Social-Aware D2D Communication Enabling Cellular Network: Where Mobile Network Meets Social Network

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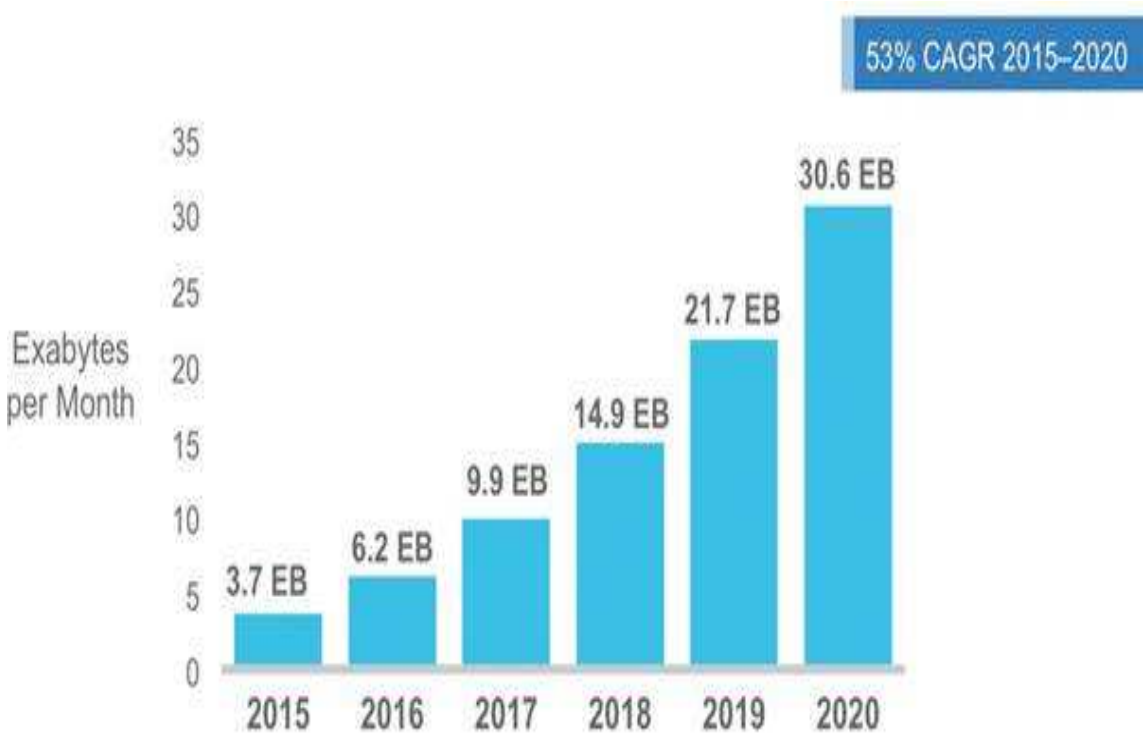
Talk at Department of Computer Science, Aberystwyth University, 10/10/2016

Mobile Network: Brief History

- 1G: mobile communication **started**, but very limited system capacity
- 2G: mobile communication **spread**, mainly limited to 'phone', i.e., voice
  - People taste 'mobile' freedom, like it, demands kept increasing
- 3G: started fundamental paradigm shift – allow non-orthogonal access to support **more** users and **ever-increasing** applications
  - It was no longer a 'phone' but a 'smart phone'
  - New applications, multimedia, mobile Internal, social networks, digital economy etc. spread like **wild** fire
- 4G: **we** fire fighter hurriedly brought 4G out
- Very near future: while 4G was just in layout stage, we knew it will not be enough very soon, and we have to think something – **B4G or 5G**

Cisco Forecast 2015-2020

- Global mobile data traffic grew 74 percent in 2015
- In 2015 mobile video traffic was more than 55 percent of traffic
- More than 50 percent of global mobile data traffic was offloaded in 2015
- Mobile data traffic will increase 18-fold between 2015 and 2020



1 exabyte= 10^{18} bytes

- Monthly global mobile data traffic will surpass 30 exabytes by 2020
- 75 percent of the world's mobile data traffic will be video by 2020

Birth of Social Networks

- Our digital world reality: where those huge volume of mobile traffics come from? $\Rightarrow$ **social networks**
  - Just look at **WeChat** (this is biggest digital world, although not in here)
- Birth of social networks $\Rightarrow$ thanks to mobile networks
  - Mobile devices carried by human beings who form social networks of certain **social structures and phenomenons**
  - More and more people are living in two worlds: 'real' **physical** world and 'virtual' **digital** world
- **Communication** and **computing** are two pillars of our digital world
  - The complaint is **we** do all hard donkey work, and **you** get all credits
  - Technically, it is very very hard to double the rate, but you all take for granted whatever you need you get it

New G Mobile Network

- Mobile communications landscape shows current technology could not meet demand
  - You with your smart phones are creating this exponentially increasing demand
- Once again we are going to 'save' world with **new generation** mobile network
  - How many of you remember this? **The future is bright the future is orange**
  - We are saying **The future is social network the future is new mobile network**
- We are exploiting many technological components to create this new G, e.g.:
  - Keep shrinking cell size to reuse resources as much as possible
  - Massive MIMO
  - Enable direct **device-to-device** (D2D) communication to enhance bandwidth efficiency and increasing system capacity while reducing power consumption
- New G mobile network, among many other fancy things, will be **D2D** enabling

Turn the Table around

- People live in social networks, and social networks live in mobile networks
  - So far just one-way traffic, **we** do all hard works, and **you** get all you wanted
- No point just complain, we should **leverage** social network characteristics
  - To design this new G of D2D enabling mobile network
- And people are '**selfish**' owing to many factors, such as valuable resources, privacy and security considerations
  - Many users may not be pleased to devote some of their precious resources to safeguarding interests of strangers
- Current D2D researches have assumed implicitly at least users are always willing to act in a cooperative unselfish way
  - Overestimate achievable performance, leading to inappropriate D2D protocols

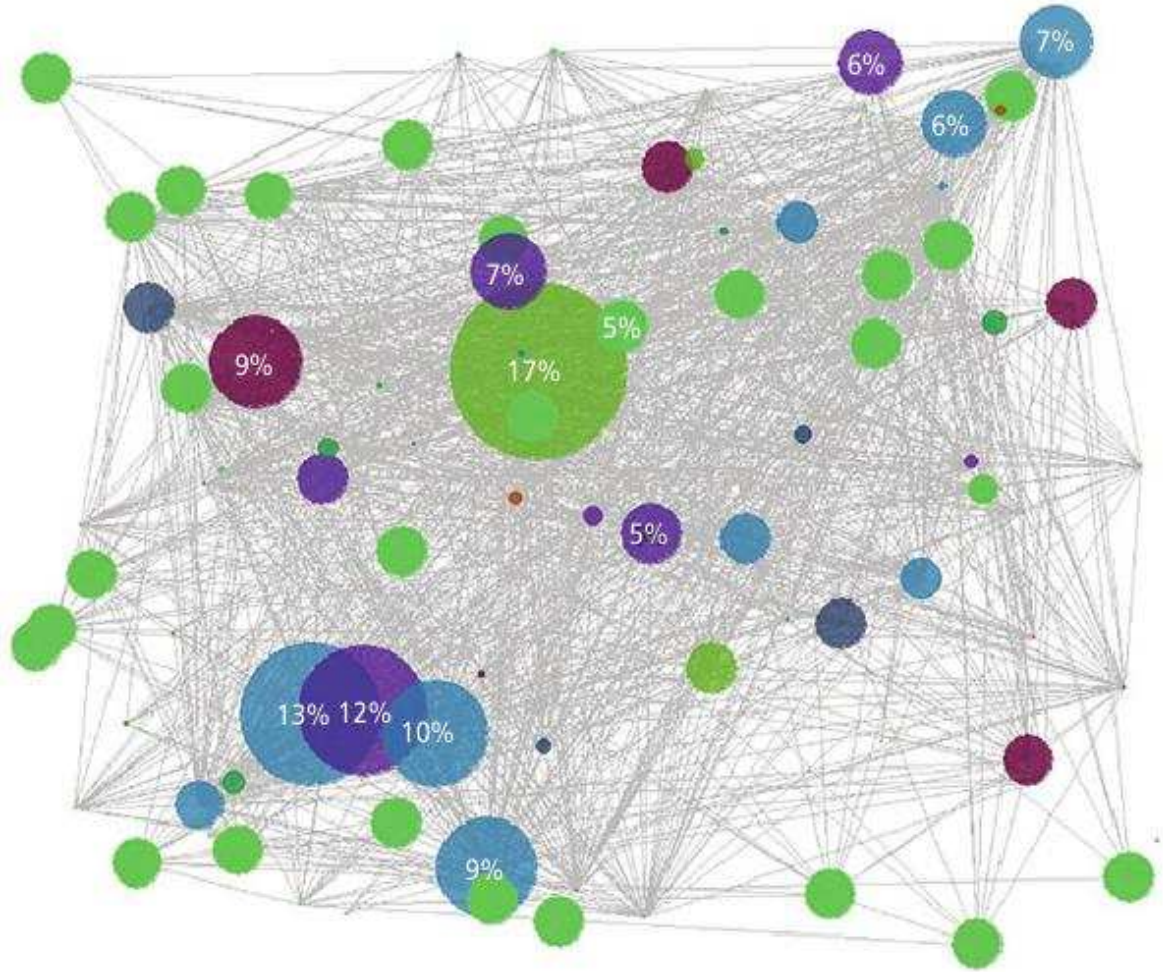
Social Characteristics

1. Social **tie**: characterise strength that two individuals are related to each other
   - In mobile network, social ties identify weak or strong connections among mobile users
2. Social **community**: identify groups of individuals sharing same interests or behaviours
   - In mobile network, social communities represent social groupings by interests or background
3. Social **centrality**: quantify structural importance of an individual
   - A central user has a stronger capability of connecting others in the network
4. Social **bridge**: manifest as connections between communities
   - A bridge provides path to connect two communities, along which information or influence can flow between two groups

Reality Mining

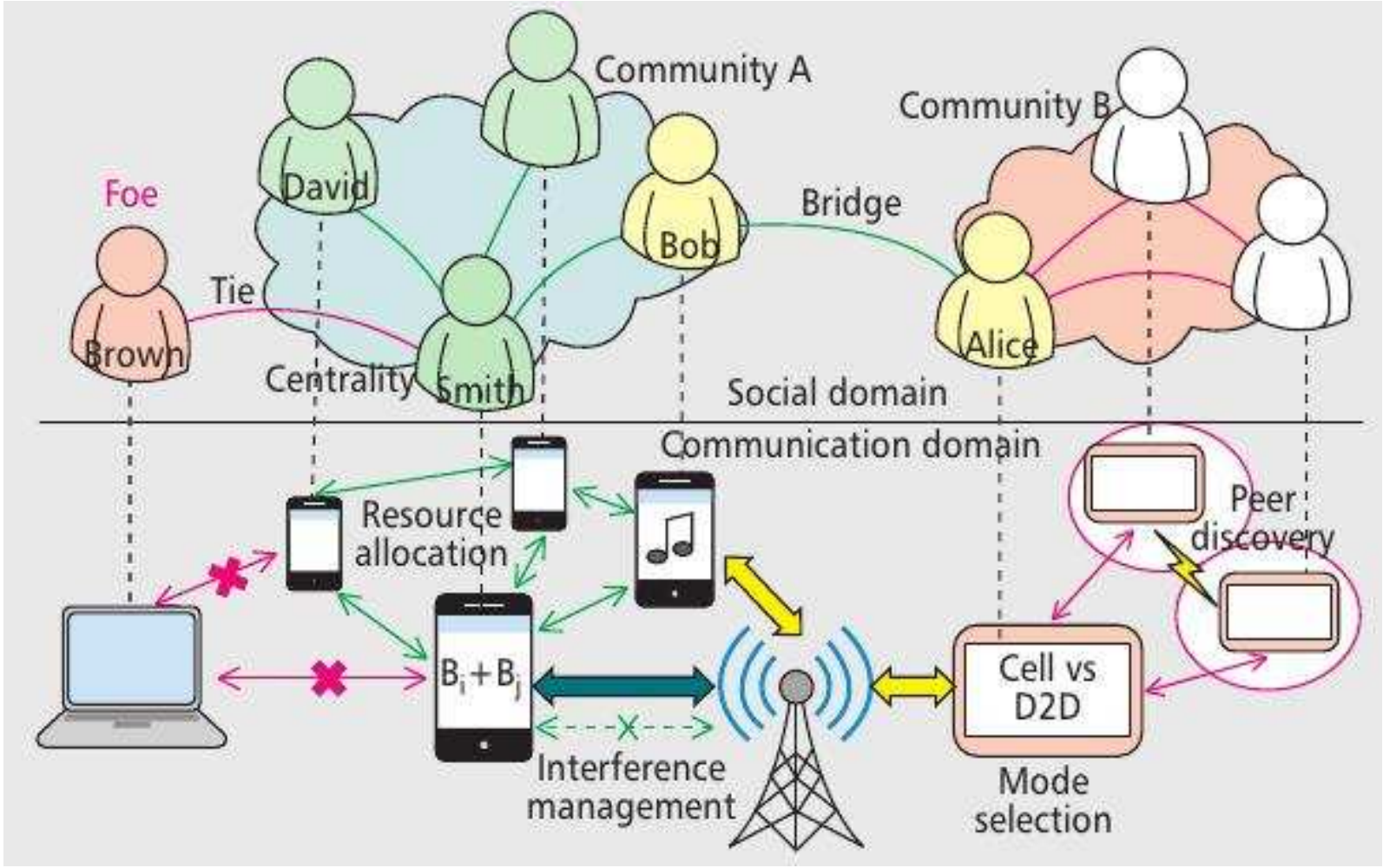
100 smart phones given to MIT staff and students for nine months to observe human social interactions and dynamics

- Users are coloured to identify 9 different **communities**
- User in community has different **centrality**, by size of circle
- Social **ties**: some user pairs have strong relations, while others have weak ones
- When strong relations occur across two communities, social **bridge** is observed



What We Want

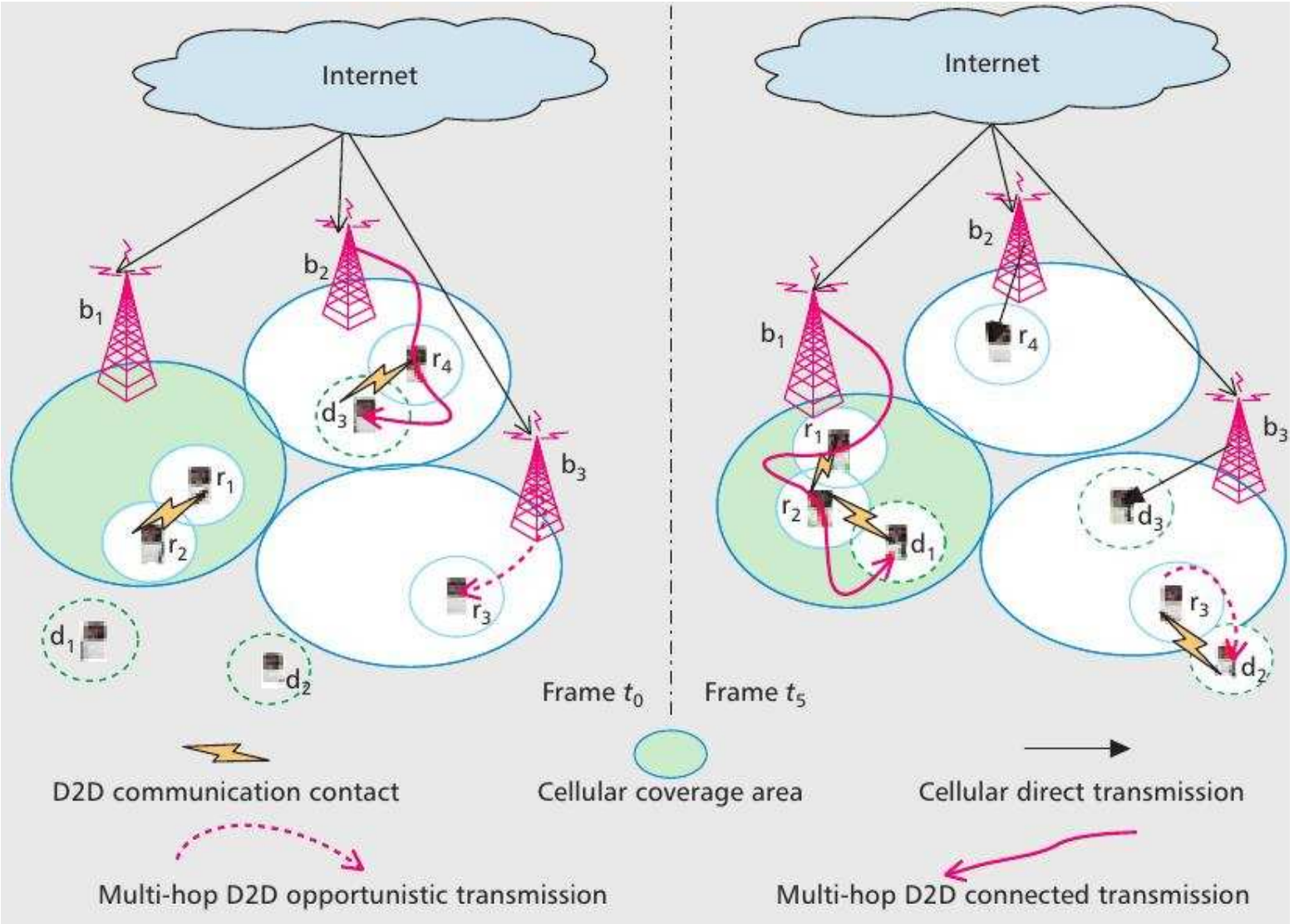
- Social networks have benefited greatly from advance of mobile communication technology



- We want to leverage social network characteristics for establish new paradigm of mobile network design

D2D Enabling Cellular Network

In communication domain, apart from original cellular mode, there are two new D2D enabling modes



b: base station; r: mobile relay or helper; d: mobile destination

Transmission Modes in D2D Enabling Network

1. **Cellular direct**: BS delivers content to mobile destination directly
   - This is original cellular communication mode
   - Mobiles download/share same large popular content with this mode is too costly

2. **D2D connected**: BS establishes with the help of some mobile relays a connection to mobile destination, and content is delivered via the established link
   - Very much like in ad hoc network, first establishing an end-to-end connection, and all transmissions through this connection

3. **D2D opportunistic**: new paradigm relying on store–carry-and-forward, and does not need existence of end-to-end connection
   - BS delivers content to a mobile helper, who stores content in its buffer, carry it when moving around, and waiting for next contact opportunity to forward it
   - Particularly suitable for non-real-time content delivery

Key Technical Problems

1. Service and Peer **Discovery**: identify candidate D2D pairs and required services
   - Network mediates discovery process, a centralized single-point-of-failure solution, having stability and scalability difficulties
   - Ad hoc network approach, peer discovery by mobiles themselves, e.g., through beaconing

2. Communication Mode **Selection**: how to utilize all potential transmission modes to maximize data transmission capacity from all BSs to all mobiles

3. Spectrum Resource **Allocation**: how to share spectrum between D2D and cellular to attain maximum system throughput

4. Interference **Coordination** and Management: how to manage interference between cellular and D2D and across multiple cells
   - Interference coordination for D2D connected can be managed centrally by BSs
   - Interference coordination for D2D opportunistic is much more challenging, and may require distributed management involving handsets

Conventional Solutions

- We have been working on communication-domain designs/solutions
  - Collaborative vehicular content dissemination with directional antennas, *IEEE Trans. Wireless Commun.*, vol.11, **2012**
  - Optimal beaconing control for epidemic routing in delay tolerant networks, *IEEE Trans. Vehicular Technology*, Vol.61, **2012**
  - An optimal relaying scheme for delay-tolerant networks with heterogeneous mobile nodes, *IEEE Trans. Vehicular Technology*, vol.63, **2013**
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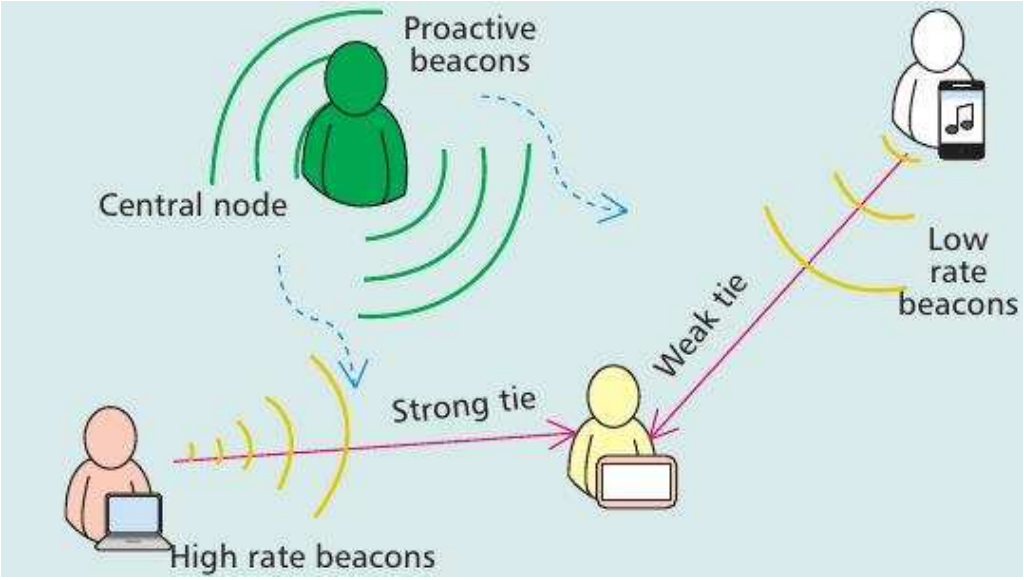
  - Multiple mobile data offloading through disruption tolerant networks, *IEEE Trans. Mobile Computing*, vol.13, **2014**
  - Optimal mobile content downloading in device-to-device communication underlaying cellular networks, *IEEE Trans. Wireless Communication*, vol.13, **2014**
  - A dynamic graph optimization framework for multihop device-to-device communication underlaying cellular networks, *IEEE Wireless Commun.*, Vol.21, **2014**
  - Buffer-aided D2D communications: opportunities and challenges, *IEEE Commun. Mag.*, Vol.53, **2015**
  - Contact-aware data replication in roadside unit aided vehicular opportunistic networks, *IEEE Trans. Mobile Computing*, vol.15, **2016**

Social-Enhanced Solutions: Social Ties

- **Social tie**-aware **peer discovery**:
  - links correlated to strong ties offer more communication contacts and have higher data loads



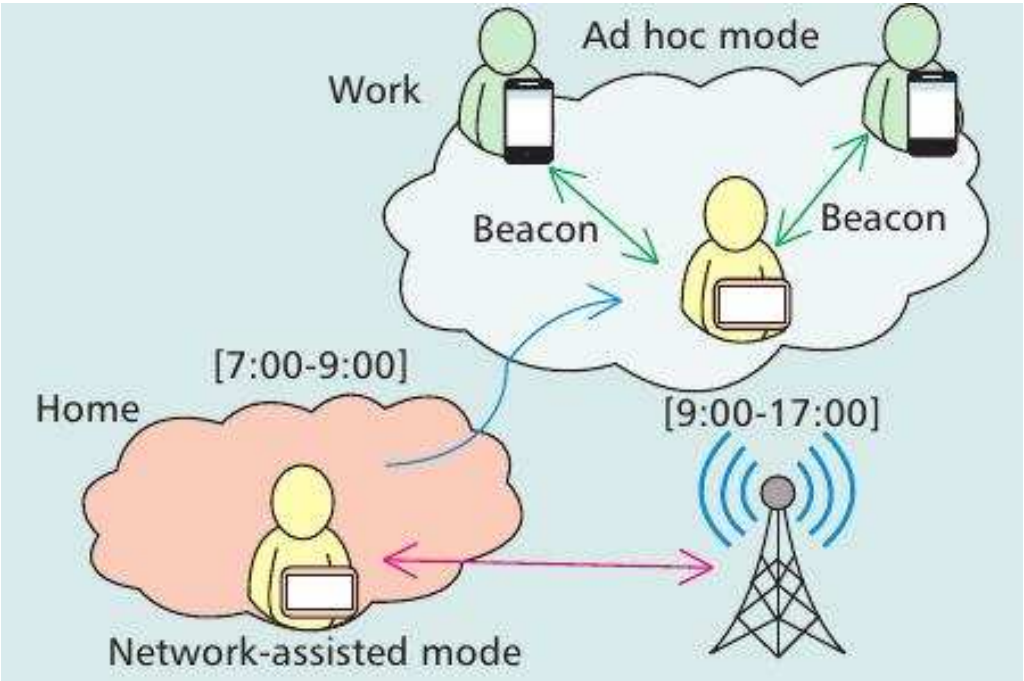
- Instead of randomly beaconing, adjust **beacon rates** according to strengths of ties

- Allocating more spectrum and energy resources to users with strong ties increases peer discovery ratio, avoid congestion, and improve spectral efficiency

- **Social tie**-aware resource allocation and **relay selection**: Since strength of a tie reflects trustfulness of two peers
  - In relay selection, taking social tie information into account improves **privacy** and **security**

Social-Enhanced Solutions: Social Community

- **Peer discovery**: community structure and encounter patterns help peer discovery process
  - User in community with dense population can utilise community encounter patterns to aid ad hoc based peer discovery procedure
- **Resource allocation**: user obtains content and information from community neighbors with less effort, owing to similar interest



- Allocating more resources in D2D communication for these community links helps to reduce duplicated network load
- **Mode selection**: relies on knowledge of channel condition, inter-cell interference and network load
  - Community structure information simplifies detection and helps to make mode selection quickly and accurately

Social-Enhanced Solutions: Social Centrality

- High degree **centrality** indicates that the user plays **key role** in data dissemination
- As multiple communication paths are built up on it, a central node has **higher demand** on **resources**
- **Centrality** users should possess **high capacity** for data transmission volume and frequency
- A central node has high proximity-encounter possibility with nearby devices
- Central devices may provide **alternatives** to **relieve** synchronization and communication work load on base stations
- Instead of randomised beaconing, central node can **proactively** send **beacons** to improve peer discovery ratio

Social-Enhanced Solutions: Social Bridges

1. A **bridge** undertakes task to provide information and content exchange among communities
   - Prone to **congestion** under heavy network load conditions
2. Resource allocation needs to schedule **more resources** to bridge users
   - **To avoid congestion**
3. Mode selection needs to give **higher preference** of cellular communication to bridge nodes
   - **To avoid congestion**
4. Bridge user **detection**, bridge-aware resource **allocation** and mode **selection** schemes are challenging problems
   - Have potential for significantly improving overall **throughput** and **coverage** of D2D enabled cellular network

Social-Aware D2D Summary

How **ties**, **community**, **centrality** and **bridge** information can help designing better **peer discovery**, **mode selection**, **resource allocation** and **interference management**:

	Ties	Community	Centrality	Bridge
Peer discovery	Beacon rate adjustment	Peer density Encounter patterns	Proactive beacons Communication demands	/
Mode selection	/	Community density Community interests	Cellular preferential Bottleneck detection	Inter-community demands
Resource allocation	Communication demands Security and privacy	Community-oriented sharing Communication demands	Resource demands Bottleneck prediction	Dissemination dominant Bottleneck prediction
Interference management	Relay selection Spectrum allocation	Resource partition Distributed coordination	/	/

Social Meets D2D: Quantitative Evaluation

System set up for simulated D2D enabling network:

1. Use **Reality Mining** trace, the most recognised human social and mobility trace, to drive simulation

2. In the area covered by Reality trace, multiple BSs, each with a coverage radius of 400 m, provide a seamless coverage

3. Maximum transmission range of D2D nodes is 50 m, and achievable link data rate depends on distance of two UEs

4. Other network parameters are based on standard wireless propagation settings
   - **D2D** channel based on scenario that two communicating UEs are physically in close proximity
   - **Cellular** channel is simulated according to urban microcell scenario

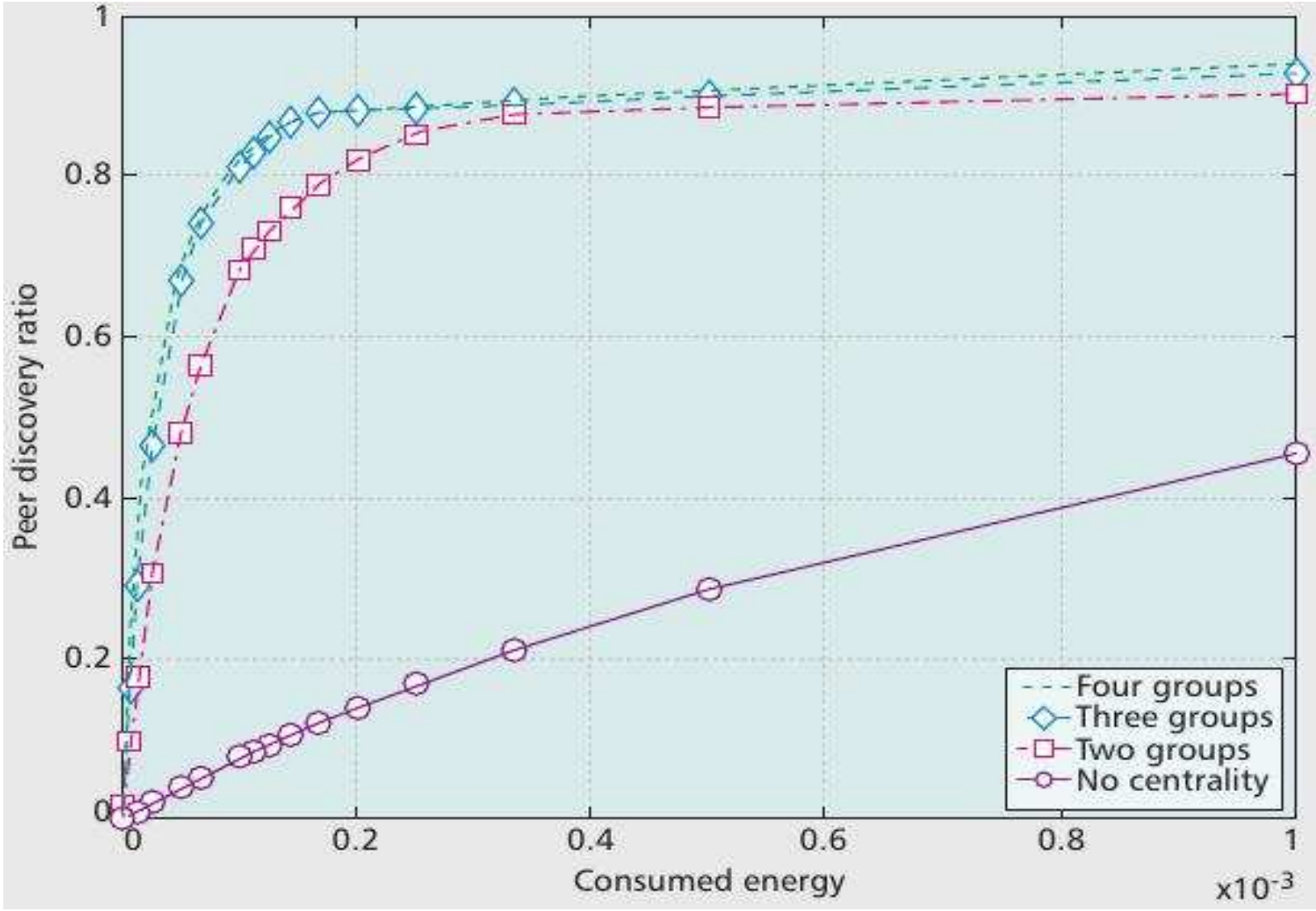
Social-Aware D2D Designs

1. **Centrality-Aware Peer Discovery**: adjust users' beacon rates proportional to centrality values
   - Group users by their centrality values, and allocate a different beacon rate to each group

2. **Bridge-Aware Mode Selection**: first communication-domain throughput-maximisation to decide transmission modes. Then:
   - Amend results by setting all bridge users to cellular mode in downloading phase
   - Set them to D2D mode in data sharing phase to disseminate data to other users

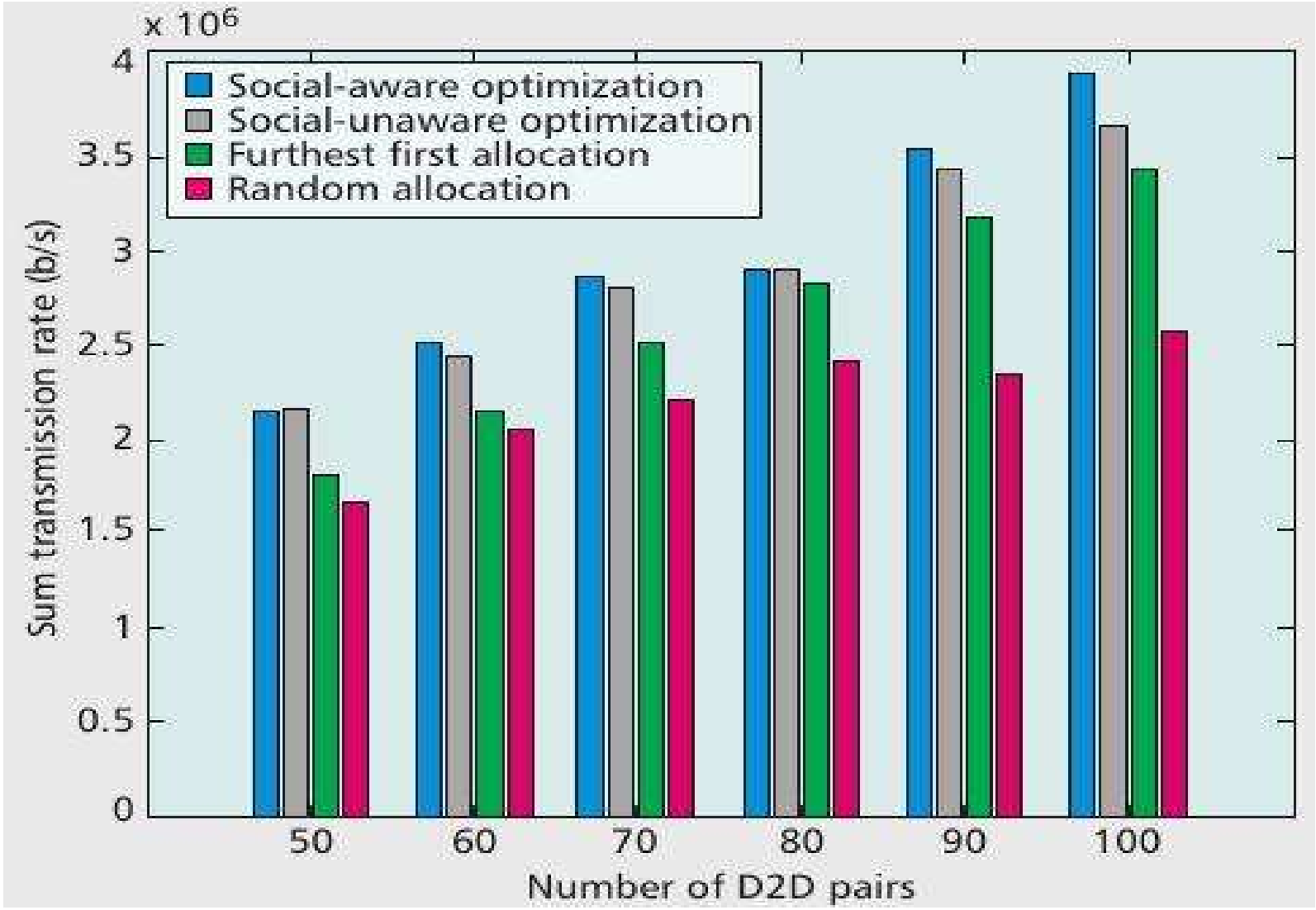
3. **Community and Ties Guided Resource Allocation**:
   - Allocate D2D pairs with same resources of cellular users in different communities (usually not in physical proximity)
   - Within a community, allocate resources for D2D pairs to be proportional to their social tie strengths

Peer Discovery Efficiency

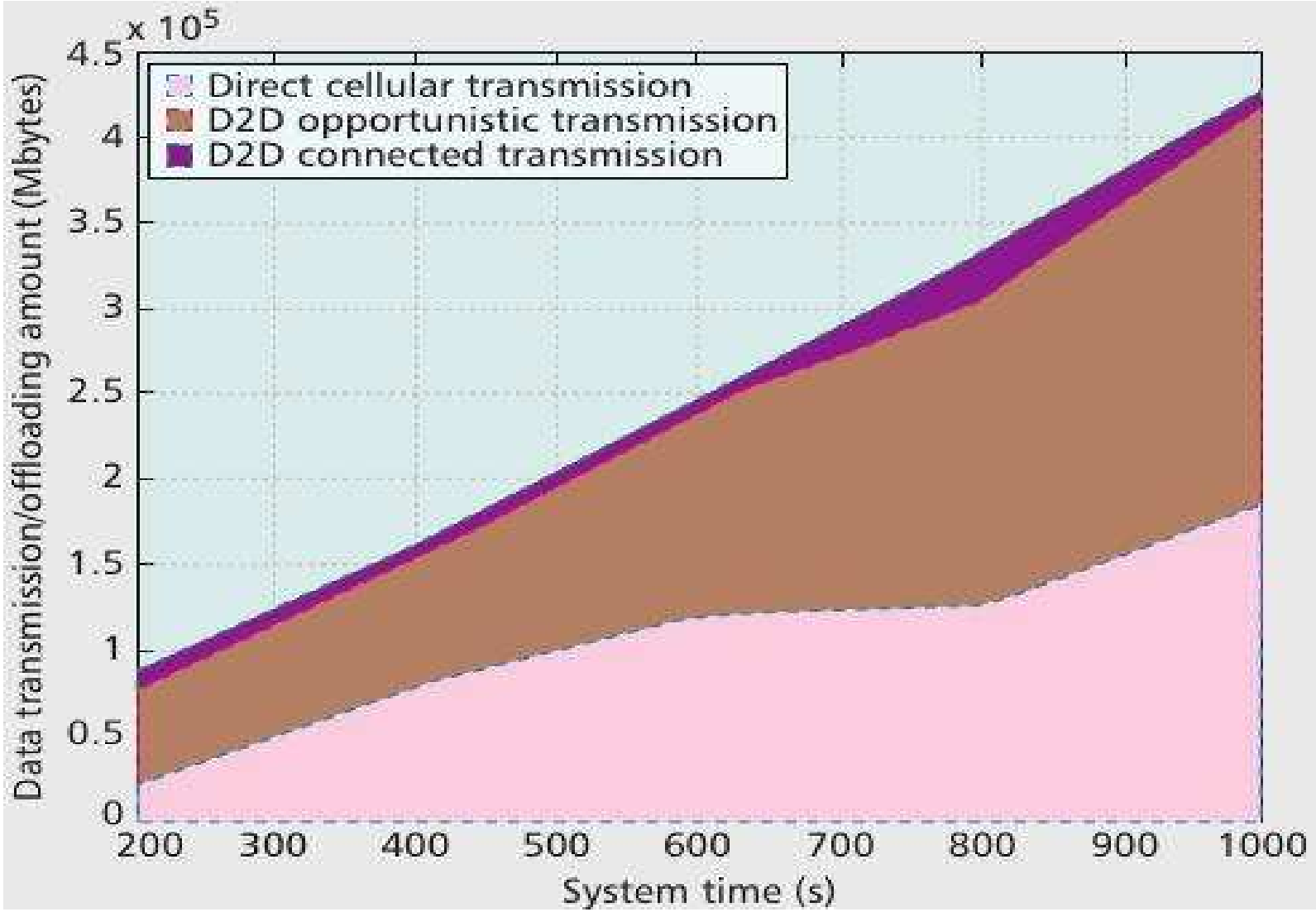


Comparison of **peer discovery** performance as function of normalised energy consumed for **non-social centrality aware** and **social centrality aware** schemes

Resource Allocation Performance



Spectrum efficiency comparison in terms of sum rate (**further first**: resources of cellular users to D2D pairs that are furthest away from them; **non-social aware optimal**: throughput-maximisation)



Throughputs attained by three different modes as function of content downloading latency

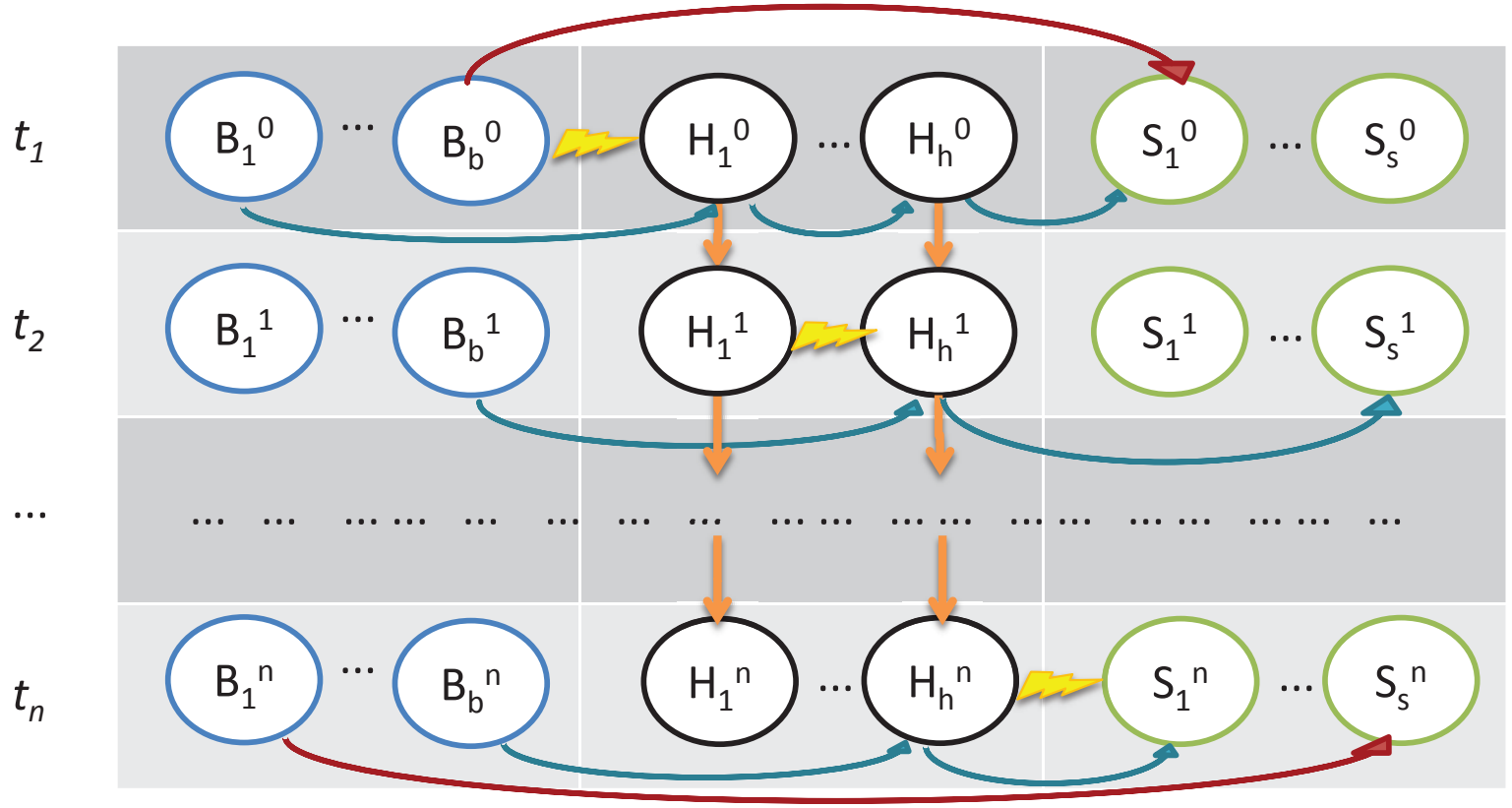
- **Throughputs** attained by three different modes as function of content downloading latency for System with social bridge guided mode selection
  - **D2D opportunistic** offloads large amount of data from the traditional cellular transmission

User Selfishness

- Most researches do not consider impact of user **selfishness**
  1. Standard D2D researches simply 'demand' users operate cooperatively and unselfishly to forward or to store data for others as required
  2. Social network researches focus on D2D mechanisms based on social information and social properties, and do not analyze impacts of user selfishness either
- How to characterize selfishness, one way is
  1. **Individual** selfishness: as an individual, a user tends to show unwillingness when required to selflessly forward or store data for others
  2. **Social** selfishness: as a member of a community, a user although may be more willing to help members of same community, may be unwilling to do so for users outside community
- For two D2D modes, we may also define two corresponding selfishness modes
  1. D2D **connected** selfishness: degree of users' unwillingness to cooperate in connected D2D transmission
  2. D2D **opportunistic** selfishness: degree of users' unwillingness to participate in D2D opportunistic transmission
  - User's opportunistic selfishness is higher than its connected selfishness
- Very **challenging** to qualitatively and quantitatively study impacts of user selfishness on D2D enabling cellular network

Dynamic Graph Model

- In communication domain, we have developed a dynamic graph model to optimize D2D enabling cellular network



B: base station; H: mobile helper; S: mobile subscriber

Involving User Selfishness

- In original dynamic graph model at each time frame
  - Boolean connection matrix $\mathcal{N}$: access states of user pairs
  - Boolean cover matrix $\mathcal{V}$: access states between base stations and users

- To model users' **unwillingness** to participate in D2D communications
  - Helper may forbid any potential D2D connected transmission that it may establish with **connected selfishness probability** p
  - Helper may forbid any potential D2D opportunistic transmission that it may establish with **opportunistic selfishness probability** q

- At each time frame, random forbiddance to two D2D modes are specified by
  - **Connected selfishness matrix** $\mathcal{R}$
  - **Opportunistic selfishness matrix** $\mathcal{G}$

- Combining $\mathcal{N}$ with $\mathcal{R}$ and $\mathcal{G}$ **explicitly** models selfishness in D2D enabling cellular network

Investigate Impact of User Selfishness

- With this explicit modeling of user selfishness, we are able to employ **modified** dynamic graph framework to investigate impacts of user selfishness
- Our investigation reveals some intriguing effects of various user selfishness modes and their **interplay** to achievable performance of D2D enabling cellular network
- Observations and insights drawn will be beneficial to current standardizing process of **D2D protocols** for next-generation mobile networks
- Our **initial** work reported in
  - "Impact of selfishness in device-to-device communication underlaying cellular networks," *IEEE Trans. vehicular Networks*, under minor revision
- Considerable **future** works are required

Conclusions

- Social networks we inhibit inhibit in mobile networks
  - Understand interplay between social network's characteristics and mobile communication problems
  - Beneficial to exploit social network's characteristics in mobile network design
  - Critical to consider user selfishness in D2D protocol design
- Open up new direction for designing next-generation social-aware D2D enabling cellular system
  - where our new digital world will inhibit in

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