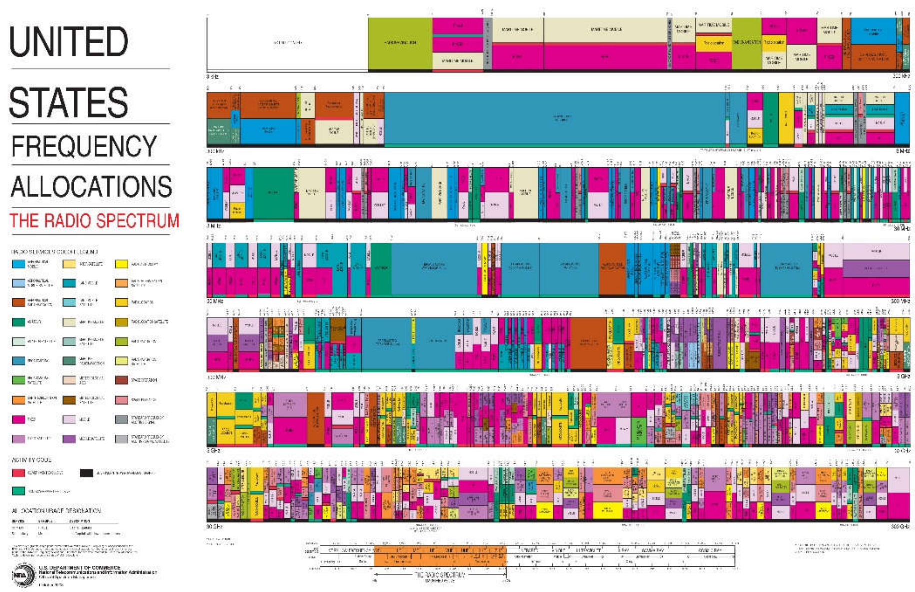
- Database-assisted Spectrum Access under SGUM

Database Assisted Spectrum Access

- Spectrum is scarce
  - Most spectrums have been exclusively licensed
  - More and more wireless devices emerge



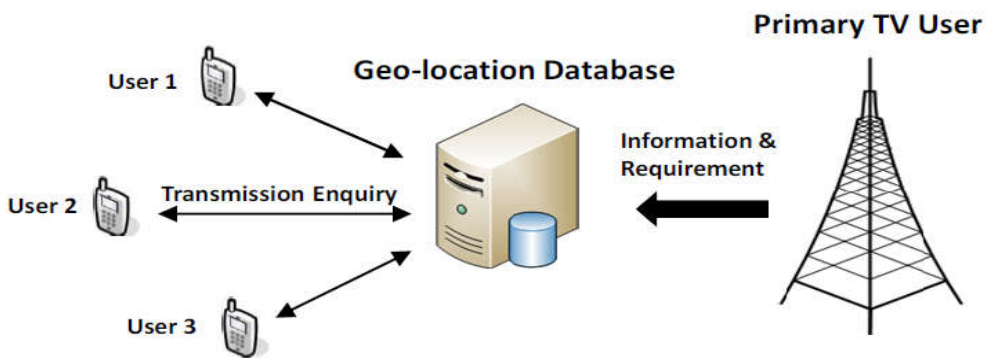
- Spectrum is under-utilized
  - E.g., average spectrum utilization in Chicago is lower than 20%

Database Assisted Spectrum Access

- Dynamic spectrum access with cognitive radios
  - Address spectrum under-utilization problem
  - Primary user (PU) -- licensed spectrum holder
  - Secondary user (SU) -- unlicensed spectrum user
  - Enable SUs share the spectrum with PUs

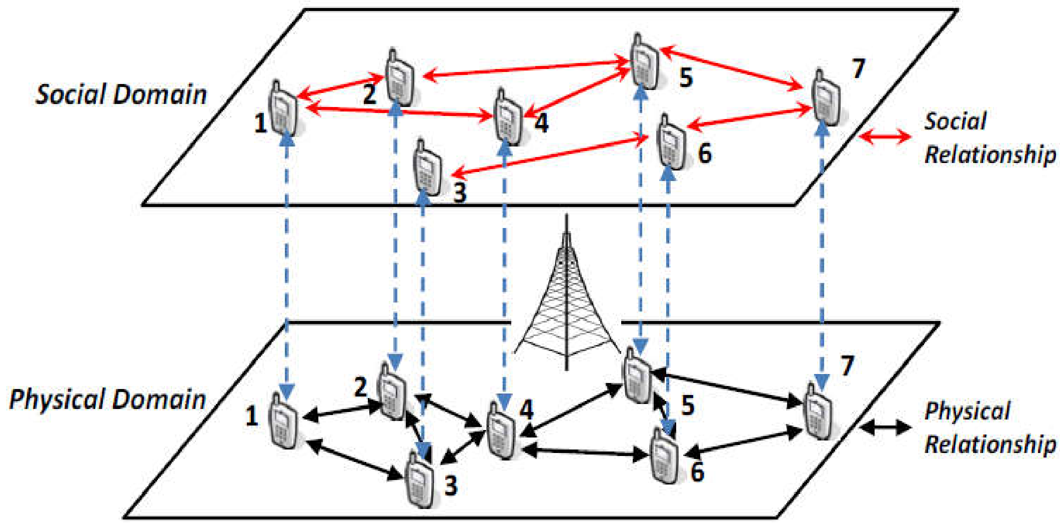
Database Assisted Spectrum Access

- FCC recent ruling on TV spectrum utilization
  - White-space users determine spectrum availability via Geo-location database
  - User sends its geo-location information to database
  - Database feedbacks vacant channel sets and allowable power level
  - Obviate the need of spectrum sensing by individual users



- Challenges for achieving efficient shared spectrum access
  - Access the same vacant channel → cause severe interference
  - Effective cooperation stimulation for spectrum access is needed

Social Group Utility Maximization



- Physical-social coupling among white-space users
  - Physical domain: physical coupling subject to interference
  - Social domain: social coupling due to social ties among users

Database Assisted Spectrum Access

- A set of white-space users N={1,2,…,n}
- Vacant channel set X_i
  - User-specific by consulting the database
- Physical graph G^p={N,E^p}
  - Two users are connected by a physical edge → they can generate significant interference to each other
- Individual user utility

$$U_i(x) = -\sum_{j \in N_i^p} P_j d_{ji}^{-\alpha} I_{\{x_i = x_j\}} - w_{x_i}^i$$

  - Each user aims to reduce its received interference

- Social group utility

$$S_i(x) = U_i(x) + \sum_{j \in N_i^s} a_{ij} U_j(x)$$

Database Assisted Spectrum Access

- SGUM game for database assisted spectrum access
  - Stimulate effective cooperation for interference mitigation
- Potential game: if the game has a potential function $\phi(x)$ such that

$$S_i(x_i, x_{-i}) - S_i(y_i, x_{-i}) = \phi(x_i, x_{-i}) - \phi(y_i, x_{-i})$$

  - Property: any strategy that maximizes potential function is a Nash equilibrium
- Potential function of the game

$$\phi(x) = \underbrace{-\frac{1}{2}\sum_{i=1}^{n}\sum_{j\in N_i^p} P_j d_{ji}^{-\alpha} I_{\{x_i=x_j\}} - \sum_{i=1}^{n} w_{x_i}^i}_{\text{Due to physical coupling}} \underbrace{-\frac{1}{2}\sum_{i=1}^{n}\sum_{j\in N_i^p\cap N_i^s} a_{ij} P_j d_{ji}^{-\alpha} I_{\{x_i=x_j\}}}_{\text{Due to social coupling}}$$

Due to physical coupling

Due to social coupling

THEOREM: Social group utility maximization game for database assisted spectrum access is a potential game and always admits a SNE.

Distributed Spectrum Access Algorithm

- Distributed algorithm for social group utility maximization (SGUM)
  - Inspired by adaptive CSMA for network utility maximization **[Jiang'2010]**
  - Key idea: coordinate users' asynchronous channel selection updates to form a Markov chain, and drive it to the stationary distribution given as Gibbs distribution, which maximizes potential function of the SGUM game

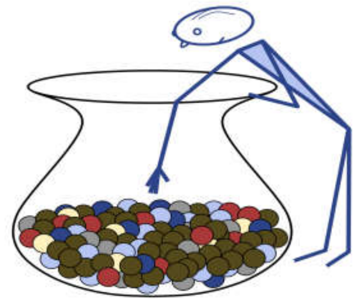
Distributed Spectrum Access Algorithm

- Each user i repeats following operations in parallel:
  - Compute the social group utility $S_i(x_i, x_{-i})$ on the chosen channel x_i by inquiring the individual utility information from social neighbors

  - Generate a timer value following the exponential distribution
  - Count down until the timer expires

Distributed Spectrum Access Algorithm

- Each user i repeats following operations in parallel:
  - Once the timer expires, choose a new channel y_i randomly



  - Compute the social group utility $S_i(y_i, x_{-i})$ on the new channel y_i
  - Decision update: stay in the new channel y_i with probability

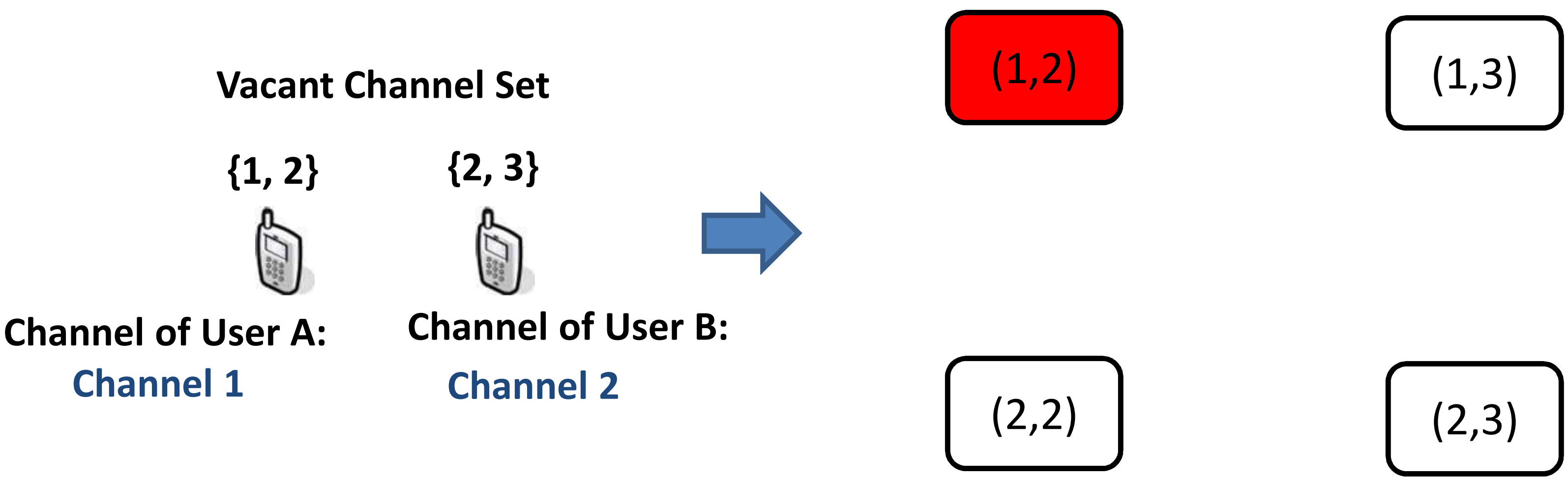
$$Q \triangleq \frac{\exp(\theta S_i(y_i,x_{-i}))}{\max\{\exp(\theta S_i(y_i,x_{-i})),\exp(\theta S_i(x_i,x_{-i}))\}};$$

or move back to the original channel x_i with probability $1 - Q$

Distributed Spectrum Access Algorithm

- The distributed algorithm induces a Markov chain
  - System state: the channel selection profile of all users
  - Each state transition involves one user: due to the property of exponential distribution for channel update count-down
  - Two-user Markrov chain example:

Markov Chain For Dynamic Channel Selection



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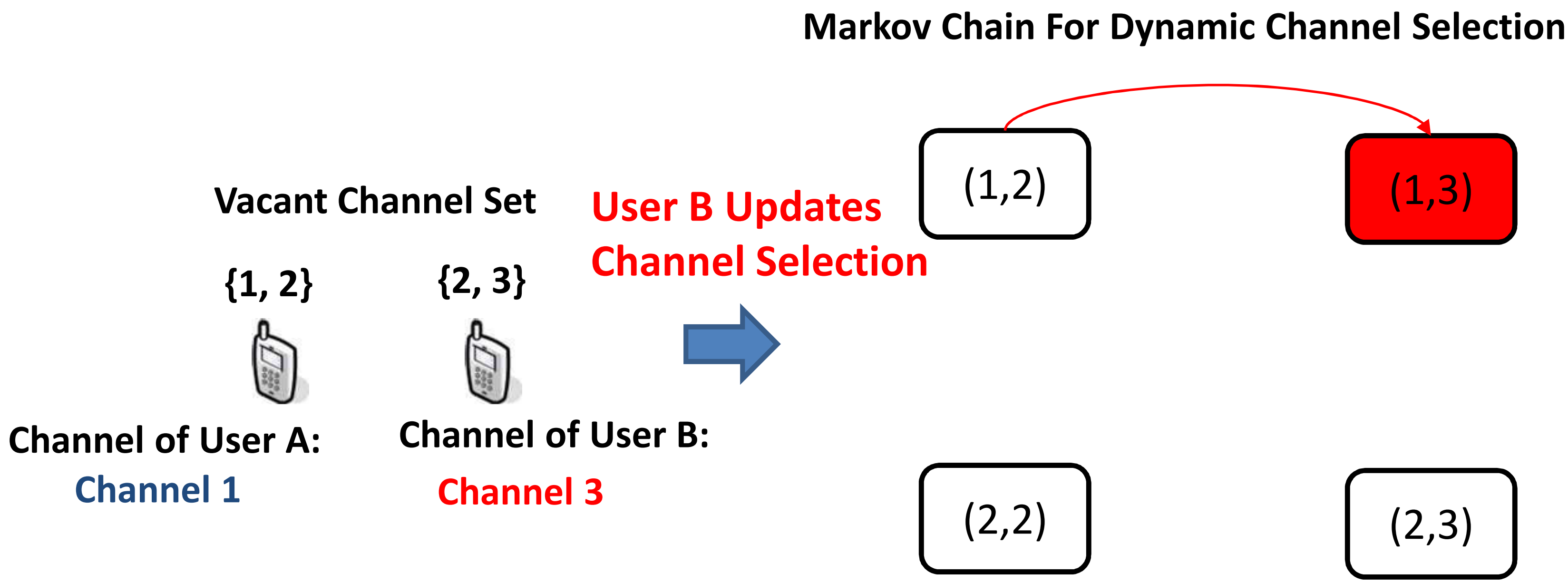

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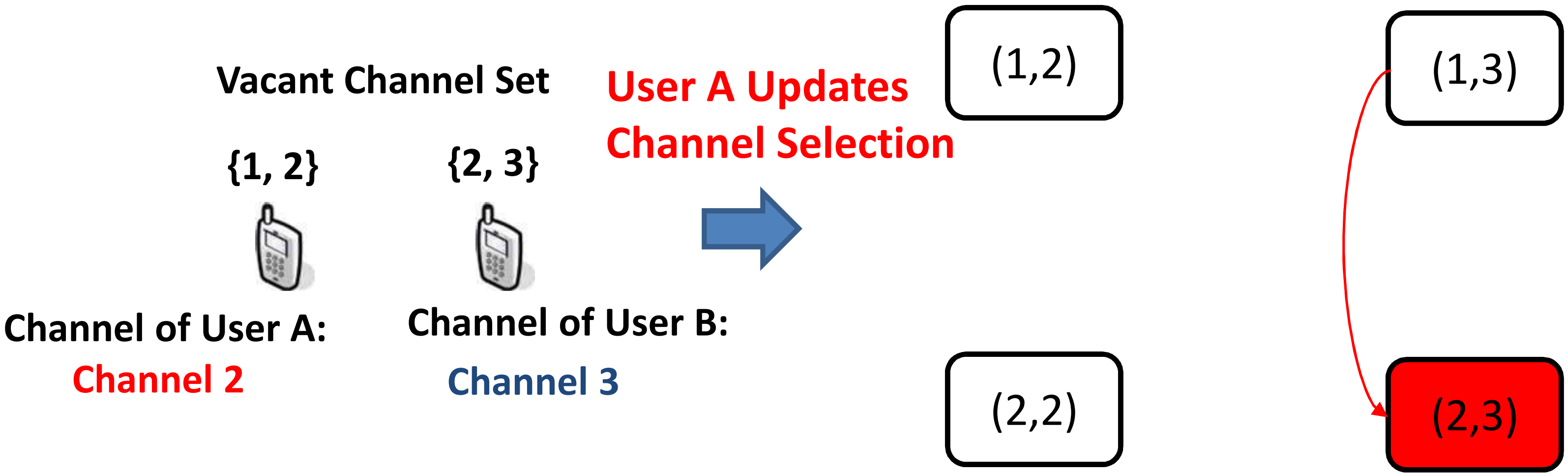

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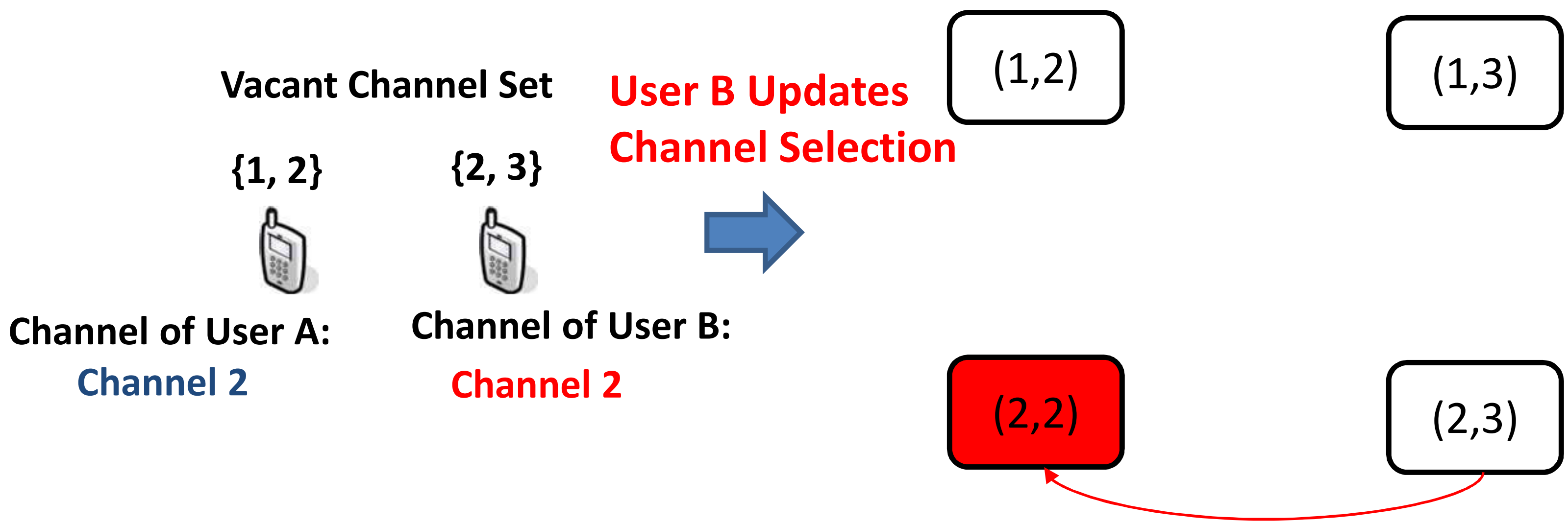
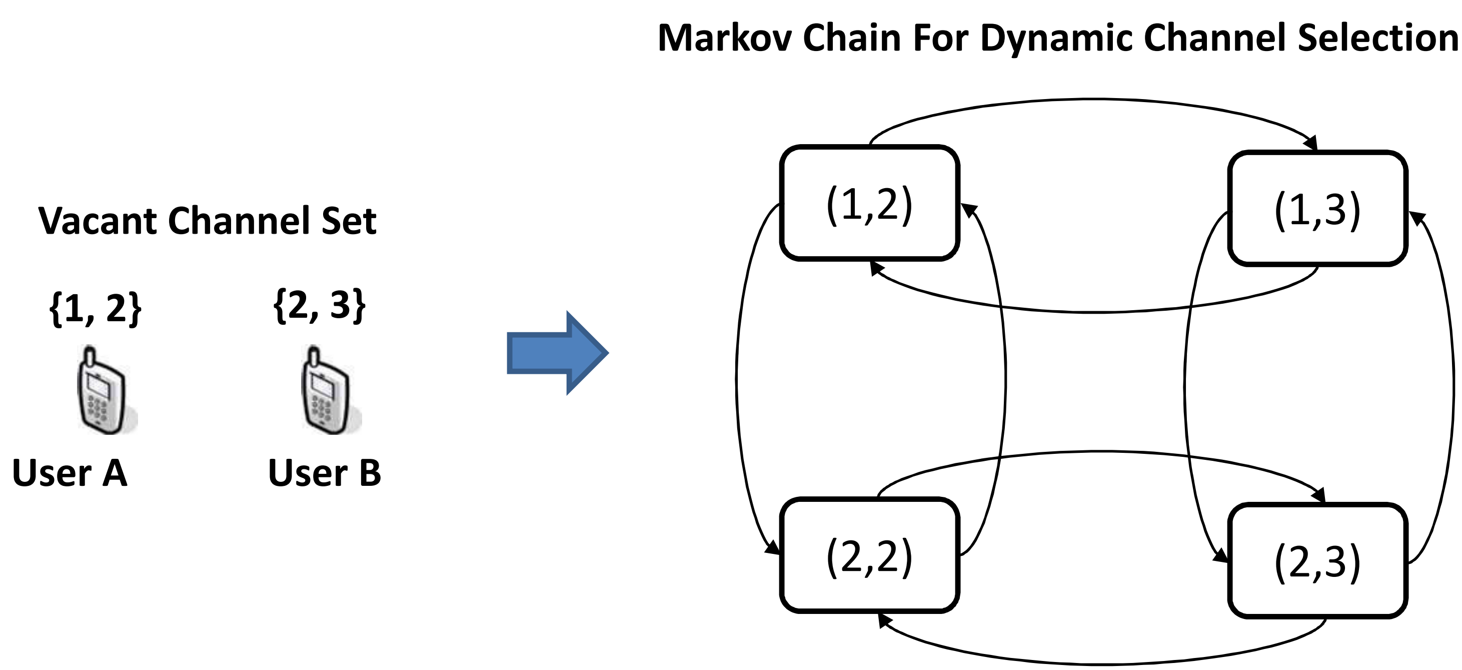


Distributed Spectrum Access Algorithm

- The distributed algorithm induces a Markov chain
  - System state: the channel selection profile of all users
  - Each state transition involves one user: due to the property of exponential distribution for channel update count-down
  - Two-user Markov chain example: diagram of all feasible state transitions



Distributed Spectrum Access Algorithm

- The distributed algorithm induces a Markov chain
  - System state: the channel selection profile of all users
  - Each state transition involves one user: due to the property of exponential distribution for channel update count-down
  - Two-user Markov chain example

THEOREM: The distributed spectrum access algorithm induces a time-reversible Markov chain with the unique stationary distribution given as

$$q_x^* = \frac{\exp(\theta\phi(x))}{\sum_y \exp(\theta\phi(y))}$$

- As $\theta \to \infty$, the SNE $x^{SNE} = \underset{x}{\operatorname{argmax}}\, \phi(x)$ can be achieved

Distributed Spectrum Access Algorithm

- Performance gap from social optimal solution
  - $\mathrm{V(x)} = \sum_{i=1}^{n} U_i(x)$ denotes the total individual utility of all users
  - $V^* = \max_{x} \mathrm{V(x)}$ denotes the maximum network utility
  - $\rho = V^* - V(x^{SNE})$ denotes the performance gap by distributed spectrum access algorithm

THEOREM: The performance gap ρ of the SNE by distributed spectrum access algorithm is at most

$$\frac{1}{2}\sum_{i=1}^{n}\sum_{j\in N_i^p \cap N_i^s}(1-a_{ij})P_j d_{ji}^{-\alpha} + \frac{1}{2}\sum_{i=1}^{n}\sum_{j\in N_i^p \setminus N_i^p \cap N_i^s} P_j d_{ji}^{-\alpha}$$

- ρ decreases as the social tie strength a_{ij} increases
- $\rho = 0$ when all users are altruistic, i.e., $a_{ij} = 1, \forall i, j$

Convergence v.s. Performance

- In practice, convergence time could be a key concern
  - Can we significantly reduce the convergence time at the cost of small performance loss?
- The convergence time can be exponentially reduced by setting a smaller θ

THEOREM: The convergence time of the distributed spectrum access algorithm is bounded by

$$K_1 \theta \exp(K_2 \theta),$$

where K_1, K_2 are constants.

- The performance loss of setting a smaller θ is insignificant

THEOREM: For the distributed spectrum access algorithm with a finite θ, its performance loss from the SNE (i.e., $\theta \to \infty$) is bounded by

$$\frac{1}{\theta} \sum_{n=1}^{N} \ln M_n,$$

where M_n is the number of vacant channels of user n.

Convergence v.s. Performance

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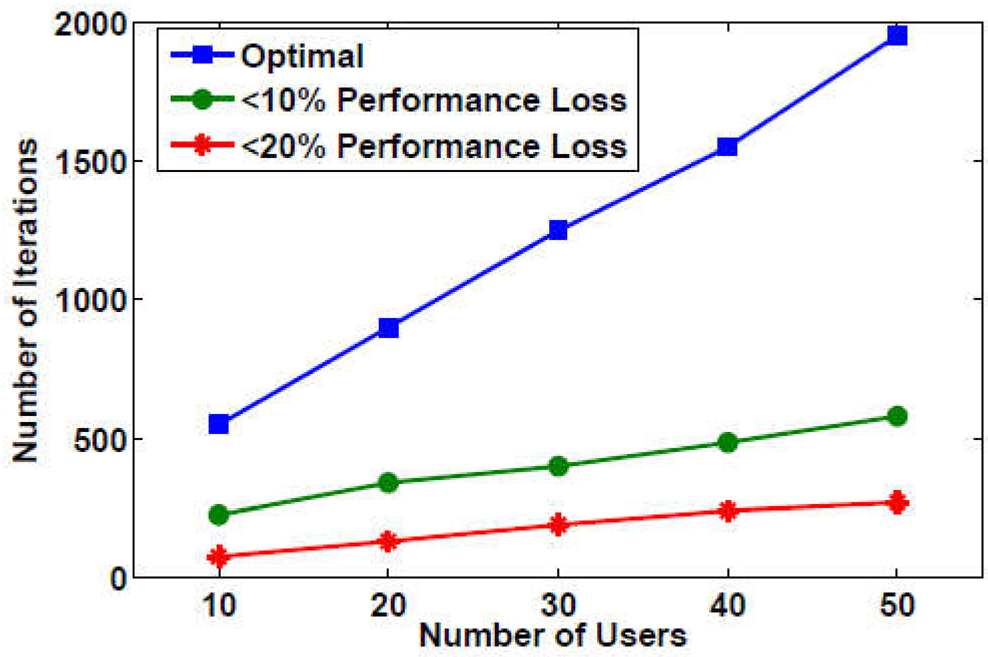
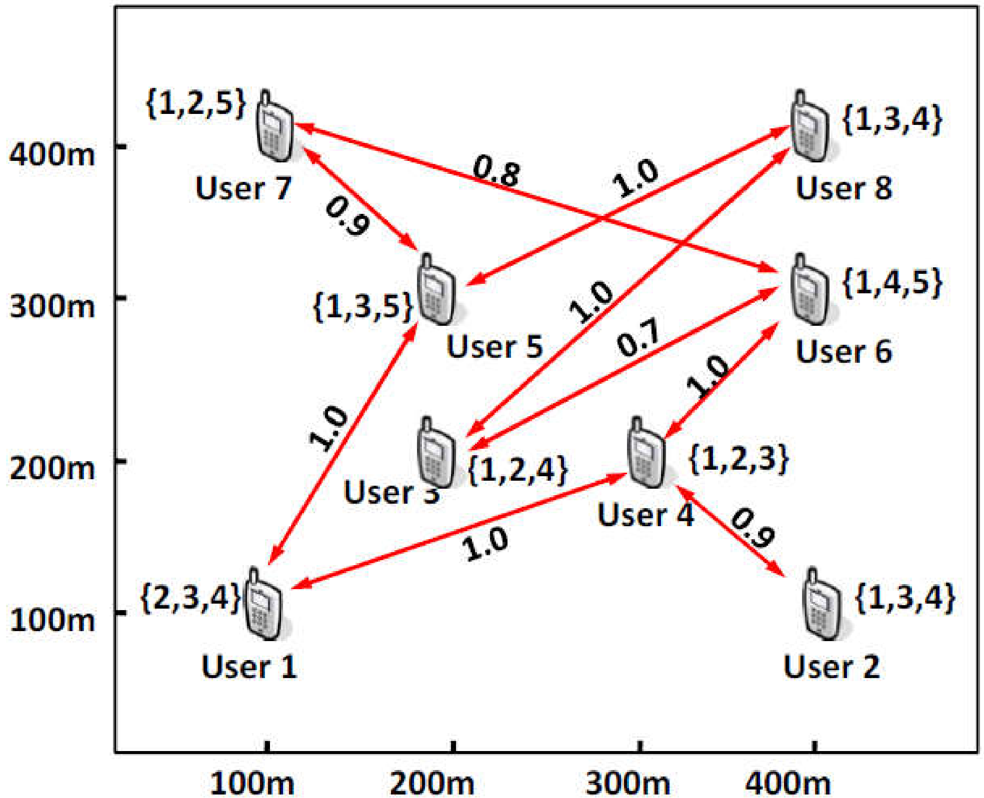


Numerical Results

- N=8 users randomly scatter over a square area
- Social graph is represented by red edges



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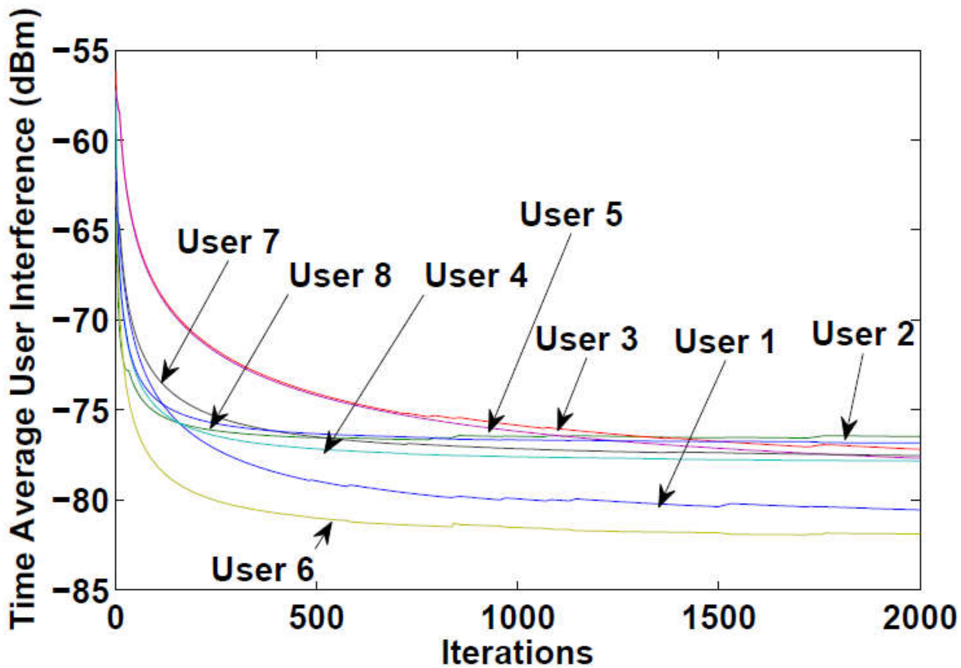
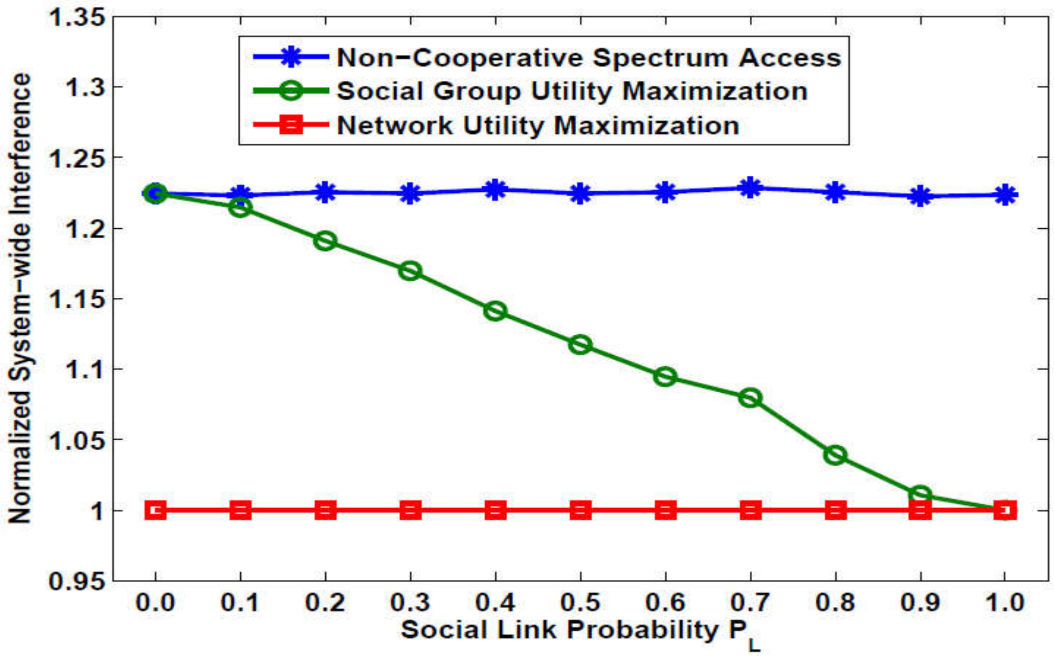


- Distributed spectrum access algorithm can drive users' time average interference decreasing

Numerical Results

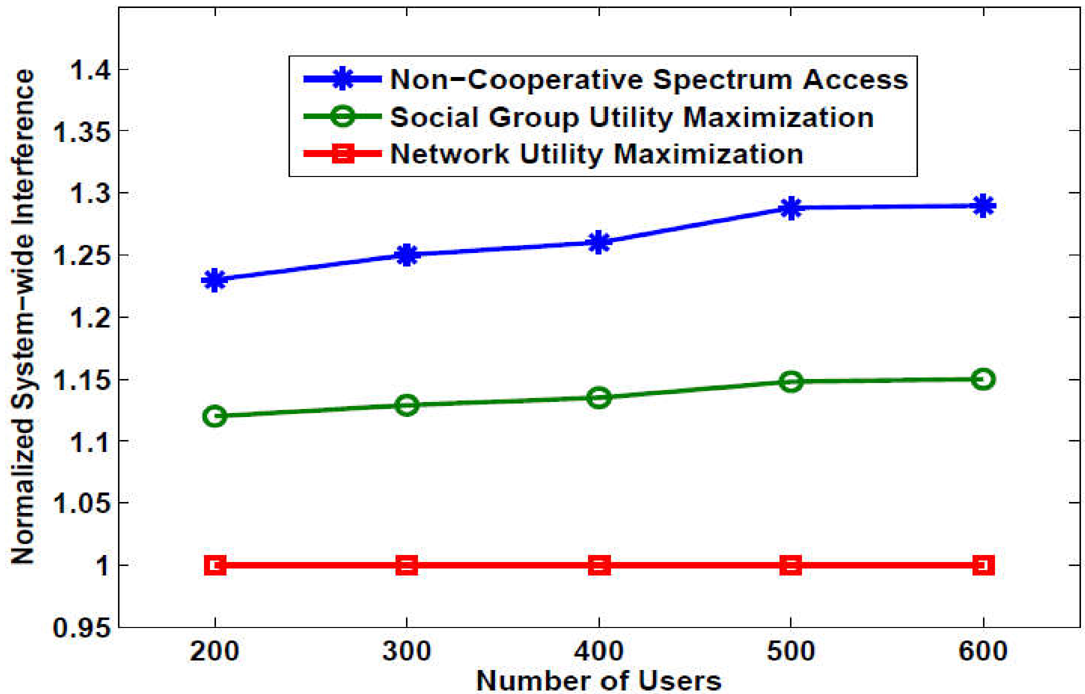
- N=100 users randomly scatter over a square area
- Social graph is represented by Erdos-Renyi random graph
  - There exists a social link between two users with a probability P_L



- Performance improves as the social link density increases
- Span the continuum space between NCG and NUM

Numerical Results

- Users randomly scatter over a square area
- Social graph is based on real data trace: friendship networks of Brightkite



- Performance gap, compared with NUM, is at most 15%.

Summary

- Introducing Social Awareness into Networking
  - Developed social group utility maximization (SGUM) framework, which offers rich modeling flexibility and bridges the gap between non-cooperative game and network utility maximization, two traditionally disjoint paradigms
  - Studied SGUM applications in random access control and database-assisted spectrum access, and quantify the impact of social ties on networking

Summary

- Future work
  - Study SGUM for more applications and investigate the impact of negative social ties (e.g., malicious user)