Course: Content Distribution in Wireless Networks

Topic: Network Coding and Opportunistic routing in mobile social networks

Master 2 IFI Ubinet 2014-2015

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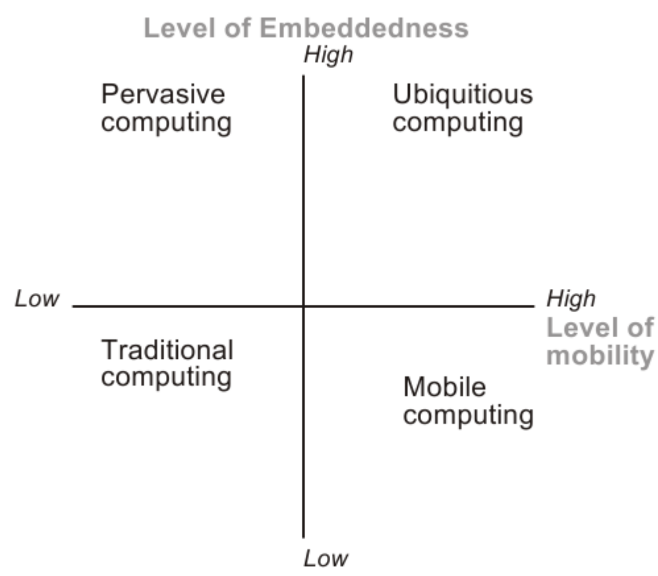
Ubiquitous / Pervasive / Mobile computing

- In 1991, Marc Weiser (Xerox PARC), formulated his vision of a new area in computer science: ubiquitous computing.
- To enable people to move around and interact with computers more naturally than they were used to do. Computers should become good, invisible tools. In his sense, an invisible tool is one that does not draw the user's attention towards itself.

- Another term: pervasive computing.
- Embedding computation power into the environment.
- Pervasive computing does not take node or user mobility into account.



A. Heinemann, *Collaboration in Opportunistic Networks*, PhD dissertation, Darmstadt 2007

Opportunistic networks

- Increasing integration of wireless short-range communication technologies (Bluetooth, 802.11 WiFi) into mobile devices

  -> spontaneous communication, interaction and collaboration are possible.
- Spontaneous communication: opportunistic networking
- Promising evolution in mobile ad-hoc networking.
- Formed by mobile devices communicating while users are in close proximity.
- There are two prominent characteristics present in opportunistic networks: 1) A user provides his personal device as a network node. 2) Users are a priori unknown to each other.

A. Heinemann, *Collaboration in Opportunistic Networks*, PhD dissertation, Darmstadt 2007

About…

- This course is about:
  - Network coding as a new networking paradigm
    - Fundamentals
    - Applications of NC to wireless networks, to opportunistic networking
  - Opportunistic routing in MANET
    - Mobility models: social networks in motion
    - Opportunistic routing in heterogeneous MANETs: strategies and performance analysis

Not about…

- This course is not about:
  - Software implementations
  - Security and privacy issues of MANETs
  - Incentives to encourage collaboration, competition in mobile networks (game theory)
  - …

Outline

I. Network coding: beyond routing
   1. Introduction
   2. Application of NC to wireless networks: *Xor in the air*

II. Opportunistic routing
   1. Motivation for opportunistic networking
   2. Routing in DTN with uniform mobility
      1. Some uniform mobility models and their characterization
      2. Two-hop routing, epidemic routing and performance modeling
      3. Spray-and-Wait routing: trade-off between resource consumption and performance
   3. Routing in heterogeneous DTN: mobile social networks
      1. Introduction to mobile social networks: the small-world effect, characterization of human mobility
      2. Utility-based routing (UBR): accounting for social relationships
      3. On what UBR builds on: the problem of mapping contacts to graph, community detection and decentralized decisions
   4. Network coding under Spray-and-Wait in DTN

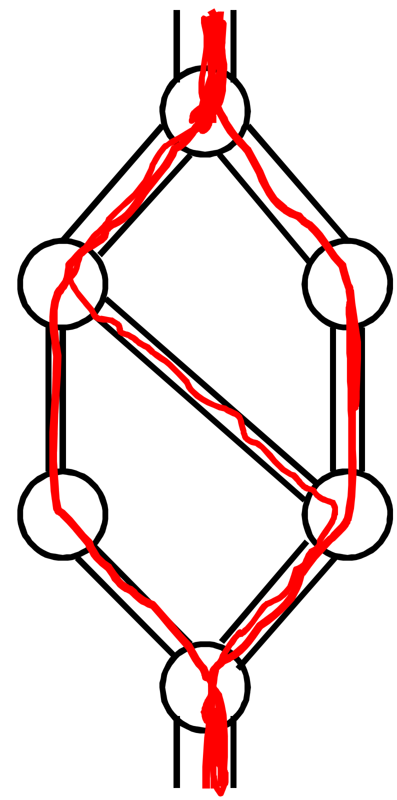
Network coding

Network coding: generalization of routing – the intermediate nodes can modify the payload of packets they have to transfer

Transport networks

- Oriented valued graph *G = (V, E, c)*
- *c(p, q):* capacity of edge *(p, q)*
- *f(p, q)*: rate or flow of edge *(p, q)*
- Examples:
  - Water pipes
  - Pipelines
  - Transportation lanes
  - Freight traffic
  - Communication networks

source *s*



Sink *t*

Conditions

Capacity c : $V \times V \to \mathbf{R}$ with $c(p, q) \geq 0$ and if (p, q) not in E then $c(p, q) = 0$

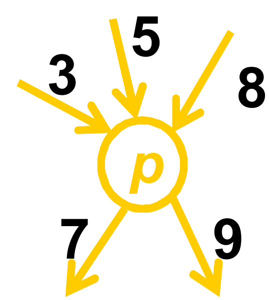
Flow f : $V \times V \to \mathbf{R}$

Source s ∈ V, sink (terminal) t ∈ V

- Accessiblity: all the vertices are on a path from *s* to *t*
- Constraint of capacity:
  - for all $p, q \in V$, $f(p, q) \leq c(p, q)$

- Anti-symmetry:
  - for all $p, q \in V$, $f(q, p) = - f(p, q)$

- Flow conservation:
  - for all $p \in V \backslash \{s,t\}$, $\Sigma\, (f(p, q) \mid q \in V) = 0$



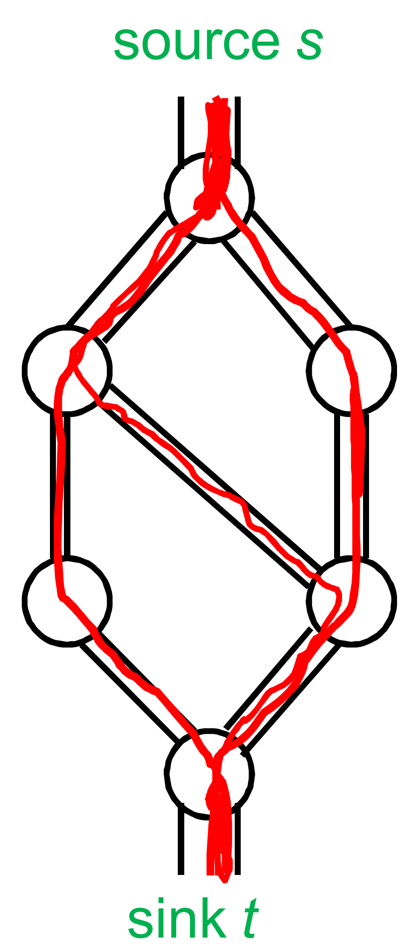
Flow

- Value of the flow

  $| f | = \Sigma (f (p, t) \mid p \in V)$

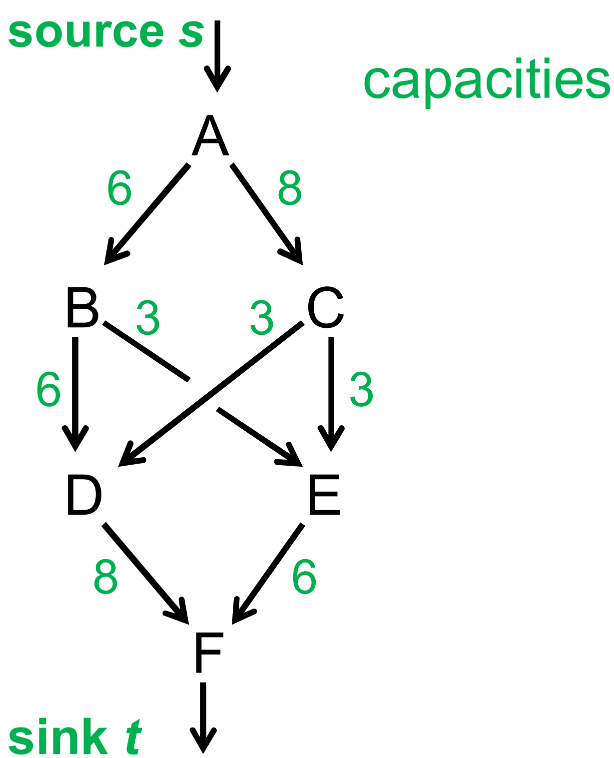
  that arrives to the sink

- Properties
  - for all $p \in V$, $f (p, p) = 0$
  - for all $q \in V$, $\Sigma (f (p, q) \mid p \in V) = 0$

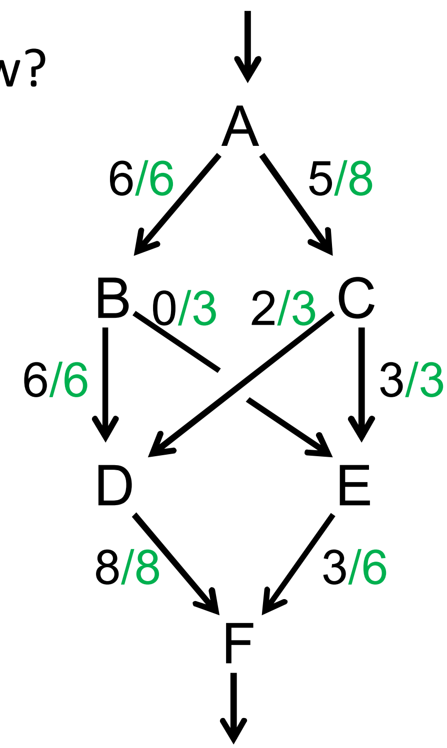


Problem of max flow

- Given an oriented valued graph: *G = (V, E, c)*
- Compute a maximum flow allocation:
  - set *f(p,q)*, for all *p,q ϵ E*, such that |f| is maximum



A maximum flow?
| *f* | = 11



Cut

- *(X, Y)* is a cut of *G* iif:

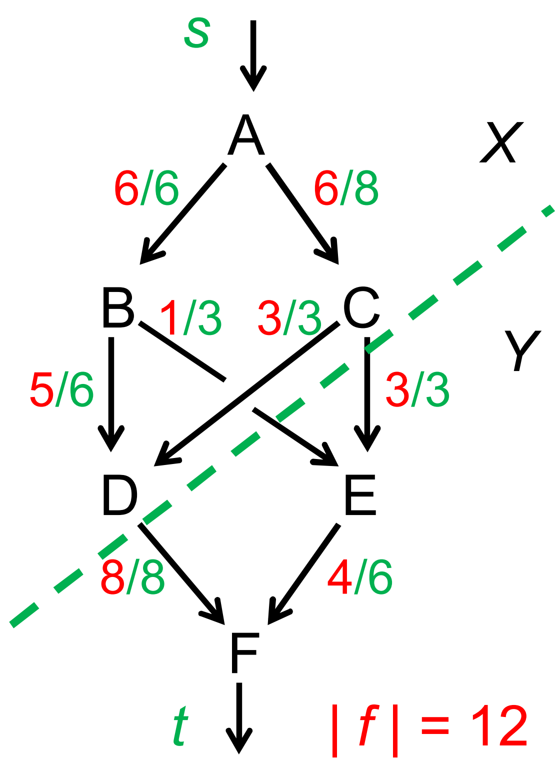
  (X, Y) partition of *V* with $s \in X$, $t \in Y$

- Capacity of the cut:

  $$c(X, Y) = \Sigma \, (\, c(x, y) \mid x \in X, y \in Y \,)$$

- Flow of the cut

  $$f(X, Y) = \Sigma \, (\, f(x, y) \mid x \in X, y \in Y \,)$$



X = {A,B,C,D} Y = {E,F} c(X,Y) = 14 f (X,Y) = 12

Properties

- Properties:
  1. For any cut *(X,Y)*, we have $f(X,Y) = |f|$
  2. For any cut *(X,Y)*, $f(X,Y) \leq c(X,Y)$
  3. *f* is a maximum flow (allocation) iif

     there exists a cut (X_0,Y_0) such that $|f| = c(X_0,Y_0)$

->Theorem of min-cut max-flow:

The maximum flow is the minimum cut capacity.

Min-cut

$X_0 = \{A,C\}$

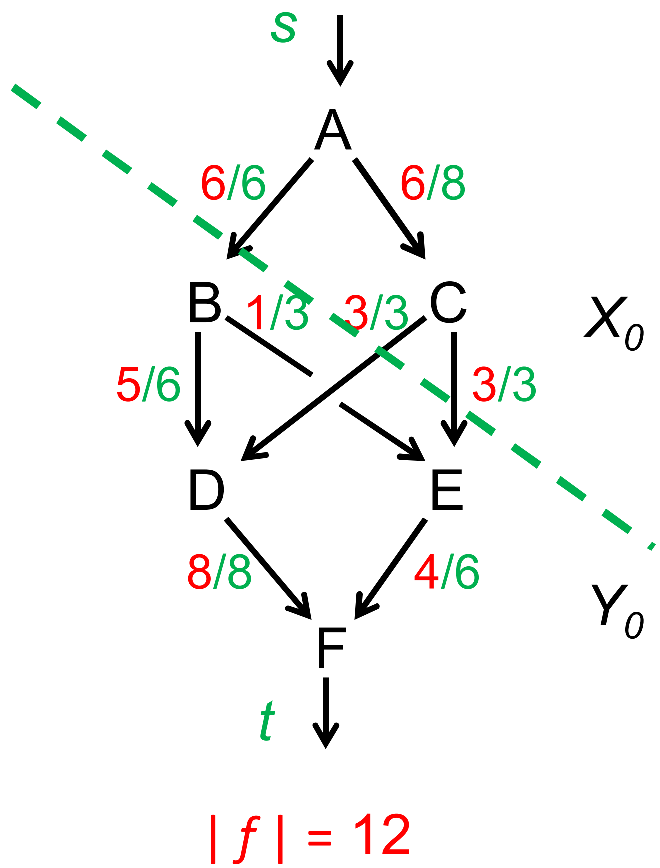
$Y_0 = \{B,D,E,F\}$

$c(X_0,Y_0) = 12$

(X_0,Y_0) of min capacity

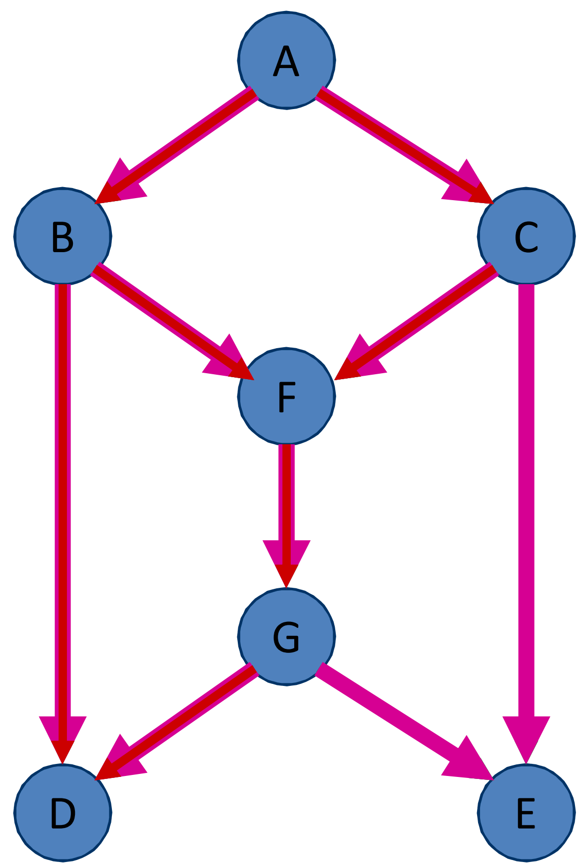
$f\,(X_0,Y_0) = 12$

Max flow



Multicast Problem

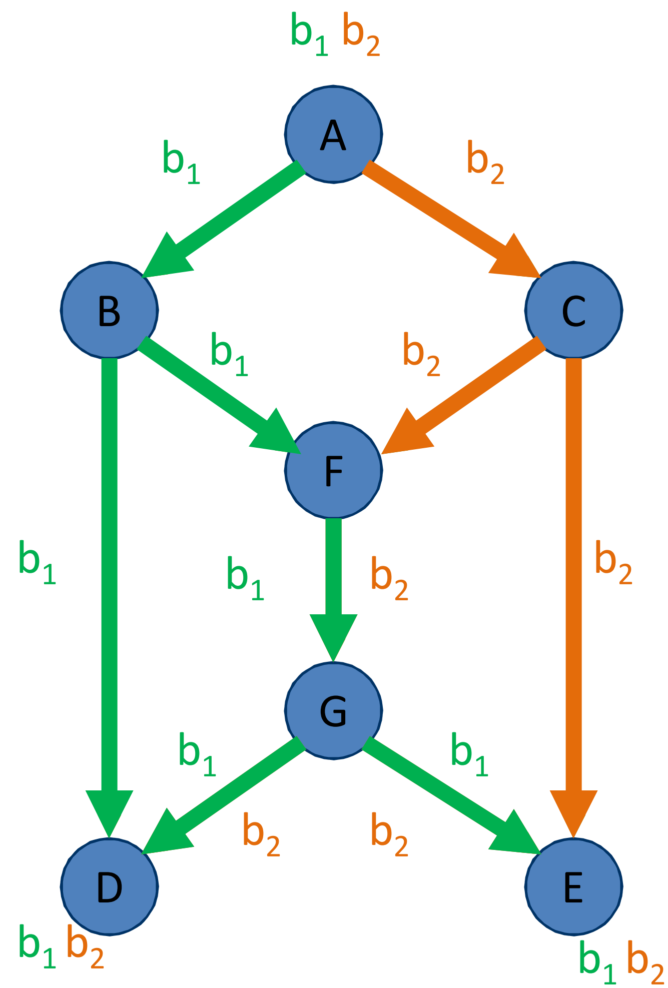
- Butterfly Networks: Each edge's capacity is 1.
- Max-Flow from A to D = 2
- Max-Flow from A to E = 2
- Multicast Max-Flow from A to D and E = 1.5
- Max-Flow for each individual connection is not achieved.



Network Coding

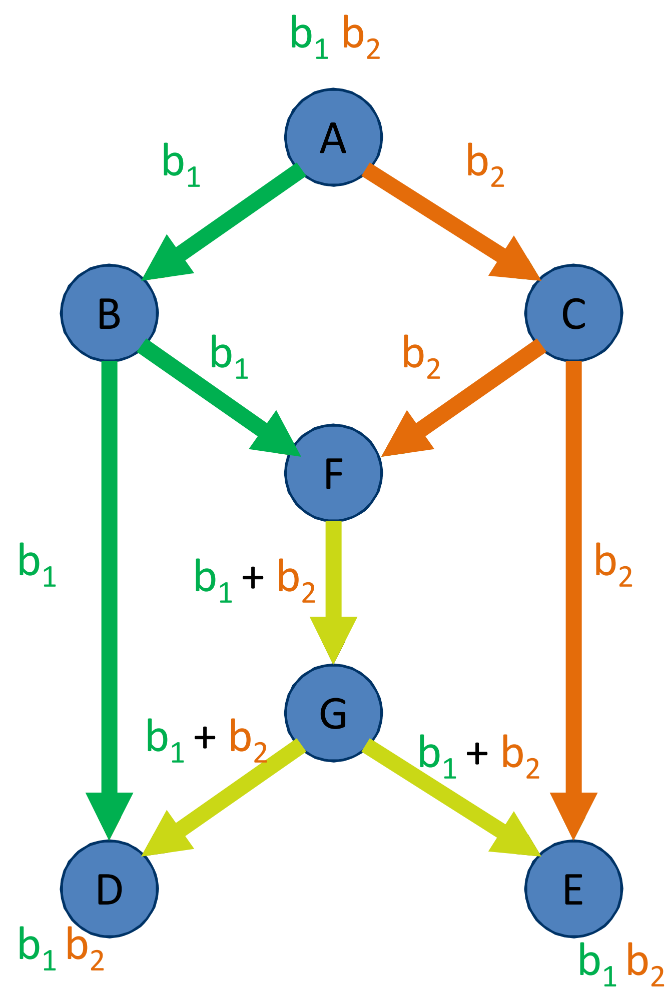
- Introduction
- Linear Network Coding
- Transfer Matrix
- Network Coding Solution
- Connection between an Algebraic Quantity and a Graph Theoretic Tool
- Finding Network Coding Solution

Introduction: multicast with routing



Introduction: multicast with network coding

- Ahlswede et al. (2000)
  - With network coding, every sink obtains the maximum flow.
- Li et al. (2003)
  - Linear network coding is enough to achieve the maximum flow, for multicast in directed networks



R. Ahlswede, N. Cai, S. R. Li, and R. W. Yeung, "Network information flow," IEEE Transactions on Information Theory, vol. 46, no. 4, July 2000.

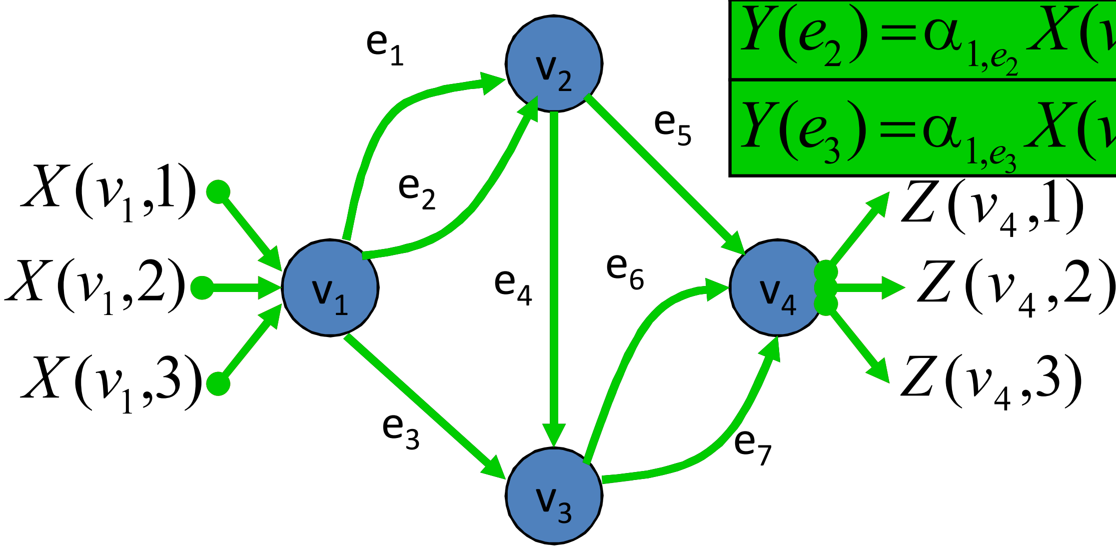
Linear Network Coding

- Random Processes in a Linear Network
  - Source Input: $X(v,l)=\{x_0(v,l),x_1(v,l),\ldots\}$
  - Info. along Edges: $Y(e)=\{y_0(e),y_1(e),\ldots\}$
  - Sink Output: $Z(v,l)=\{z_0(v,l),z_1(v,l),\ldots\}$
- Relationship between them

$$Y(e)=\sum_{l=1}^{\mu(v)}\alpha_{l,e}X(v,l)+\sum_{e':head(e')=tail(e)}\beta_{e',e}Y(e')$$

$$Z(v,j)=\sum_{e':head(e')=v}\varepsilon_{e',j}Y(e')$$

Transfer Matrix



$$Y(e_1)=\alpha_{1,e_1}X(v,1)+\alpha_{2,e_1}X(v,2)+\alpha_{3,e_1}X(v,3)$$
$$Y(e_2)=\alpha_{1,e_2}X(v,1)+\alpha_{2,e_2}X(v,2)+\alpha_{3,e_2}X(v,3)$$
$$Y(e_3)=\alpha_{1,e_3}X(v,1)+\alpha_{2,e_3}X(v,2)+\alpha_{3,e_3}X(v,3)$$
$$Y(e_4)=\beta_{e_1,e_4}Y(e_1)+\beta_{e_2,e_4}Y(e_2)$$
$$Y(e_5)=\beta_{e_1,e_5}Y(e_1)+\beta_{e_2,e_5}Y(e_2)$$
$$Y(e_6)=\beta_{e_3,e_6}Y(e_3)+\beta_{e_4,e_6}Y(e_4)$$
$$Y(e_7)=\beta_{e_3,e_7}Y(e_3)+\beta_{e_4,e_7}Y(e_4)$$
$$Z(v_4,1)=\varepsilon_{e_5,1}Y(e_5)+\varepsilon_{e_6,1}Y(e_6)+\varepsilon_{e_7,1}Y(e_7)$$
$$Z(v_4,2)=\varepsilon_{e_5,2}Y(e_5)+\varepsilon_{e_6,2}Y(e_6)+\varepsilon_{e_7,2}Y(e_7)$$
$$Z(v_4,3)=\varepsilon_{e_5,3}Y(e_5)+\varepsilon_{e_6,3}Y(e_6)+\varepsilon_{e_7,3}Y(e_7)$$

Transfer Matrix

$$Let\quad \bar{x}=(X(v_1,1),X(v_1,2),X(v_1,3))$$
$$\bar{z}=(Z(v_4,1),Z(v_4,2),Z(v_4,3))$$
$$\bar{z}=\bar{x}\cdot_{e_2} M$$
$$M=A\cdot\begin{bmatrix}\beta_{e_1,e_5} & \beta_{e_1,e_4}\beta_{e_4,e_6} & \beta_{e_1,e_4}\beta_{e_4,e_7}\\ \beta_{e_2,e_5} & \beta_{e_2,e_4}\beta_{e_4,e_6} & \beta_{e_2,e_4}\beta_{e_4,e_7}\\ 0 & \beta_{e_3,e_6} & \beta_{e_3,e_7}\end{bmatrix}\cdot B$$
$$A=\begin{bmatrix}\alpha_{1,e_1} & \alpha_{1,e_2} & \alpha_{1,e_3}\\ \alpha_{2,e_1} & \alpha_{2,e_2} & \alpha_{2,e_3}\\ \alpha_{3,e_1} & \alpha_{3,e_2} & \alpha_{3,e_3}\end{bmatrix} B=\begin{bmatrix}\varepsilon_{e_5,1} & \varepsilon_{e_5,2} & \varepsilon_{e_5,3}\\ \varepsilon_{e_6,1} & \varepsilon_{e_6,2} & \varepsilon_{e_6,3}\\ \varepsilon_{e_7,1} & \varepsilon_{e_7,2} & \varepsilon_{e_7,3}\end{bmatrix}$$

$$Y(e_1)=\alpha_{1,e_1}X(v,1)+\alpha_{2,e_1}X(v,2)+\alpha_{3,e_1}X(v,3)$$
$$Y(e_2)=\alpha_{1,e_2}X(v,1)+\alpha_{2,e_2}X(v,2)+\alpha_{3,e_2}X(v,3)$$
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$$Z(v_4,3)=\varepsilon_{e_5,3}Y(e_5)+\varepsilon_{e_6,3}Y(e_6)+\varepsilon_{e_7,3}Y(e_7)$$

Network Coding Solution

$$\bar{z} = \bar{x} \cdot M$$

$$M = A \cdot \begin{bmatrix} \beta_{e_1,e_5} & \beta_{e_1,e_4}\beta_{e_4,e_6} & \beta_{e_1,e_4}\beta_{e_4,e_7} \\ \beta_{e_2,e_5} & \beta_{e_2,e_4}\beta_{e_4,e_6} & \beta_{e_2,e_4}\beta_{e_4,e_7} \\ 0 & \beta_{e_3,e_6} & \beta_{e_3,e_7} \end{bmatrix} \cdot B$$

$$A = \begin{bmatrix} \alpha_{1,e_1} & \alpha_{1,e_2} & \alpha_{1,e_3} \\ \alpha_{2,e_1} & \alpha_{2,e_2} & \alpha_{2,e_3} \\ \alpha_{3,e_1} & \alpha_{3,e_2} & \alpha_{3,e_3} \end{bmatrix},$$

$$B = \begin{bmatrix} \varepsilon_{e_5,1} & \varepsilon_{e_5,2} & \varepsilon_{e_5,3} \\ \varepsilon_{e_6,1} & \varepsilon_{e_6,2} & \varepsilon_{e_6,3} \\ \varepsilon_{e_7,1} & \varepsilon_{e_7,2} & \varepsilon_{e_7,3} \end{bmatrix}$$

- We want $\bar{z} = \bar{x}$
- Choose A to be an identity matrix.
- Choose B to be the inverse of

$$\begin{bmatrix} \beta_{e_1,e_5} & \beta_{e_1,e_4}\beta_{e_4,e_6} & \beta_{e_1,e_4}\beta_{e_4,e_7} \\ \beta_{e_2,e_5} & \beta_{e_2,e_4}\beta_{e_4,e_6} & \beta_{e_2,e_4}\beta_{e_4,e_7} \\ 0 & \beta_{e_3,e_6} & \beta_{e_3,e_7} \end{bmatrix}$$

NETWORK

CODING

SOLUTION EXISTS IF DETERMINANT OF M IS NON-ZERO

Connection between an Algebraic Quantity and a Graph Theoretic Tool

- Let a linear network be given with source node ν , sink node ν', and a desired connection $c = (\nu, \nu', \chi(\nu, \nu'))$ of rate $R(c)$. The following three statements are equivalent.
  - 1. The connection $c = (\nu, \nu', \chi(\nu, \nu'))$ is possible.
  - 2. The Min-Cut Max-Flow bound is satisfied
  - 3. The determinant of the $R(c) \times R(c)$ transfer matrix M is non-zero over the ring $F_2[\ldots, \alpha_{l,e}, \ldots, \beta_{e,e'}, \ldots, \varepsilon_{e',j}, \ldots]$.

Ralf Koetter and Muriel Médard. An algebraic approach to network coding. IEEE/ACM Trans. on Netw. 11, 5, October 2003.

Finding Network Coding Solution

- Koetter and Medard (2003): Greedy Algorithm
- Let a delay-free communication network G and a solvable multicast problem be given with one source and N receivers. Let R be the rate at which the source generates information. There exists a solution to the network coding problem in a finite field F_{2^m} with

$$m \leq \lceil \log_2(NR+1) \rceil$$

Ralf Koetter and Muriel Médard. An algebraic approach to network coding. IEEE/ACM Trans. on Netw. 11, 5, October 2003.

Random Network Coding

- η is the number of edges and d is the number of sink nodes

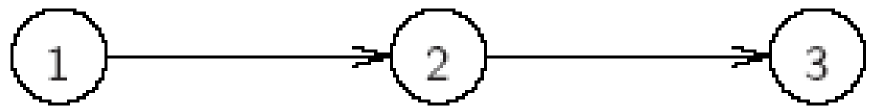
Lemma 2.5 *Let P be a nonzero polynomial in $\mathbb{F}[\xi_1, \xi_2, \ldots]$ of degree less than or equal to $d\eta$, in which the largest exponent of any variable ξ_i is at most d. Values for $\xi_1, \xi_2, \ldots$ are chosen independently and uniformly at random from $\mathbb{F}_q \subseteq \mathbb{F}$. The probability that P equals zero is at most $1 - (1 - d/q)^\eta$ for $d < q$.*

--> Choosing the coding coefficient uniformly at random in $\mathbb{F}_q$ with *q* large enough, is sufficient to ensure high probability of decoding at the sink(s)
Or: For a fixed success probability, the field size needs to be on the order of the number of links ν multiplied by the number of receivers d.
--> Fully decentralized

RLNC achieves robustness to link failures

T. Ho, R. Koetter, M. Médard, D. R. Karger, and M. Effros, "The benefits of coding over routing in a randomized setting," in IEEE International Symposium on Information Theory, 2003.
T. Ho and D.S. Lun, *Network Coding: An Introduction*, Cambridge University Press, 2008

On lossy channels: NC for unicast improves rate AND delay



ε_{12}: Erasure probability on link $(1, 2)$.
ε_{23}: Erasure probability on link $(2, 3)$.

- To cope with erasures on a channel with ε, we need to send N=K+M pkts to retrieve K info pkts (M such that (K+M)(1- ε)=K).
- The additional M pkts are not replications, but function of all K info pkts.
- The K info pkts must be retrieved from the N'≤N received pkts. Then there are 3 solutions for the 2 links problem :

On lossy channels: NC for unicast improves rate AND delay

- S sends N pkts such that $N(1-\varepsilon_{12})(1-\varepsilon_{23})=K$. Then the end-to-end rate is $K/N=(1-\varepsilon_{12})(1-\varepsilon_{23})$
- If the relay is able to decode (retrieve all K info pkts from the N_1' received) then
  - S can send N_1 such that $N_1(1-\varepsilon_{12})=K$
  - R can send N_2 such that $N_2(1-\varepsilon_{23})=K$

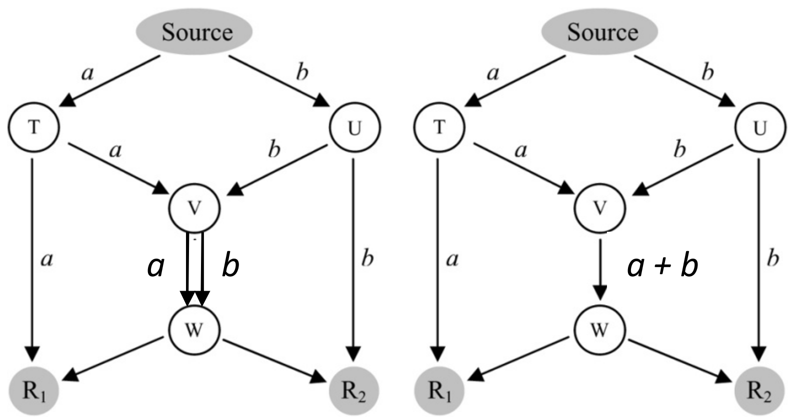
  Then the E2 rate is $\min(1-\varepsilon_{12,}1-\varepsilon_{23})\geq N(1-\varepsilon_{12})(1-\varepsilon_{23})$

  BUT: such block coding entails delay
- RLNC at relay: R generates pkts on the fly by mixing those received from S, w/o decoding

  --> no delay and max rate

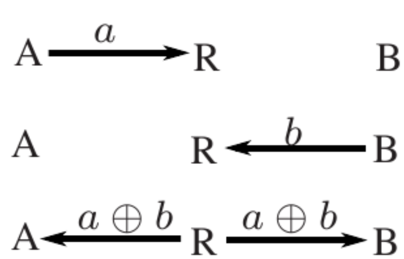
Inter-session network coding

- Intra-session network coding

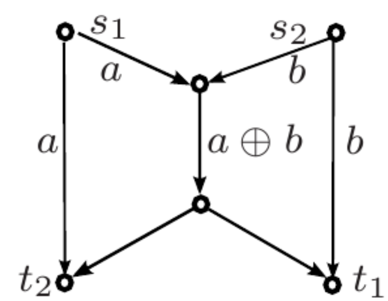


- improves the throughput of lossless multicast sessions, and of lossy unicast or multicast sessions

- Inter-session network coding



The COPE example



The butterfly example

- is necessary to achieve optimal throughput in general

Practical Issues

- Network Delay
- Centralized Knowledge of Graph Topology
- Packet Loss
- Link Failures
- Change in Topology or Capacity

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XORs in The Air: Practical Wireless Network Coding

S. Katti, H. Rahul, W. Hu, D. Katabi, M. Médard and J. Crowcroft. *XORs in the air: Practical wireless network coding*. In Proceedings of SIGCOMM 2006.

The problem

- Wireless networks are highly resource constrained
  - Bandwidth is the most expensive
  - Power is sometimes an issue too

    --> Serious problems for mesh networks
- How to optimize throughput?
  - Can we send more information?
  - Can we reduce bandwidth requirement?

    --> Do both at the same time?

An information exchange scenario

- Multi-hop unicast requires 4 transmissions
- Can we do better?

Can Network Coding help? - An idea

3 transmissions instead of 4

- Saves bandwidth & power
- 33% throughput increase

The COPE approach

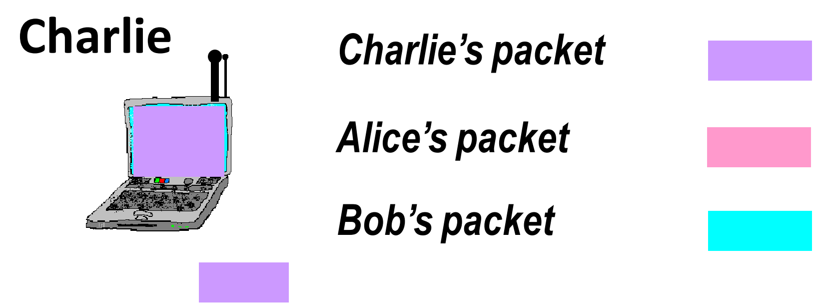
- Considers multiple unicast flows
  – Generalizes the duplex flow scenario
- Opportunistic coding using local info
  – Overhear packets to increase coding gain
  – Online, distributed and deployable
- Emulation and testbed results
  – First real-world implementation

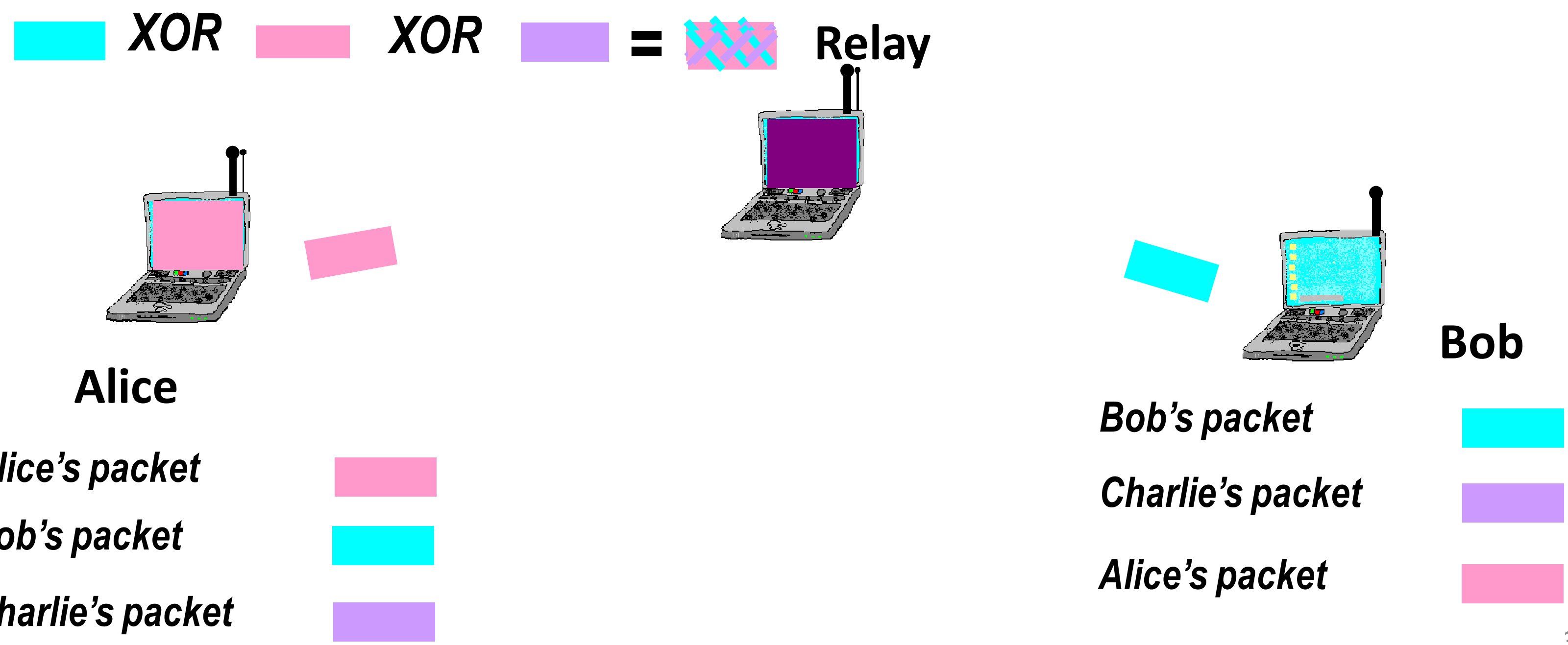
COPE: Opportunistic Coding Protocol

Alice → Bob

Bob → Charlie

Charlie → Alice





How it works…(Cont.)

- Relay – Encoding
  - Checks packets in queue
  - Combines packets traversing the same three hops in opposite directions
  - Metadata in a header between MAC and IP
  - Broadcast encoded packets
- Alice/Bob – Decoding
  - Keep copies of sent packets
  - Detect the extra header (decoding info)
  - Retrieve the right packet to decode
- Distributed and local action only!

Generalize to COPE

- Nodes snoop on the medium
  - Reception reports to neighbours
- When encoding
  - Identify what packets neighbours have
    - Reception reports and guesses
  - Encode as many packets as possible
    - Provided intended recipients can decode them
- Still distributed and local action only!

The importance of being opportunistic

- Opportunistic coding
  - Only encode if packets in queue
  - No delay penalty
  - Insensitive to flow characteristics

- Opportunistic listening
  - Helps create more coding opportunities

‘Pseudo-broadcast’

- COPE gain is from broadcast medium
- But 802.11 broadcast doesn’t work!
  - No reliability scheme to mask collision loss
  - Send packets at lowest bit rate
  - May actually reduce throughput!
- Pseudo-broadcast
  - Send encoded packets as if unicast
  - Other neighbours overhear
  - Benefit as a unicast packet

Implementation

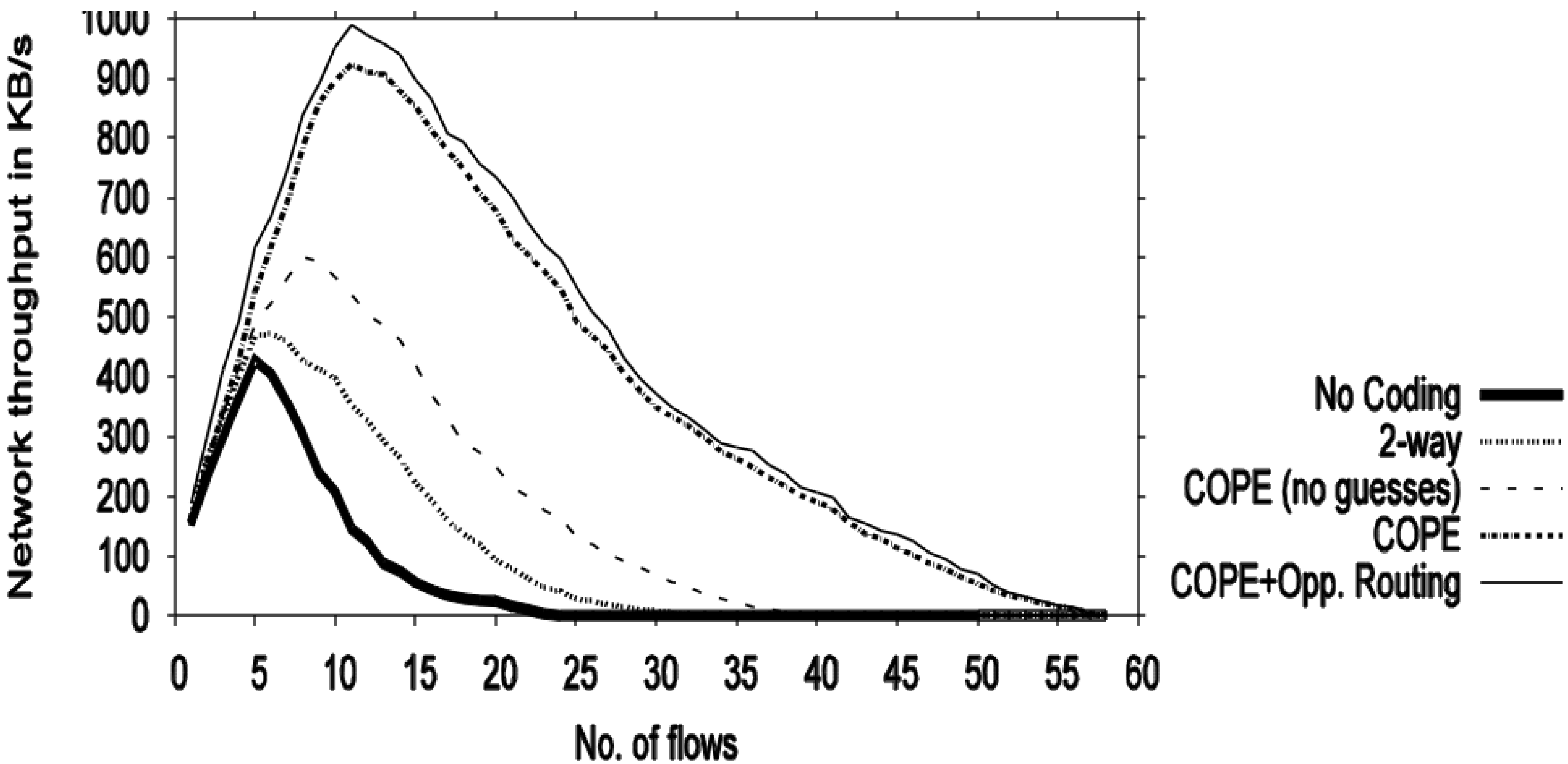
- A shim between MAC and IP
  - Agnostic to protocols above/below
- Emulations
  - General COPE
  - Emsim (part of Emstar) environment
- Testbed
  - Based on the Alice/Bob scenario
  - Extension to Roofnet code (in Click)

Emulation Scenario

- 100 nodes in 800m x 800m
  - Consider range ~50m
- Random senders/receivers
  - Senders always backlogged
  - Bit rate at 11 Mb/s
- Geographic routing
- Metric: end-to-end data traffic throughput over all flows

Emulation performance

Throughput (KB/s)



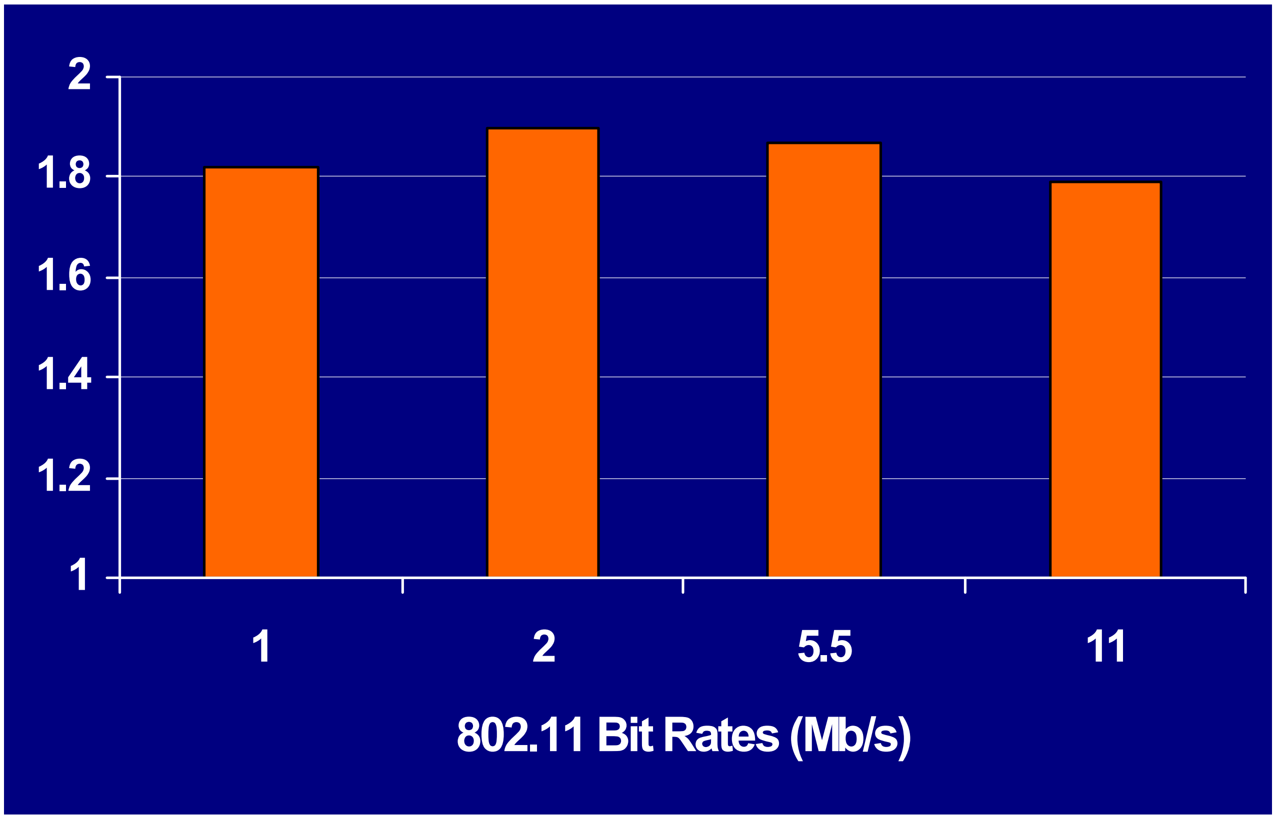
Coding always outperforms no-coding

Testbed setup

- Indoor PCs with 802.11b cards
  - Intersil Prism 2.5 802.11b chipset
  - Connected to omni-directional antenna
  - RTS/CTS disabled
  - 802.11 ad hoc mode
- Randomly chosen 3 nodes from testbed
  - Static routes
  - End nodes send UDP traffic to each other

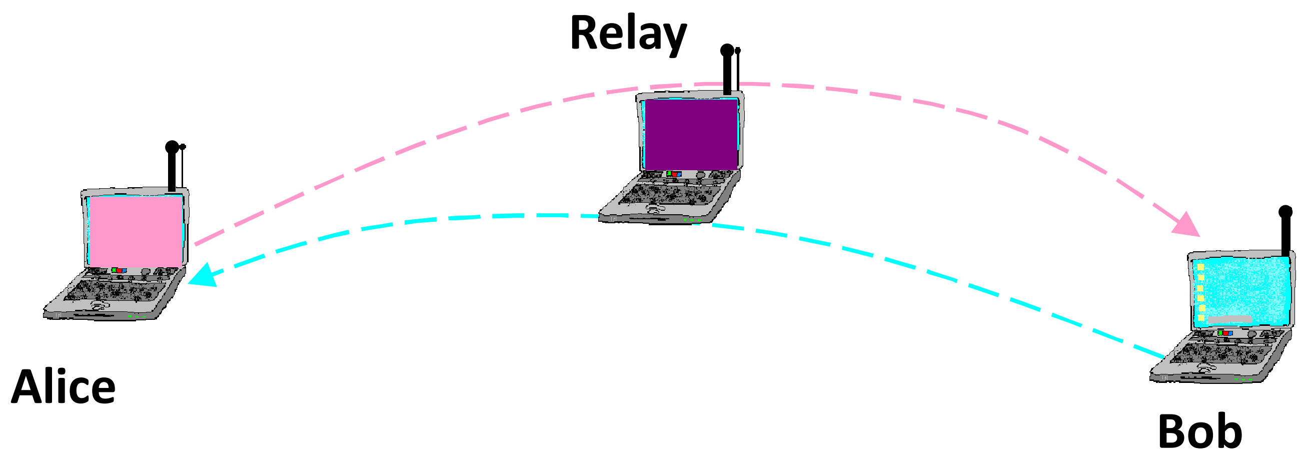
Testbed results

Ratio of Throughput with Coding to No-Coding



Encoding almost doubles the throughput

Why more than 33%?



MAC is fair -> 1/3 BW for each node

- Without coding, relay needs twice as much bandwidth as Alice or Bob
- With coding, all nodes need equal bandwidth

Summary

- Opportunistic approach allows practical integration of network coding into current stack
- Throughput can double in practice
  - Cross-layer effects
  - Congestion plays in our favour
- First implementation of network coding in a wireless environment

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Opportunistic networks

- Increasing integration of wireless short-range communication technologies (Bluetooth, 802.11 WiFi) into mobile devices

  -> spontaneous communication, interaction and collaboration are possible.
- Spontaneous communication: opportunistic networking
- Promising evolution in mobile ad-hoc networking.
- Formed by mobile devices communicating while users are in close proximity.
- There are two prominent characteristics present in opportunistic networks: 1) A user provides his personal device as a network node. 2) Users are a priori unknown to each other.

A. Heinemann, *Collaboration in Opportunistic Networks*, PhD dissertation, Darmstadt 2007

Disruption/Delay Tolerant Mobile Ad Hoc Networks: Overview

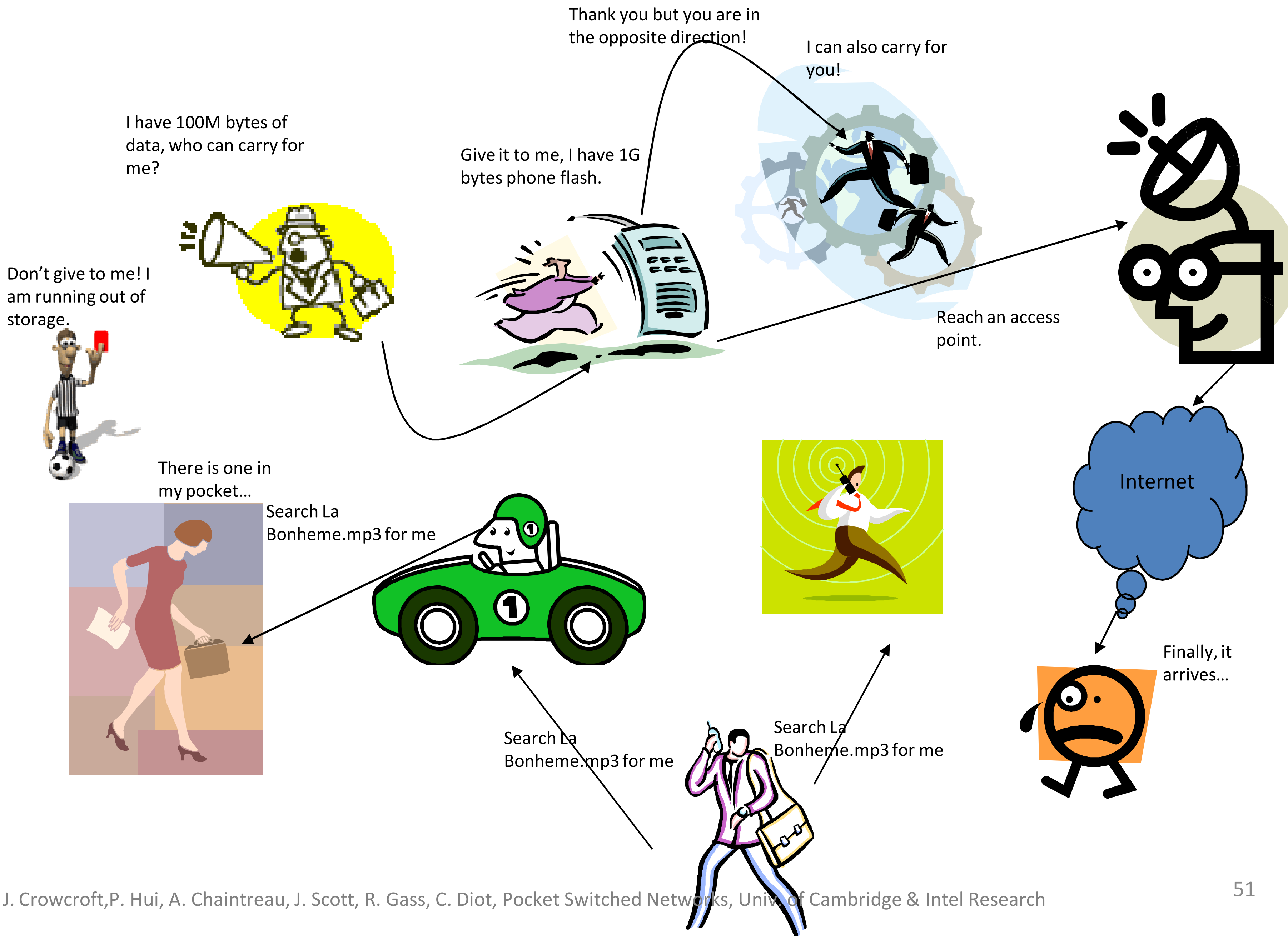
- Goal of DT-MANETs: allowing communication between mobile users, even in the absence of infrastructure, and when a contemporaneous path from S to D does not exist necessarily (due to disconnections and/or high mobility).

- Such networks can be
  - Interference-limited
  - Or connectivity-limited

  --> use of nodes as relays to achieve end-to-end communication: Store-Carry-And-Forward paradigm
- entails a certain communication delay

  --> this MANETs are also referred to as Delay Tolerant Networks (DTNs).

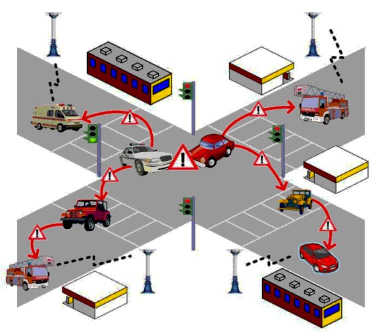
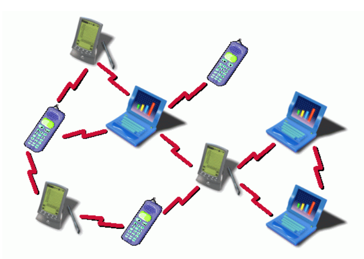
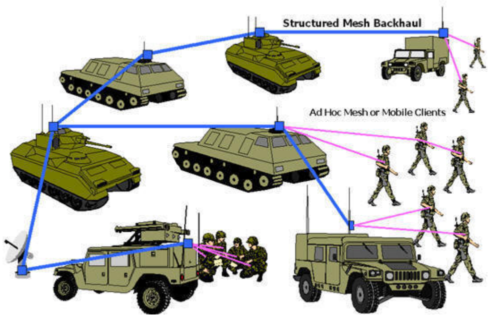
Pocket-switched networks



Applications

- Provide network access to remote communities
- Provide cheaper content access by file exchange in ad hoc mode
- Offload the telcos networks
  - Growing demand for contents --> infrastructure-centric networking paradigm has limitations
  - --> promising alternative to offload the telcos' networks: exploit the user interactions to convey information: Ad hoc Networks

- https://www.youtube.com/playlist?list=PL4buVHalBRoPhqHKMBOU2yqPLtaN5vfKC

Limitation of cellular networks

Customers Angered as iPhones Overload AT&T

By JENNA WORTHAM
Published: September 2, 2009

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Slim and sleek as it is, the iPhone is really the Hummer of cellphones.

Enlarge This Image

Michael Appleton for The New York Times
AT&T monitors its network from its operations center in Bedminster, N.J.
More Photos »

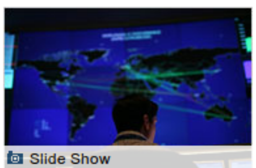
It's a data guzzler. Owners use them like minicomputers, which they are, and use them a lot. Not only do iPhone owners download applications, stream music and videos and browse the Web at higher rates than the average smartphone user, but the average iPhone owner can also use 10 times the network capacity used by the average smartphone user.

"They don't even realize how much data they're using," said Gene Munster, a senior securities analyst with Piper Jaffray.

The result is dropped calls, spotty service, delayed text and voice messages and glacial download speeds as AT&T's cellular network strains to meet the demand. Another result is outraged customers.

Cellphone owners using other carriers may gloat now, but the problems of AT&T and the iPhone portend their future. Other networks could be stressed as well as more sophisticated phones encouraging such intense use become popular, analysts say.

Multimedia



Slide Show
AT&T Races to Expand the Network

Related

Bits: Big City, Big iPhone Troubles (September 3, 2009)

"It's almost worthless to try and get on 3G during peak times in those cities," Mr. Munster said, referring to the 3G network. "When too many users get in the area, the call drops." The problems seem particularly pronounced in New York and San Francisco, where Mr. Munster estimates AT&T's network shoulders as much as 20 percent of all the iPhone users in the United States.

AT&T says that the majority of the nearly $18 billion it will spend this year on its networks will be diverted into upgrades and expansions to meet the surging demands on the 3G network. The company intends to erect an additional 2,100 cell towers to fill out patchy coverage, upgrade existing cell sites by adding fiber optic connectivity to deliver data faster and add other technology to provide stronger cell signals.

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iPhone users eating up AT&T's network

May 11, 2009 | Paul Boutin
2 Comments

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iPhone users consume two to four times as much network data volume as other smartphone users, according to traffic measurement company Comscore.

That's increasingly a problem for AT&T, which serves all those iPhone users in the US and must pay for the bandwidth to handle it all. AT&T starts at a loss by subsidizing customers' iPhones. Then, it charges them only $30 per month for unlimited data download & upload — or the same it charges users of other smartphone, even though those users are cheaper to serve.

iPhone users now make up for 7.5% of AT&T's subscribers. Their data-hungry lifestyles have strained AT&T's infrastructure so much that "AT&T will need to add cell towers and spend more on the back-haul lines that connect the towers to the rest of the network," the WSJ reports, after citing stats from Alcatel-Lucent, a network equipment maker showing how bandwidth-hogging Web browsing is. Web browsing consumers 32% of data-related airtime but 69% of bandwidth, while email used 30% of data airtime but only 4% of bandwidth, the study found.

It's easy to pontificate — as the Journal's analyst sources do — that AT&T should do away with unlimited data plans, or raise the price on iPhone users. But the company's discount pricing on the expensive iPhone and its accompanying high-bandwidth lifetyle aren't an accident. With more touchscreen iPhone competitors like the Palm Pre coming to market, and AT&T's exclusive status as iPhone carrier set to expire next year, the company is clearly willing to pour money into locking down as many iPhone customers as it can.

(Photo credit: **Anirudh Koul**)

http://www.nytimes.com/2009/09/03/technology/companies/03att.html
http://venturebeat.com/2009/05/11/iphone-users-eating-up-atts-network/

DTN : Real-world applications

- **Ring Road**: constellation of nanosatellites to provide low-cost access, bypass geographic and/or political obstacles on earth
- **Bytewalla**: connecting african villages, Android phones
- **Saami Network Connectivity**: provides Internet access to a nomadic community
- **Liberouter**: combines the SCAMPI platform with a Raspberry Pi to produce a cheap opportunistic router - also on Google Play
- **DTN-Bone**: effort of the DTNRG to establish a worldwide collection of nodes running DTN bundle agents and applications

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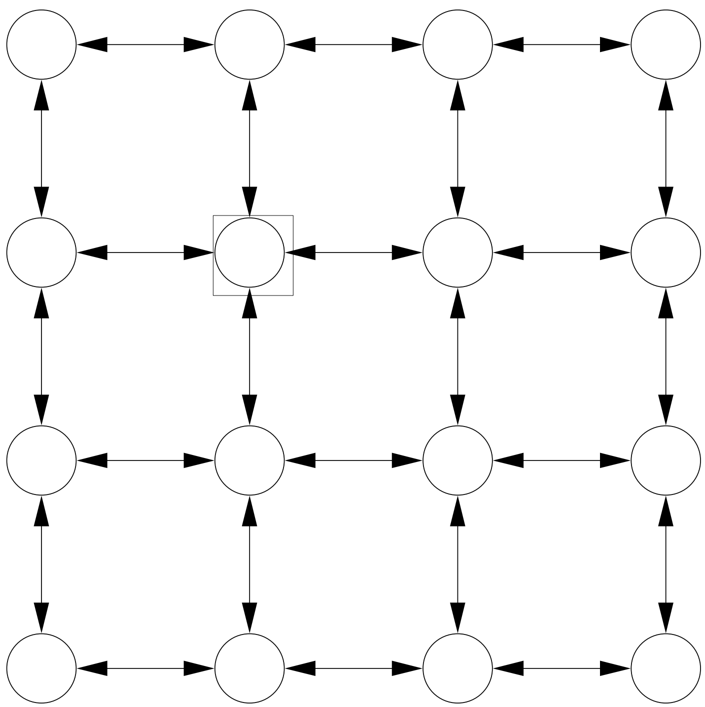
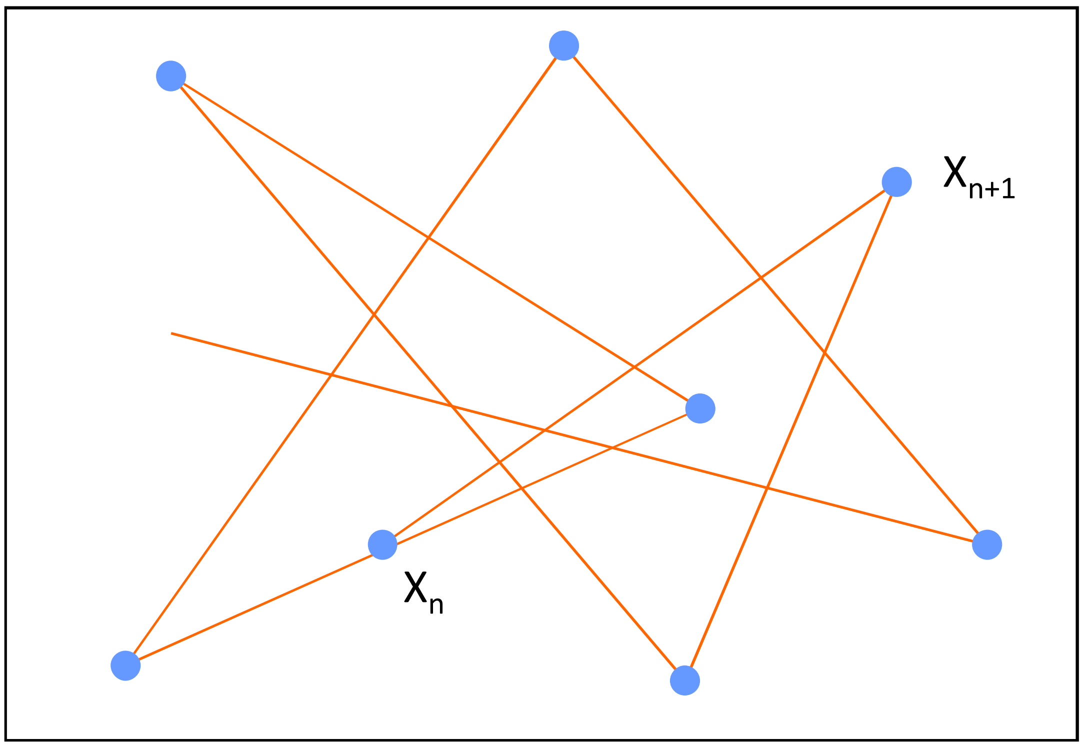
Random mobility models: Random walker



- Equal probability to jump in any direction

Random mobility models: Random waypoint and Random direction

- Node:
  - Picks next waypoint X_{n+1} uniformly in area
  - Picks speed V_n uniformly in $[v_{min}, v_{max}]$
  - Moves to X_{n+1} with speed V_n



J.-Y. Le Boudec, M. Vojnović, Random Trip Mobility Models, Tutorial ACM Mobicom 2006

- Variant: Random direction

  - Directions are uniformly distributed (0, 2π)

  - Speeds (Vi) are uniformly distributed (Vmin,Vmax)

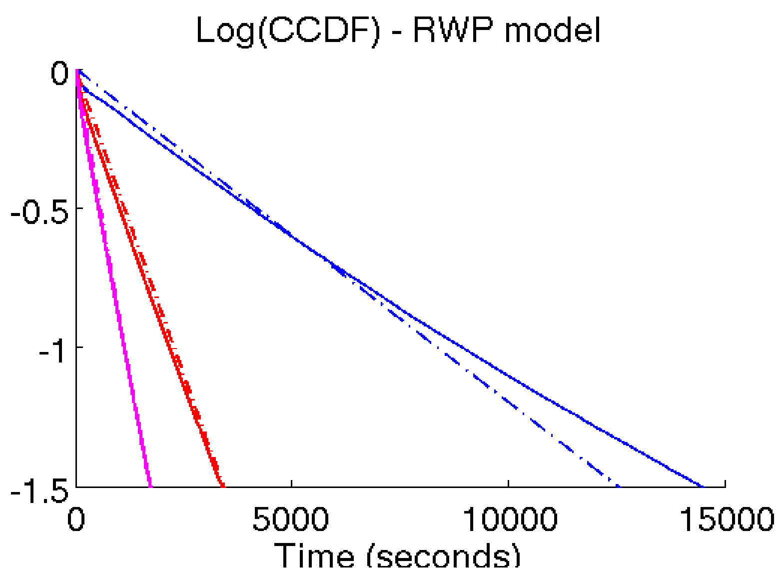
  - Travel times (Ti) are exponentially /generally distributed

Inter-meeting times under random mobility

- Inter-meeting times mobile/mobile have shown to follow an exponential distribution

  [Groenevelt et al.: The message delay in mobile ad hoc networks. Performance Evaluation, 2005]

  – $\Pr\{ X = x \} = \mu \exp(- \mu x)$
  – CDF: $\Pr\{ X \leq x \} = 1 - \exp(- \mu x)$, CCDF: $\Pr\{ X > x \} = \exp(- \mu x)$



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Network model

- Settings:
  - only a single unicast session
  - $\lambda = 1/\mu$: average number of meetings a node has per time unit
  - sparse DTN: $\lambda = N\beta$ remains constant as N increases
    --> the network is connectivity-limited
  - mobility model: fast and uniform (RW, RWP,…)

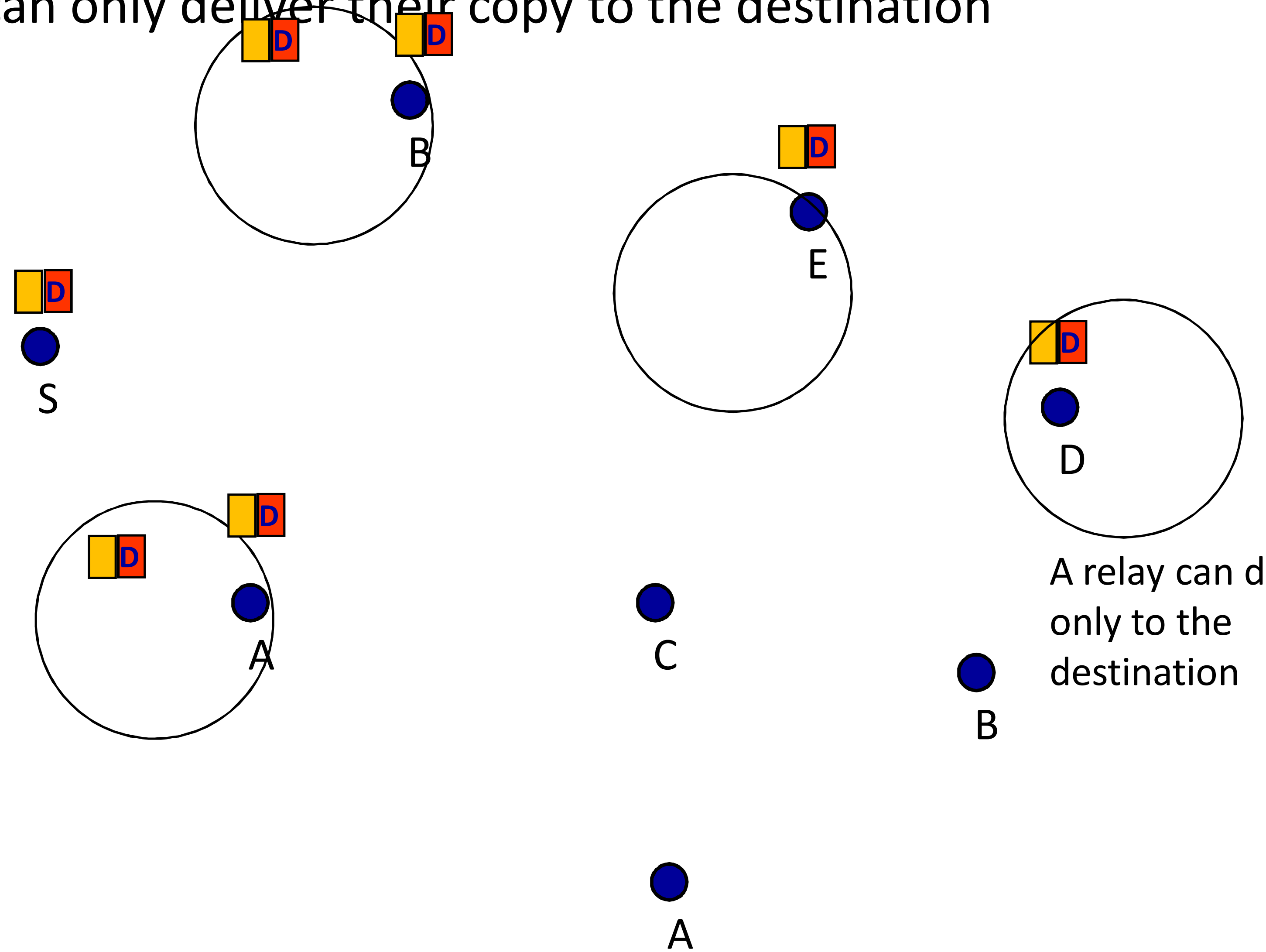
--> routing strategies must permit timely delivery of information to a certain destination with high probability: use of replication

- replication leads to energy and memory consumption
- finite duration of radio contacts --> file may be split into packets

- **Objective**: optimize the file transfer from S to D by minimizing both its delay, the memory and energy required by the store, carry and forward process

Two-hop routing

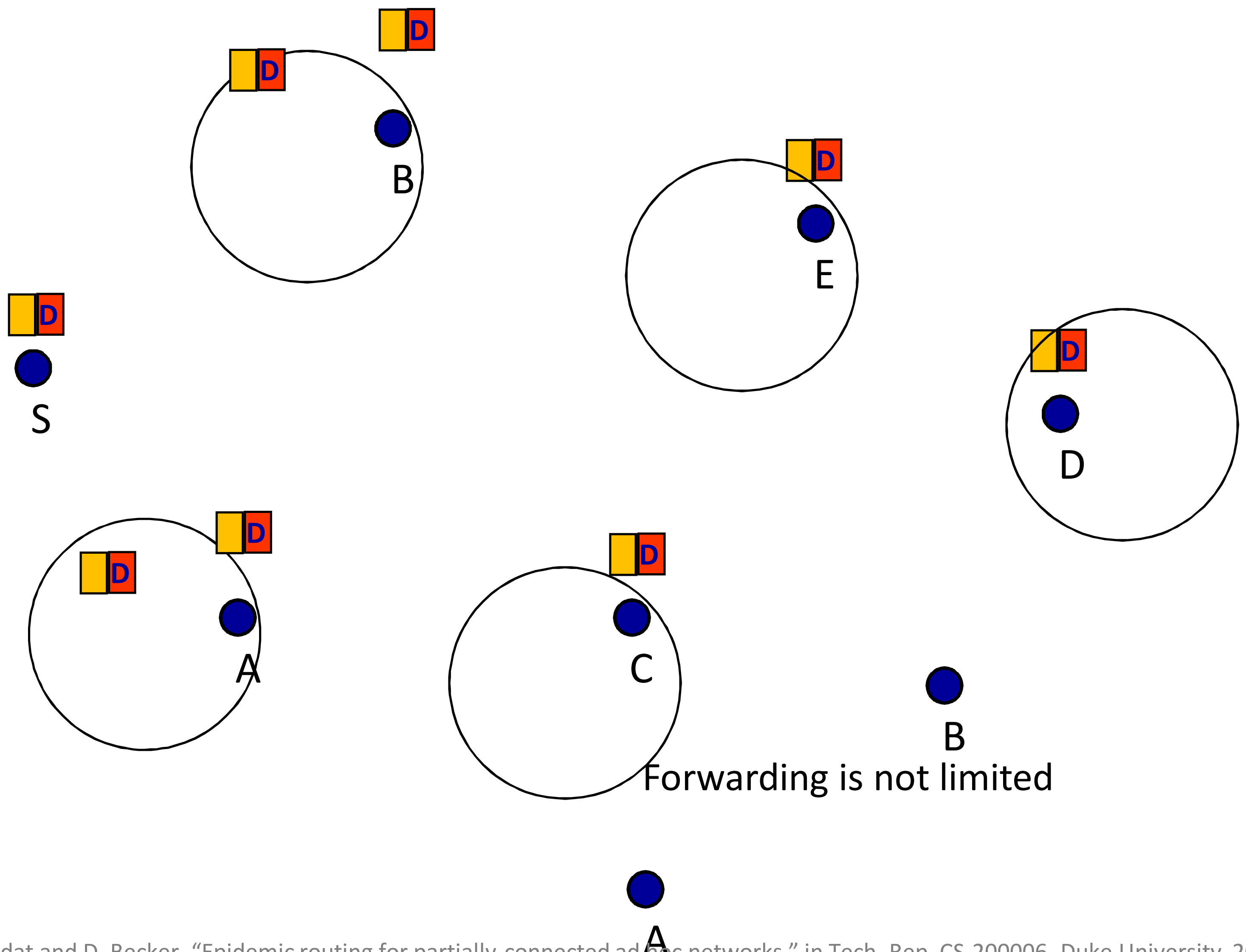
• Only the source can disseminate copies of the packet, the relays can only deliver their copy to the destination



A relay can deliver only to the destination

Epidemic routing

- The packet is flooded into the network



A. Vahdat and D. Becker, "Epidemic routing for partially-connected ad hoc networks," in Tech. Rep. CS-200006, Duke University, 2000.

A mean-field interaction model for modeling dissemination

- Time $t \in \mathbb{N}$ is discrete. There are N objects.
- Object n has state $Z_n^{(N)}(t)$ in $S = \{0, 1\}$.
- We assume that $\mathbf{Y}^{(N)}(t) = (Z_1^{(N)}(t), \ldots, Z_N^{(N)}(t))$ is a homogeneous Markov chain on S^N.
- We assume that we can observe the state of an object but not its label, i.e.,

$$\mathcal{K}^N(i_1, \ldots, i_N; i'_1, \ldots, i'_N) =$$

$$Pr\{Z_1^{(N)}(t+1) = i_1, \ldots, Z_N^{(N)}(t+1) = i_N | Z_1^{(N)}(t) = i'_1, \ldots, Z_N^{(N)}(t) = i'_N\}$$

is stable under any permutation.

$\rightarrow$ The process $\mathbf{Y}^{(N)}(t)$ is called a mean-field interaction model with N objects.

T. G. Kurtz, *Solutions of Ordinary Differential Equations as Limits of Pure Jump Markov Processes*, Journal of Applied Probability, vol. 7, no. 1, pp. 49–58, 1970.

M. Benaïm and J.-Y. Le Boudec, *A class of mean field interaction models for computer and communication systems*, Performance Evaluation, vol. 65, no. 11-12, pp. 823–838, 2008.

A mean-field interaction model for modeling dissemination

- Define the occupancy measure $\mathbf{M}^{(N)}(t)$ as the vector of frequencies of states $i \in S$ at t:
$M_i^{(N)}(t) = \frac{1}{N}\sum_{n=1}^{N} 1_{\{Z_i^{(N)}(t)=i\}}$. $\mathbf{M}^{(N)}(t)$ that takes vales in Δ.
$\mathbf{M}^{(N)}(t)$ is a homogeneous Markov chain.
- Let us define the drift $\mathbf{f}(\mathbf{m})$ for $\mathbf{m} \in \Delta$ as the expected change to $\mathbf{M}^{(N)}(t)$ in one time-slot:

$$\begin{aligned} \mathbf{f}^{(N)}(\mathbf{m}) &= \mathbb{E}[\mathbf{M}^{(N)}(t+1) - \mathbf{M}^{(N)}(t) | \mathbf{M}^{(N)}(t) = \mathbf{m}] \\ &= \sum_{\{i,i'\} \in S, i \neq i'} m_i P_{i,i'}^{(N)}(\mathbf{m})(\mathbf{e}_{i'} - \mathbf{e}_i) \end{aligned}$$

where $P_{i,i'}^{(N)}$ is the marginal transition probability:
$P_{i,i'}^{(N)}(\mathbf{m}) = Pr\{Z_n^{(N)}(t+1) = i' | Z_n^{(N)}(t) = i, \mathbf{M}^{(N)}(t) = \mathbf{m}\}$.

T. G. Kurtz, *Solutions of Ordinary Differential Equations as Limits of Pure Jump Markov Processes*, Journal of Applied Probability, vol. 7, no. 1, pp. 49–58, 1970.
M. Benaïm and J.-Y. Le Boudec, *A class of mean field interaction models for computer and communication systems*, Performance Evaluation, vol. 65, no. 11-12, pp. 823–838, 2008.

Convergence to the mean-field limit

If $\lim_{N\infty} \mathbf{f}^{(N)}(\mathbf{m}) = \mathbf{f}(\mathbf{m})$ exists for all $\mathbf{m} \in \Delta$,
Then $\mathbf{M}^{(N)}(t)$ converges to a deterministic process $\mu(t)$ that satisfies:

$$\begin{cases} \frac{d\mu(t)}{dt} = \mathbf{f}(\mu(t)) \\ \mu(0) = \mu_0 \text{ constant in } N \end{cases}$$

More exactly (Kurtz Th 3.1), $\forall \delta$:

$$\lim_{N\infty} Pr\{\sup_{s \leq t} ||\mathbf{M}^{(N)}(t) - \mu(t)|| > \delta\} = 0$$

T. G. Kurtz, *Solutions of Ordinary Differential Equations as Limits of Pure Jump Markov Processes*, Journal of Applied Probability, vol. 7, no. 1, pp. 49–58, 1970.
M. Benaïm and J.-Y. Le Boudec, *A class of mean field interaction models for computer and communication systems*, Performance Evaluation, vol. 65, no. 11-12, pp. 823–838, 2008.

Performance modeling of dissemination under two-hop routing or epidemic routing

$$\mathbf{M}^{(N)}(t) = \begin{bmatrix} M_0^{(N)}(t) \\ M_1^{(N)}(t) \end{bmatrix} = \begin{bmatrix} 1 - M_1^{(N)}(t) \\ M_1^{(N)}(t) \end{bmatrix}$$

- Two-hop routing: $f_1(m_1) = \lambda s(1 - m_1)$, where s is the fraction of sources (constant in N)
- Epidemic routing: $f_1(m_1) = \lambda m_1(1 - m_1)$
- Let us rename $\mu_1(t)$ as $x(t)$, standing for the fraction of infected nodes.
- Let $X^{(N)}(t)$ be the number of infected nodes: $X^{(N)}(t)$ can be approximated by $Nx(t)$.

T. G. Kurtz, *Solutions of Ordinary Differential Equations as Limits of Pure Jump Markov Processes*, Journal of Applied Probability, vol. 7, no. 1, pp. 49–58, 1970.
M. Benaïm and J.-Y. Le Boudec, *A class of mean field interaction models for computer and communication systems*, Performance Evaluation, vol. 65, no. 11-12, pp. 823–838, 2008.

Performance modeling of dissemination under two-hop routing or epidemic routing

From that we approximate $X^{(N)}(t)$ by the solution of:

Epidemic

$$\frac{dX^{(N)}(t)}{dt} = \beta X^{(N)}(t)(N - X^{(N)}(t)), \quad X^{(N)}(0) = 1$$

Two-hop

$$\frac{dX^{(N)}(t)}{dt} = \beta 1(N - X^{(N)}(t)), \quad X^{(N)}(0) = 0$$

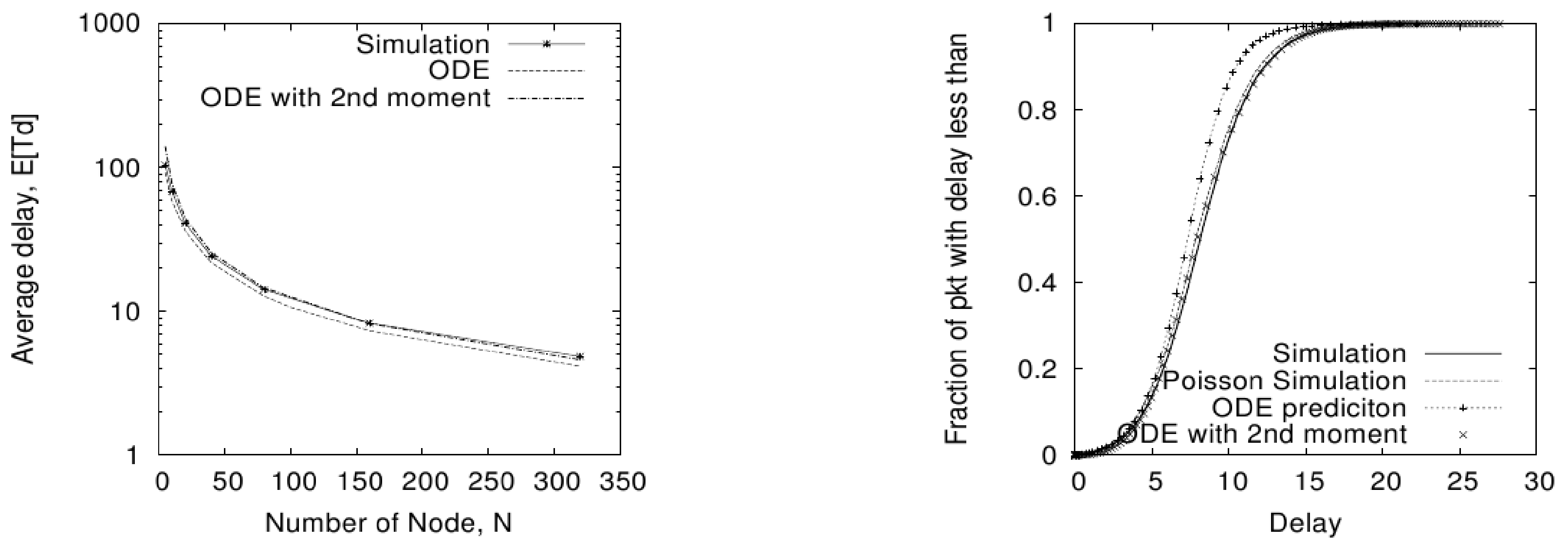
- Defining T_d as the packet delivery delay, we can derive $P(t) = Pr\{Td < t\}$:

$$\frac{dP(t)}{dt} = \lambda x(t)(1 - P(t))$$

Proof: Exercise class

Zhang, X., Neglia, G., Kurose, J., Towsley, D.: Performance Modeling of Epidemic Routing. Computer Networks 51, 2867–2891 (2007)

Accuracy of the modeling



(a) Average delay for different N

(b) CDF of delay with $N = 160$

Figure 1: Delay under epidemic routing

Zhang, X., Neglia, G., Kurose, J., Towsley, D.: Performance Modeling of Epidemic Routing. Computer Networks 51, 2867–2891 (2007)

Comparison between two-hop and epidemic

	2-hop	epidemic
Mean delay	$\sqrt{\frac{\pi}{2}}\frac{N}{\lambda\sqrt{N-1}}$	$\frac{log(N)}{\beta(N-1)}$
Mean number of copies until delivery	$\sqrt{\frac{\pi}{2}}\sqrt{N}$	$\frac{N-1}{2}$

without any limitation on the number of copies !

Zhang, X., Neglia, G., Kurose, J., Towsley, D.: Performance Modeling of Epidemic Routing. Computer Networks 51, 2867–2891 (2007)

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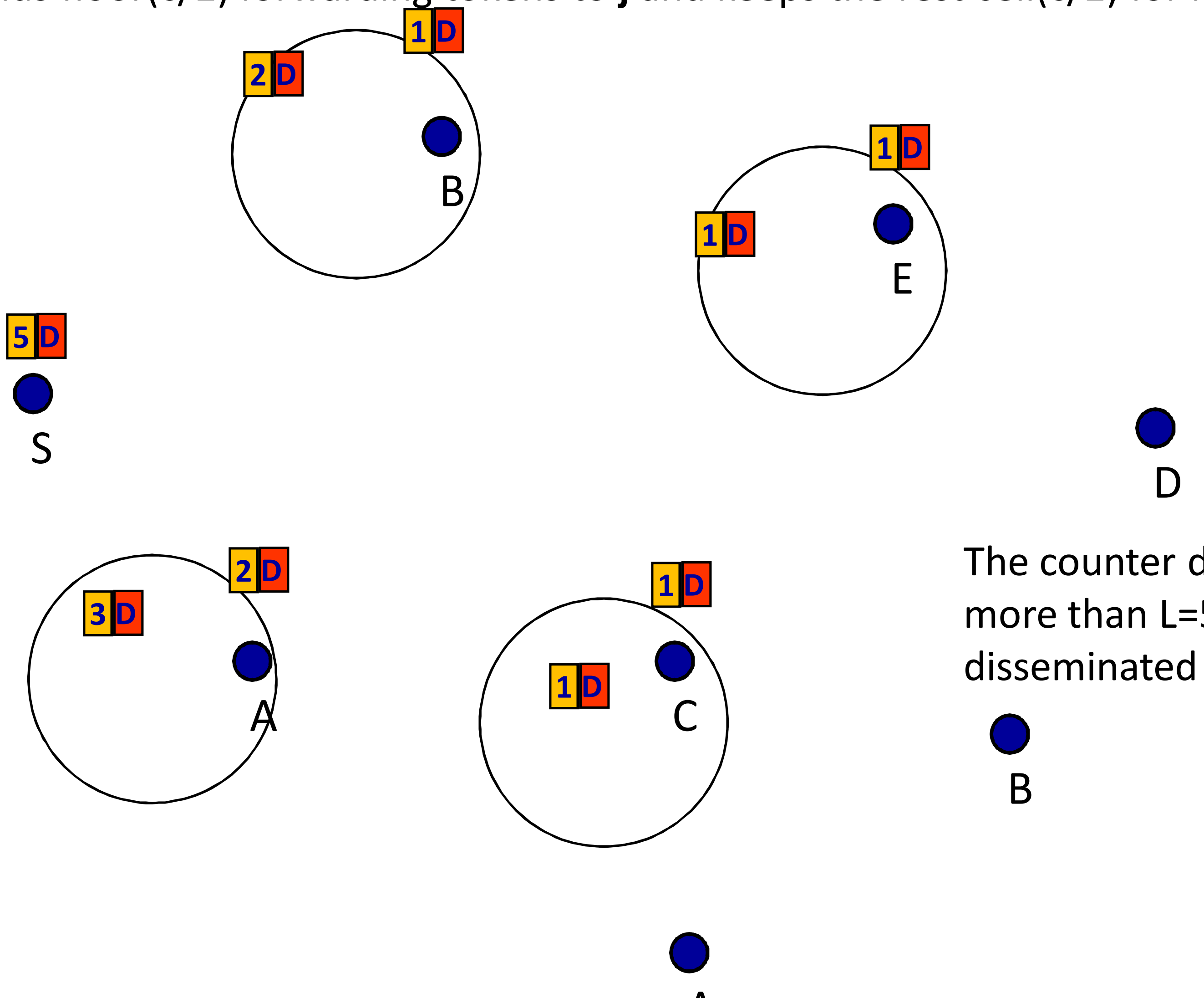
Spray-and-Wait routing

- Goal: control the total number of disseminated copies thanks to a counter per packet
- **i** hands floor(c/2) forwarding tokens to **j** and keeps the rest ceil(c/2) for itself



The counter does not allow for more than L=5 copies to be disseminated

T. Spyropoulos, K. Psounis, and C. Raghavendra, "Efficient routing in intermittently connected mobile networks: the multi-copy case," IEEE/ACM Trans. Netw., vol. 16, no. 1, pp. 77–90, Feb 2008.

Spray-and-Wait versus Epidemic

- Epidemic routing:
  - no limit on the number of transmissions (≤ nb of pkts . N)
  - mean time for delivery of one packet: ≤ $\log_2(N)$

- Spray-and-Wait:
  - number of transmissions ≤ nb of pkts . L
  - When all nodes move in an IID manner, for any given max number of copies L, Spray-and-Wait minimizes the expected delivery time.

T. Spyropoulos, K. Psounis, and C. Raghavendra, "Efficient routing in intermittently connected mobile networks: the multi-copy case," IEEE/ACM Trans. Netw., vol. 16, no. 1, pp. 77–90, Feb 2008.

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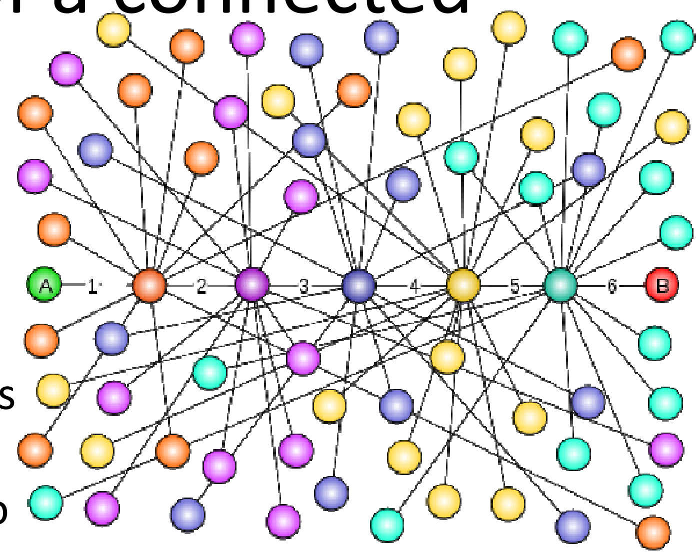
Why measuring human mobility?

- Mobility increases the capacity of dense mobile networks [Grossglauser and Tse]
- May also create disconnections in sparse MANETs
- But: Human mobility patterns determine communication opportunities

Duncan Watts (after Milgram's experiment)

- Six degrees - the science of a connected age, 2003



Six degrees of separation is the idea that everyone is on average approximately six steps away, by way of introduction, from any other person in the world, so that a chain of "a friend of a friend" statements can be made, on average, to connect any two people in six steps or fewer.

Understanding why to leverage this feature of social networks

- Why are there short chains of acquaintances linking together arbitrary pairs of strangers?

- In a *random* network, if everybody has 100 friends distributed randomly in the world population, this isn't strange.
- In 6 hops, you can reach 10^{12} people > 6.10^{9} (world pop.)

- BUT: our social networks tend to be clustered.

Random-graph theory

- In mathematical terms a network is represented by a graph. A graph is a pair of sets G(V,E), where V is a set of N vertices V_1, V_2, ..., V_N and E is a set of edges.
- The theory of random graphs was introduced by Paul Erdos and Alfred Renyi (1959-1961) after Erdos discovered that probabilistic methods were often useful in tackling problems in graph theory.
- Problem: generating random graphs close to those arising in the real-world (same features)

R. Albert and A.-L. Barabasi: Statistical mechanics of complex networks, Rev. Mod. Phys., Vol. 74, No. 1, January 2002

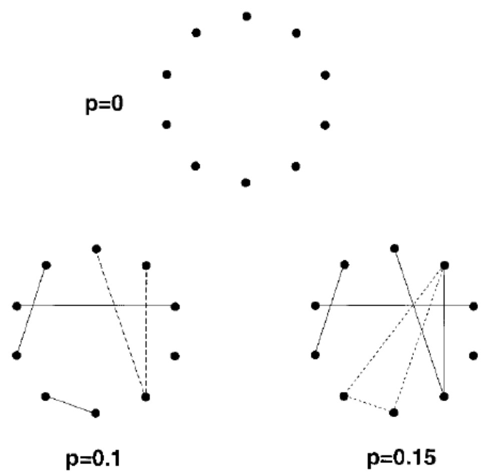
Some network measures

- **Characteristic Path Length (L)** :
  - the average length of the shortest path connecting each pair of nodes
- **Diameter**: maximum value of path length
- **Clustering Coefficient (C)** is a measure of local interconnection
  - if node *i* has k_i immediate neighbors, C_i, is the fraction of the total possible $k_i*(k_i-1) / 2$ connections that are realized between i's neighbors. C is just the average of the Ci's.
  - Clustering measures the fraction of neighbors of a node that are connected themselves

R. Albert and A.-L. Barabasi: Statistical mechanics of complex networks, Rev. Mod. Phys., Vol. 74, No. 1, January 2002

The Erdos-Renyi model (1959)

- N nodes, any two nodes are connected by an edge with probability p



- Random-graph theory studies the properties of the probability space associated with graphs with N nodes as $N \rightarrow \infty$. Many properties of such random graphs can be determined using probabilistic arguments.
- Among the questions addressed by Erdos and Renyi, some have direct relevance to an understanding of complex networks:
  - Is a typical graph connected?
  - How does its diameter depend on its size?

R. Albert and A.-L. Barabasi: Statistical mechanics of complex networks, Rev. Mod. Phys., Vol. 74, No. 1, January 2002

Social networks

- Most of our friends come from our geographical or professional neighborhood.

  + Our friends tend to have the same friends

  --> High clustering coefficient

But also

- There seems to exist short paths between any pair of nodes

  --> Low diameter

R. Albert and A.-L. Barabasi: Statistical mechanics of complex networks, Rev. Mod. Phys., Vol. 74, No. 1, January 2002

How to model real networks?

- Regular Graphs have a high clustering coefficient
  - but also a high diameter
- Random Graphs have a low diameter
  - but a low clustering coefficient

--> Combine both to model real networks: the Watts and Strogatz model

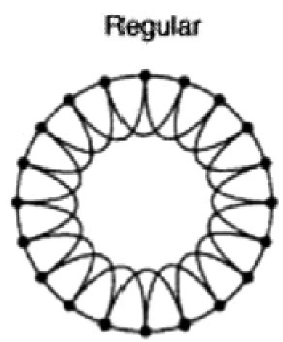
Regular Graph (k=4)

Long paths

$L = n/(2k)$

Highly clustered

$C=3/6$



Regular ring lattice

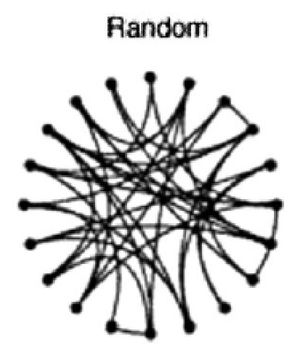
Random Graph (k=4)

Short path length

$L=\log_k N$

Almost no clustering

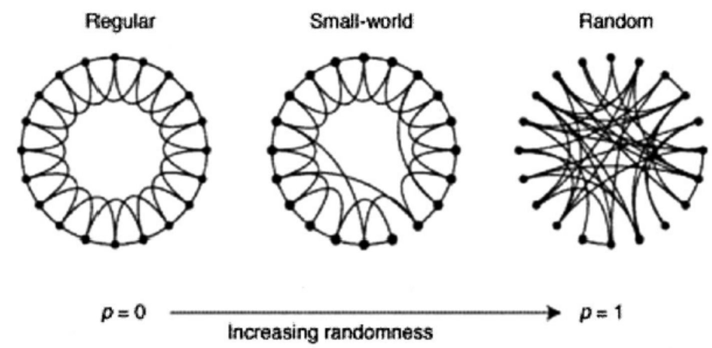
$C=k/n$

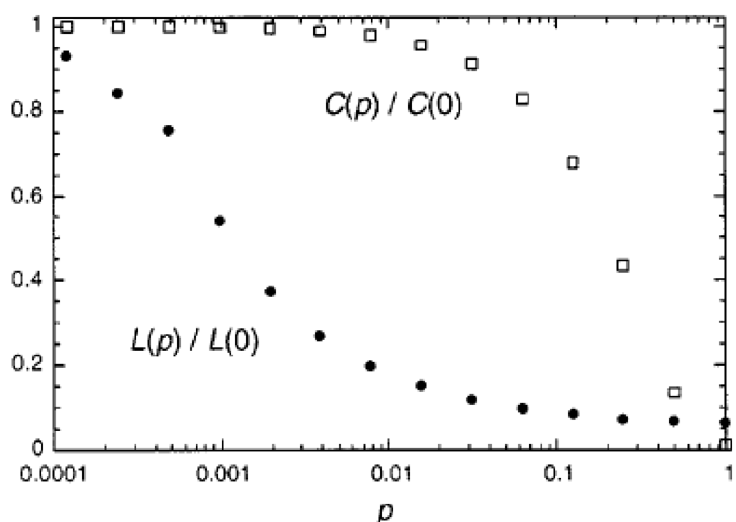


R. Albert and A.-L. Barabasi: Statistical mechanics of complex networks, Rev. Mod. Phys., Vol. 74, No. 1, January 2002

Small-World Networks

- Random rewiring of regular graph (by Watts and Strogatz)
  - With probability *p* rewire each link in a regular graph to a randomly selected node
  - Resulting graph has properties, both of regular and random graphs
    - --> High clustering and short path length





R. Albert and A.-L. Barabasi: Statistical mechanics of complex networks, Rev. Mod. Phys., Vol. 74, No. 1, January 2002

The small-world feature of human mobile networks

- Opportunistic networks exploit human mobility and consequent device-to-device contacts to disseminate content.
- Human social networks are known to be clustered: we are more likely to meet and spend time with our immediate social circles such as family, friends or coworkers while we meet infrequently with more casual acquaintances and accidentally with strangers.
- However, despite this high clustering, any pair of nodes is typically separated by a surprisingly small number of hops: known as the *small-world* phenomenon.
- These properties have been shown to appear in opportunistic mobile networks too.

Mobility datasets of contact traces

- Definition: a contact is the period of time during which two devices are in mutual radio transmission range and can exchange data.
- Some traces (more on *crawdad*):
  - WLAN Access Point associations from the Dartmouth and ETH Zurich campus
  - Bluetooth contacts from the MIT

	DART	ETH	GOW	MIT
# People and context	1044 campus	285 campus	473 Texas	92 campus
Period	17 weeks	15 weeks	6 months	3 months
Type	AP associations	AP associations	Self-reported location	Bluetooth scanning
# Contacts total	4′200′000	99′000	19′000	81′961
# Contacts per dev.	4′000	350	40	890

TABLE I: Mobility traces characteristics.

- A contact trace file is made of:

```
[Time stamp] | [Node1 ID] | [Node2 ID] | [Duration]
```

From the contact trace to the contact graph

- For each pair of nodes *(i,j)*, from *(frequency,duration)*, a weight w_{ij} is extracted

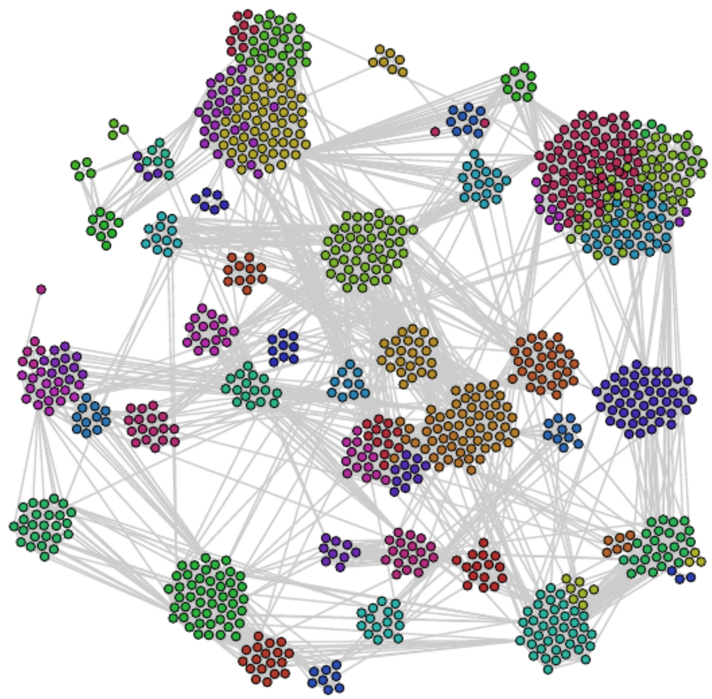


Fig. 1: Contact Graph of DART trace.

T. Hossmann, T. Spyropoulos, F. Legendre, A complex network analysis of human mobility, NETSCICOM 2011

The small-world feature of human mobile networks

	Clustering Coefficient				Avg. Path Length			
	1%	**2%**	**3%**	**4%**	**1%**	**2%**	**3%**	**4%**
DART	0.71	0.63	0.57	0.54	7.4	3.7	2.9	2.6
ETH	-	0.66	0.57	0.53	-	6.1	5.6	4.0
GOW	0.28	0.27	0.27	0.26	4.5	3.4	3.0	2.8
MIT	-	-	0.56	0.57	-	-	4.6	3.8

TABLE II: Clustering Coefficients and Average Path Lengths using different graph densities. Missing values in cases where there is no giant component.

--> The small-world behavior, typical for social networks, is also observed in the network of physical encounters.

T. Hossmann, T. Spyropoulos, F. Legendre, A complex network analysis of human mobility, NETSCICOM 2011

Not IID mobility anymore: impact on the inter-meeting times?

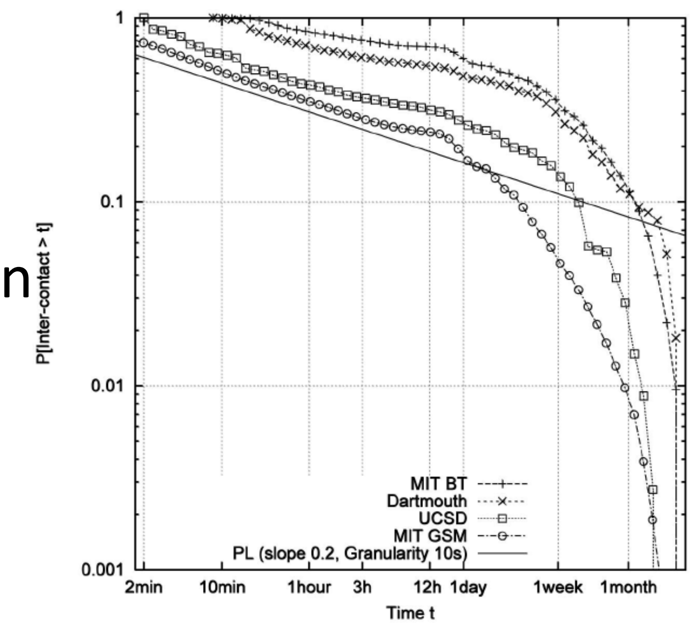
- IID mobility:
  - Inter-meeting times mobile/mobile have shown to follow an exponential distribution

Groenevelt et al.: *The message delay in mobile ad hoc networks*. Performance Evaluation, 2005

- Human mobility:

  - Inter-meeting times have shown to follow power law distribution

CCDF: Pr{ X > x } = $(x/d)^{-\alpha}$



Chaintreau et al.: *Impact of human mobility on the design of opportunistic forwarding algorithms*. Infocom, 2006

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Routing in heterogeneous mobile networks: Utility-based routing

- In PSN, to overcome the problem of sporadic and short-lived connectivity, opportunistic routing schemes have been proposed such that:
  - a message may be stored and carried by a node for long periods of time until a communication opportunity arises (*mobility-assisted*)
  - local forwarding decisions are made independently, and often with little or no knowledge about the destination's position, with the goal that a message will eventually be delivered (*opportunistic*)
  - multiple copies of the same message may be propagated in parallel (*replication*), to increase the probability of at least one being delivered.
- We have seen: two-hop routing, epidemic and spray-and-wait under IID mobility
- But: nodes are heterogeneous in terms of their ability to deliver a message,

  --> greedy replication may fail to discover the "better" relays
- Given a fixed budget of message copies, how can we best allocate it to a network consisting of nodes with varying capabilities and behaviors?

  --> instead of naively (greedily) handing copies to the first nodes encountered, choose relays according to some utility function: utility-based replication

Utility-based routing

- Problem: in a heterogeneous environment, where a limited budget of L message copies needs to be distributed to L relays, a mechanism is necessary to distinguish the "better" relays and avoid using the least useful ones (given some optimization criterion).
- However, this problem is not trivial, in particular because candidate relays are encountered in an online fashion.
- Utility-based Spraying:
  - each node **i** maintains a utility function $\mathbf{U_i(j)}$ for every other node **j** in the network.
  - $\mathbf{U_i(j)}$ reflects the probability that node **i** will deliver a message to node **j** , and it may be based on a number of different parameters (e.g. encounter history, mobility, friendship, etc.)
  - if a node **i** (either the source or a relay) carrying a message copy for a destination **d** and having a forwarding counter c >1, meets node **j** with no copy of the message, the message is copied to **j** if:
    - rule 1: if $\mathbf{U_j(d) > U_{th}}$ for some $\mathbf{U_{th}}$ threshold
    - rule 2: if $\mathbf{U_j(d) > U_i(d)}$
  - **i** hands floor(c/2) forwarding tokens to **j** and keeps the rest ceil(c/2) for itself

T. Spyropoulos, T. Turletti, and K. Obraczka, "Routing in delay-tolerant networks comprising heterogeneous node populations," IEEE Trans. on Mob. Comp., vol. 8, pp. 1132 – 1147, 2009.

Some utility functions

- Last-Seen-First (LSF) Spraying
  - Choose as relays the nodes that have seen the destination most recently.
  - Each node **i** maintains a timer $\boldsymbol{\tau_i(j)}$ for every other node **j** in the network, which records the time elapsed since the **i** and **j** last encountered each other as follows: initially set $\boldsymbol{\tau_i(i)}$ = 0 and $\boldsymbol{\tau_i(j)}$ = ∞.
  - If **i** encounters **j**, set $\boldsymbol{\tau_i(j) = \tau_j(i)}$ = 0; otherwise increase each $\boldsymbol{\tau_i(j)}$ at every time unit.
  - Finally $\boldsymbol{U_i(j)} = 1/(1+ \boldsymbol{\tau_i(j)})$

- Most Mobile First (MMF) Spraying:
  - Assume that each of these nodes carries a label that states the type of the node, e.g. “BUS”,“TAXI”, “PEDESTRIAN”, “BASE STATION”.
  - Assume there are m total node labels.
  - Define the utility of node **i** as $\boldsymbol{U_i(j)} = \boldsymbol{U_i}$ = LABEL(i).
  - Labels are put in a preference order: $LABEL_1 < LABEL_2 <\cdots< LABEL_m$

T. Spyropoulos, T. Turletti, and K. Obraczka, “Routing in delay-tolerant networks comprising heterogeneous node populations,” IEEE Trans. on Mob. Comp., vol. 8, pp. 1132 – 1147, 2009.

Some utility functions

- Most Social First (MSF):
  - Define the sociability of a node:

$$N_i(n) = \{j \neq i : \exists t \in [(n-1)T, nT] \text{ for which } I_{ij}(t) = 1\}$$

$$S_i(n) = \frac{\|N_i(n)\|}{T}$$

  - Maintain a running average of its perceived sociability index at a node:

$$\hat{S}_i = (1-\alpha)\hat{S}_i + \alpha \frac{N_i(n)}{T}$$

$$U_i(j) = U_i = \hat{S}_i$$

T. Spyropoulos, T. Turletti, and K. Obraczka, "Routing in delay-tolerant networks comprising heterogeneous node populations," IEEE Trans. on Mob. Comp., vol. 8, pp. 1132 – 1147, 2009.

An example of exploiting the social clustering into communities: BubbleRap

- The same idea: as mobility is often unpredictable in PSN, and topology changes can be rapid, rather than exchanging much control traffic to create unreliable routing structures, search for some characteristics of the network which are less volatile than mobility.
- If we can detect these social mobility patterns online in a decentralized way, we can put the algorithms into practical applications.

P. Hui, J. Crowcroft, and E. Yoneki, "Bubble rap: Social-based forwarding in delay tolerant networks," IEEE Trans. on Mob. Comp., vol. 10, no. 11, pp. 1576 – 1589, Nov 2011.

An example of exploiting the social clustering into communities: BubbleRap

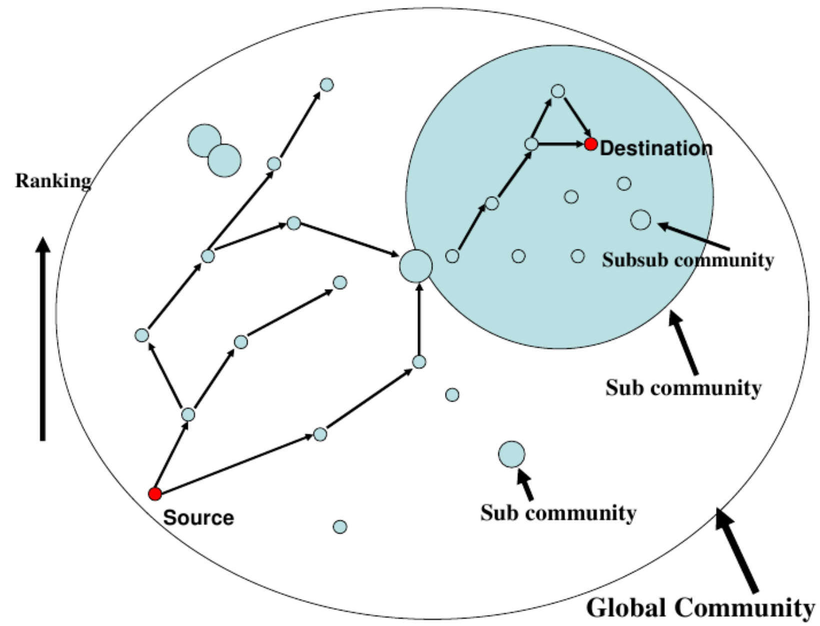
- Combines the knowledge of community structure with the knowledge of node centrality to make forwarding decisions.
  - Each node belongs to at least one community.
  - Each node has a global ranking (i.e. global centrality) across the whole system, and also a local ranking within its local community.

P. Hui, J. Crowcroft, and E. Yoneki, "Bubble rap: Social-based forwarding in delay tolerant networks," IEEE Trans. on Mob. Comp., vol. 10, no. 11, pp. 1576 – 1589, Nov 2011.

An example of exploiting the social clustering into communities: BubbleRap

Algorithm 1: BUBBLE RAP

```
begin
    foreach EncounteredNode_i do
        if (LabelOf(currentNode) == LabelOf(destination)) then
            if (LabelOf(EncounteredNode_i) ==
                                    LabelOf(destination))
                                and
            (LocalRankOf(EncounteredNode_i) >
                                    LocalRankOf(currentNode))
            then
                EncounteredNode_i.addMessageToBuffer(message)
        else
            if (LabelOf(EncounteredNode_i) ==
                                    LabelOf(destination))
                                or
            (GlobalRankOf(EncounteredNode_i) >
                                    GlobalRankOf(currentNode))
            then
                EncounteredNode_i.addMessageToBuffer(message)
end
```



P. Hui, J. Crowcroft, and E. Yoneki, “Bubble rap: Social-based forwarding in delay tolerant networks,” IEEE Trans. on Mob. Comp., vol. 10, no. 11, pp. 1576 – 1589, Nov 2011.

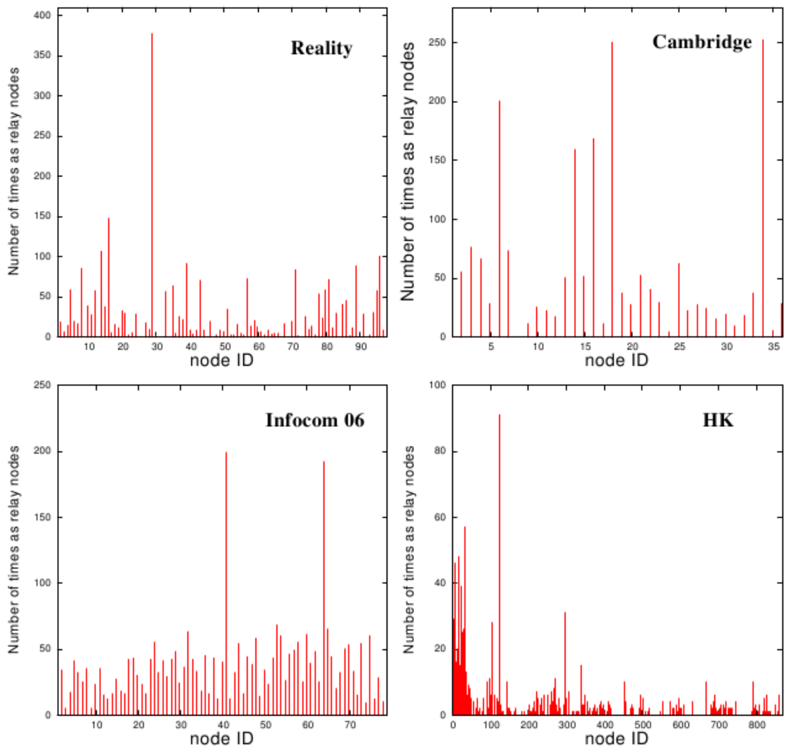
An example of exploiting the social clustering into communities: BubbleRap

- Rank is the betweeness centrality: number of times a node acts as a relay for other nodes on all the shortest delay paths.

- small number of nodes which have extremely high relaying ability,
and a large number of nodes have moderate or low centrality values,

- human heterogeneity: people differ in their popularity.
For instance, a salesperson or politician interacts with many others, making themselves highly-ranked nodes in our graph, compared to (say) the average computer scientist.

--> Choose popular hubs as relays



P. Hui, J. Crowcroft, and E. Yoneki, "Bubble rap: Social-based forwarding in delay tolerant networks," IEEE Trans. on Mob. Comp., vol. 10, no. 11, pp. 1576 – 1589, Nov 2011.

Estimating the rank online

- The total degree (unique nodes seen by a node throughout the experiment period) is not a good approximation of the node centrality.
- Instead the degree per unit time (for example the number of unique nodes seen per 6 hours) and the node centrality have a high correlation value.
- More generally: how to consider that there is an edge between two nodes in the social graph, in terms of the number, frequencies or duration of the meetings between those 2?

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Inferring human communities

- Problem 1: from the contact trace to the contact graph
- Community detection :
  - Many community detections algorithms: Girvan-Newman (WNA), modularity maximization, Louvain, clique-based
  - K-CLIQUE allows for overlapping communities, but was designed for binary graphs --> problem of turning the mobility trace into a binary graph
  - Weighted Network Analysis (WNA) can work on weighted graphs directly, but it cannot detect overlapping communities.
  - Problem 2: decentralized processing (see ref)

P. Hui, E. Yoneki, S. Yan Chan, and J. Crowcroft. *Distributed community detection in delay tolerant networks*. In Proceedings of ACM/IEEE MobiArch 2007.

Example of K-clique community detection

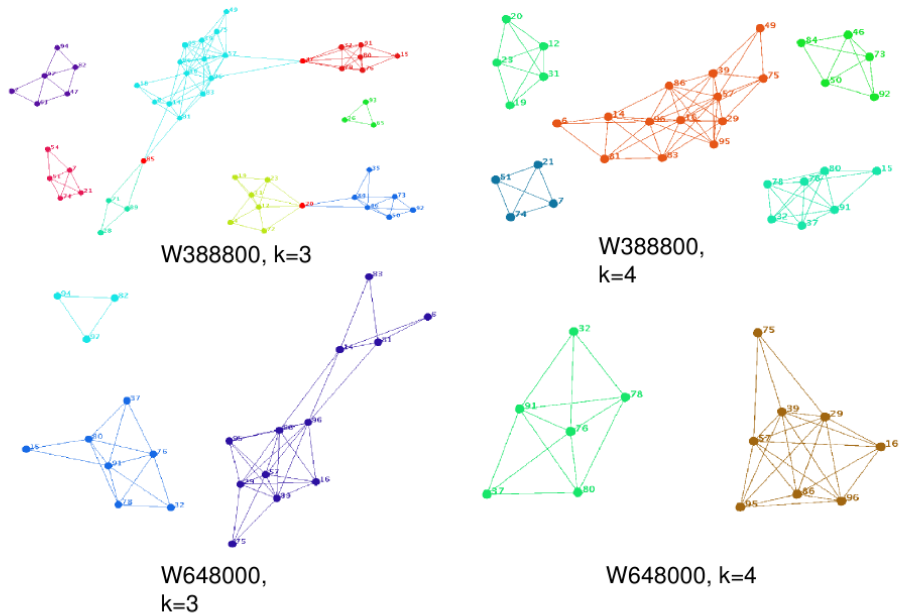
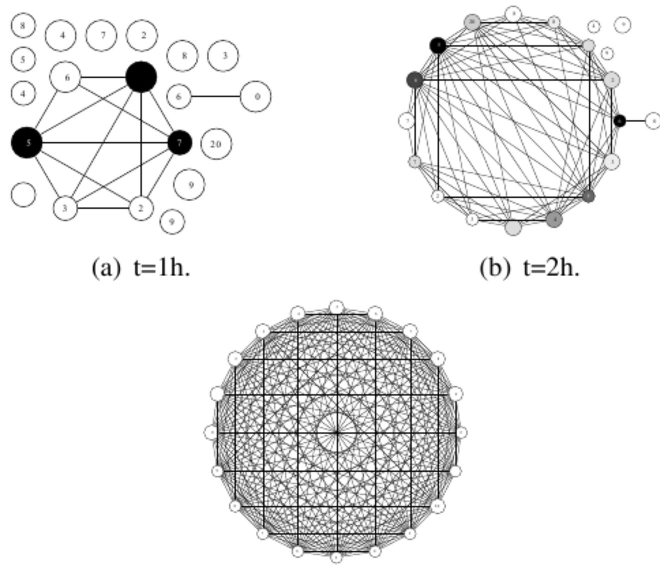


Figure 3: Communities based on contact durations with weight threshold = 388800s (4.5days), 648000s (7.5days) and k=3,4 (*Reality*)

- A *k*-clique is a completely connected subgraph of *k* nodes.
- 2 *k*-cliques are said to be adjacent if they share *k − 1* nodes
- A *k*-clique community is an union of all *k*-cliques that can be reached from each other through a series of adjacent k-cliques.

From the contact trace to the contact graph

- Aggregate the entire sequence of contacts of a trace to a static, weighted contact graph *G(N,W)* with weight matrix W = $\{w_{ij}\}$: strength of the relationship between nodes i and j.
- Various metrics possible: age of last contact, contact frequency or aggregate contact duration.



(a) t=1h. (b) t=2h. (c) t=72h.

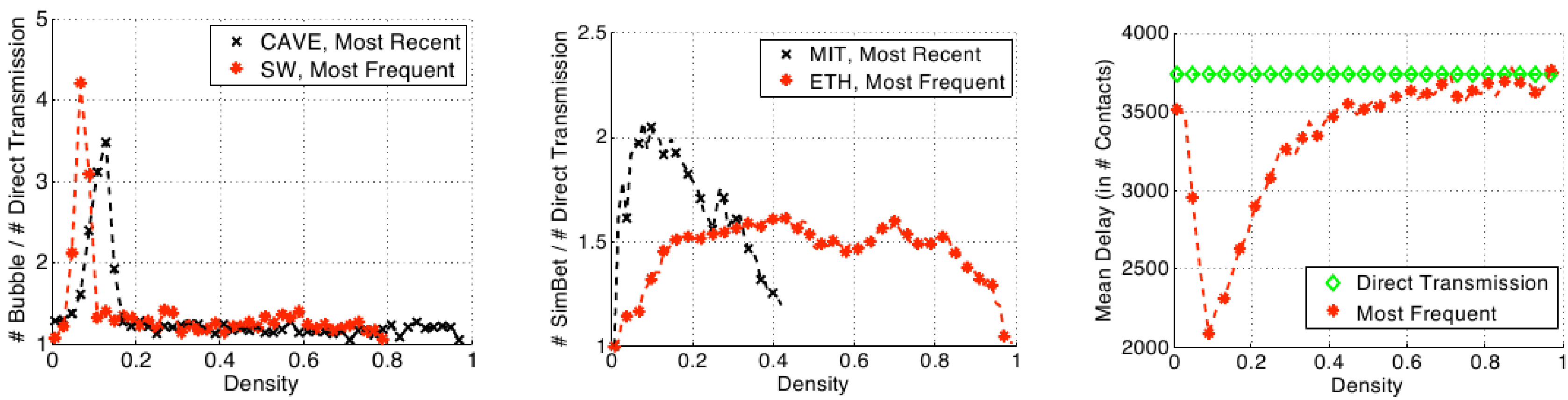
Aggregated contacts for the ETH trace at different time instants.

Density-based Aggregation

- A more useful and robust approach than time-based aggregation, can be to choose the aggregation function such that the resulting social graph has a given density:

$$d(G_n) = \frac{|E_n|}{|E|}$$

- If we want to operate the social graph at a certain density, say, $d(G_n) = 0.2$, we choose the "best" edges, according to some criterion, such that E_n will have the desired cardinality:
  - Most Recent Contacts
  - Most Frequent Contacts



(a) Bubble Rap DR performance increase

(b) SimBet DR performance increase

(c) SimBet Delivery Delay (CAVE)

T. Hossmann, F. Legendre, T. Spyropoulos, *From Contacts to Graphs: Pitfalls in Using Complex Network Analysis for DTN Routing*, in IEEE NetSciCom 09, Rio de Janeiro, Brazil, April, 2009

Density-based Aggregation online

- An online algorithm that uses concepts from unsupervised learning and spectral graph theory to infer this “correct” graph structure.
- Allows each node to locally identify and adjust to the optimal operating point.

T. Hossmann, F. Legendre, T. Spyropoulos, *From Contacts to Graphs: Pitfalls in Using Complex Network Analysis for DTN Routing*, in IEEE NetSciCom 09, Rio de Janeiro, Brazil, April, 2009

Conclusion

- A lot of other community-based routing algorithms for mobile social DTN (PSN): SimBet, PeopleRank, etc…
- Some other problems to overcome:
  - What are the contacts that matter: are they regular contacts, or random contacts?
  - Considering content caching, what are the relays the content should be placed to?
  - What social features to consider to better match social mobility?
  - What do we put inside “social information”: needs to understand what type of social information is the most relevant for forwarding, and analyze the impact of choosing a “good” and meaningful social information on social forwarding decisions.
  - …

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Efficient Network Coded Data Transmission in DTN

Yunfeng Lin, Baochun Li, Ben Liang, "Efficient Network Coded Data Transmissions in Disruption Tolerant Networks," in the Proceedings of IEEE INFOCOM 2008, Phoenix, Arizona, April 2008.

Yunfeng Lin, Baochun Li, Ben Liang, "Stochastic Analysis of Network Coding in Epidemic Routing," in IEEE Journal on Selected Areas in Communications, Special Issue on Delay and Disruption Tolerant Wireless Communication, Vol. 26, No. 5, pp. 794-808, June 2008.

Motivation – Constraints in DTN

- Opportunistic connections between nodes
- Nodes have limited transmission capabilities
- Buffer space limitations
- Battery power limited
- Nodes are mobile
- Delay in packet delivery will be large
- Node density is low

Network model

- Settings:
  - only a single unicast session
  - λ: average number of meetings a node has per time unit
  - sparse DTN: $\lambda = N\beta$ remains constant as N increases
    --> the network is connectivity-limited
  - mobility model: fast and uniform (RW, RWP,…)

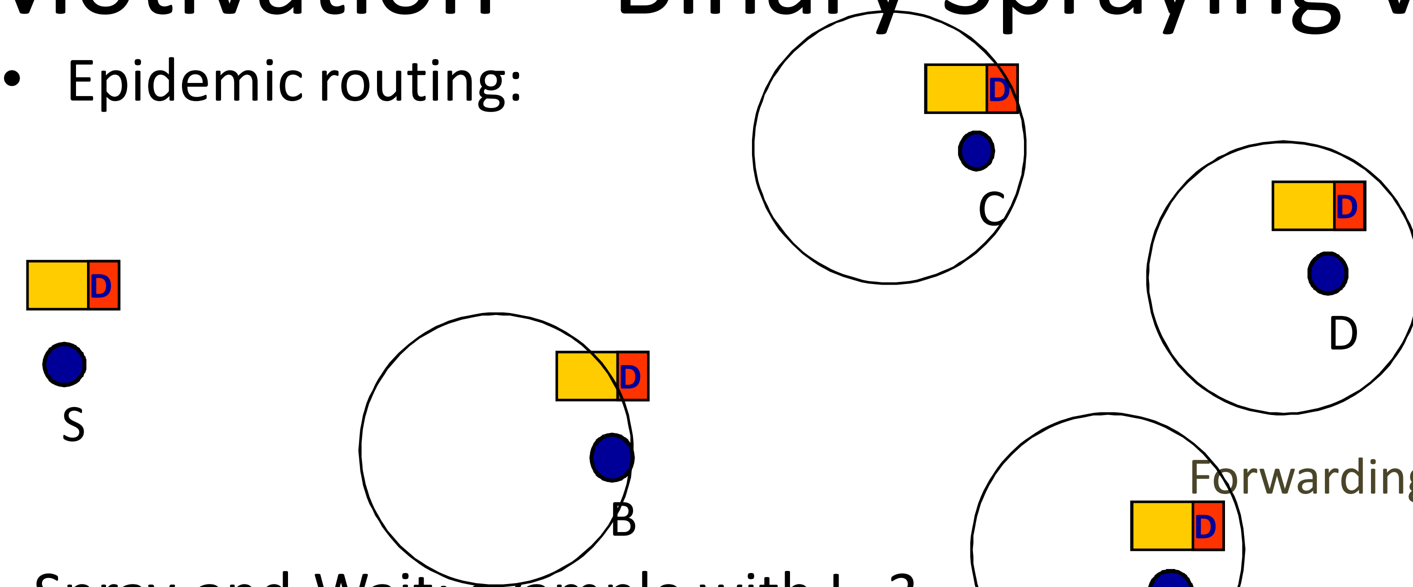
--> routing strategies must permit timely delivery of information to a certain destination with high probability: use of replication

- replication leads to energy and memory consumption
- finite duration of radio contacts --> file split into packets

- **Objective**: optimize the file transfer from S to D by minimizing both its delay, the memory and energy required by the store and forward process

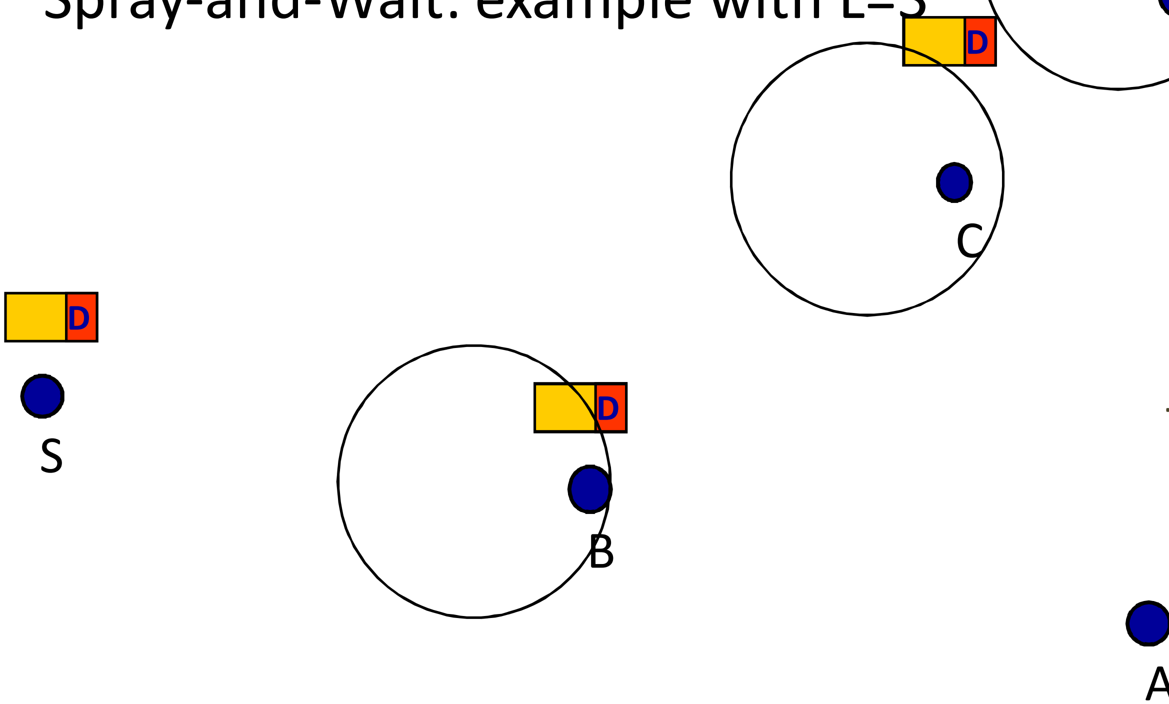
Motivation – Binary Spraying vs. ER

- Epidemic routing:



Forwarding is not limited

- Spray-and-Wait: example with L=3

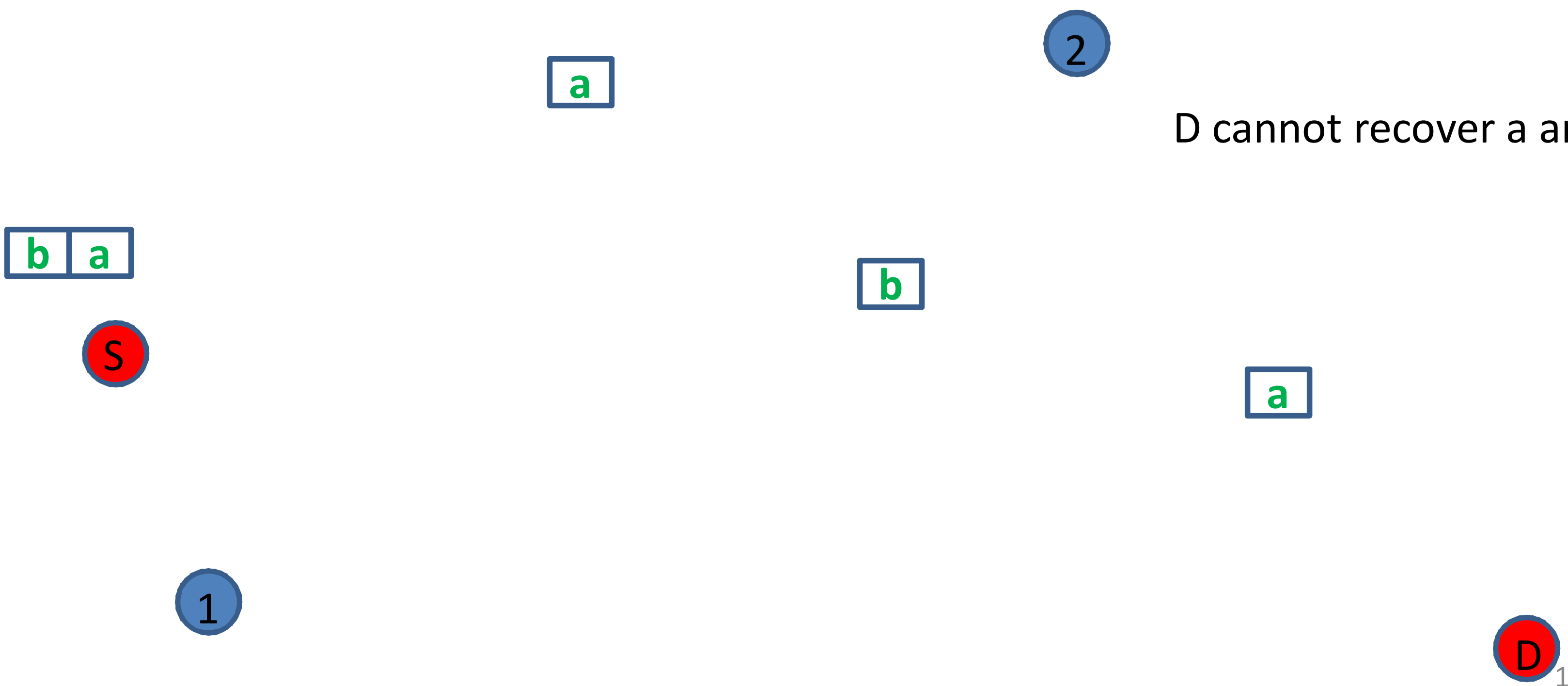


There are already 3 copies, no more forwarding

Binary Spraying Vs ER (cont'd)

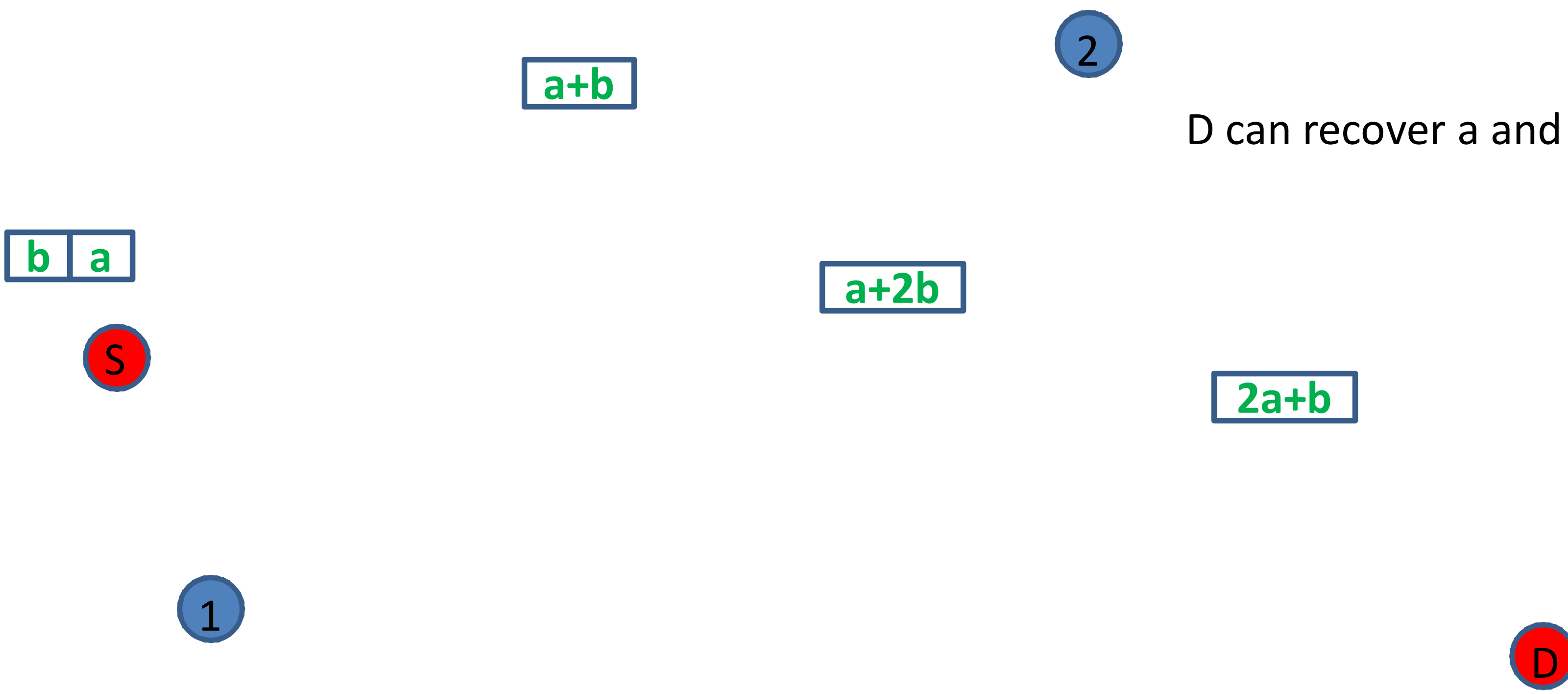
- Epidemic routing:
  - no limit on the number of transmissions (≤ nb of pkts . N)
  - mean time for delivery of one packet: ≤ $\log_2(N)$
- Spray-and-Wait:
  - number of transmissions ≤ nb of pkts . L
  - mean time for delivery of one packet: ≤ $\log_2(L)+N/L$

Motivation – NC Vs Replication



D cannot recover a and b

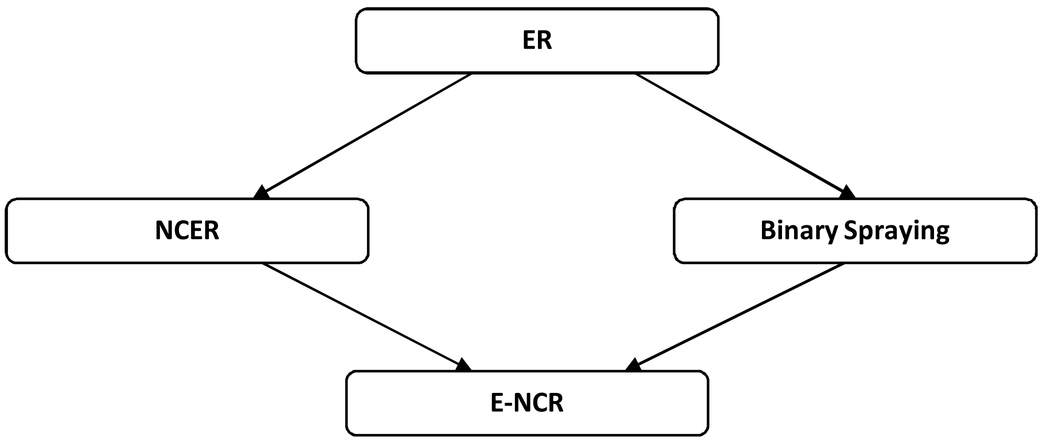
Motivation – NC Vs Replication



D can recover a and b

Protocol - Principle

- This protocol called the E-NCR, is a combination of Network coding and Binary spraying.

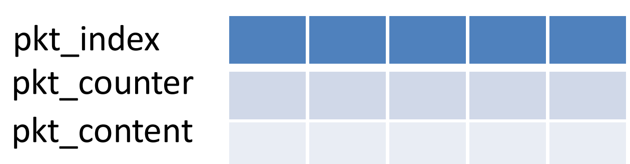


NCER – Network Coding based Epidemic routing
ER – Epidemic Routing
E-NCR - Efficient Network coding based routing

Protocol - Assumptions

- There is one source S with *K* info packets to be transmitted, *n* relay nodes and a destination D
- For every opportunistic contact, only one packet can be transmitted.
- Relay nodes have buffer space B, defined as $1 \leq B \leq K$
- No other background traffic
- A packet in the buffer of a node is purged as soon as an ACK is received from D or the Time-to-live field reaches zero.

Buffer structure:



E-NCR: an example

K=2
K'=3
L=7

Buffer structure:
pkt_index
pkt_counter
pkt_content

Time	Node 1	Node 2	Buffer content Node 1	Buffer content Node 2
0	S		1 / 2 / 3 7 / 7 / 7 d=a+b / e=2a+3b / f=a+2b	
1	S	R1	1 / 2 / 3 4 / 7 / 7 d / e / f	1 3 d
2	S	R2	1 / 2 / 3 4 / 4 / 7 d / e / f	2 3 e
3	R1	R2	1 / 2 2 / 1 d / e	2 / 1 2 / 1 e / d
4	R2	R3	2 / 1 1 / 1 e / d	2 1 3d+5e

Protocol - Description

SOURCE-RELAY:

```
K' = K + some more encoded packets
L = c * log k, where c is some constant
i = 0;
S = K';
do
{
   if(detect any node and <i,l> not already there with that node)
   {
      send an encoded packet <i, L, co-efficients, packet>
       i++;
   }

}while(S != i);
```

Protocol - Description

RELAY-RELAY, SENDER SIDE:

```
do
{
 if(detect any node X)
 {
     get spray list of X; //list element is a tuple <i, l>,where i is index of packet, 'l' is the
                //remaining spray count
     do
     {
          compare this->spraylist with x->spraylist;
     if(any this->spraylist-><i, l> such that l >=0 and i does not exist in x->spraylist)
          {
          send encoded packet <i, floor(l/2)> to node x;
          update tuple <i, l> to <i, ceil(l/2)>;
          }
     }while(end of x->spraylist);
 }
}while(true);
```

Protocol - Description

RELAY-RELAY, RECEIVER SIDE:

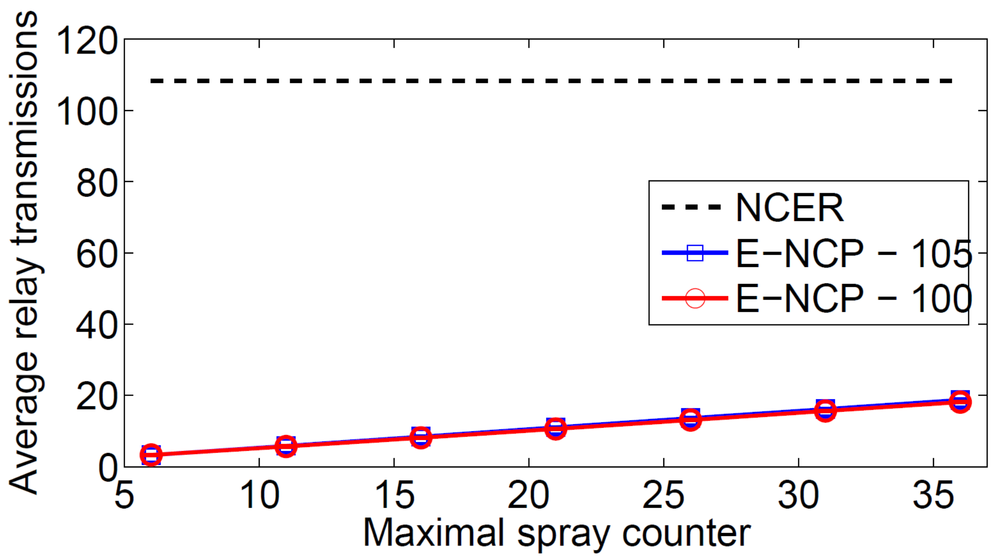
```
if(packet received)
{
    if(buffer size == max_buffer_size)
    {
    encode incoming packet with all
    packets in list;
    }
    else
    {
    place packet in free slot;
    }
    add <i,l> of incoming packet to spray
    list;
}
```

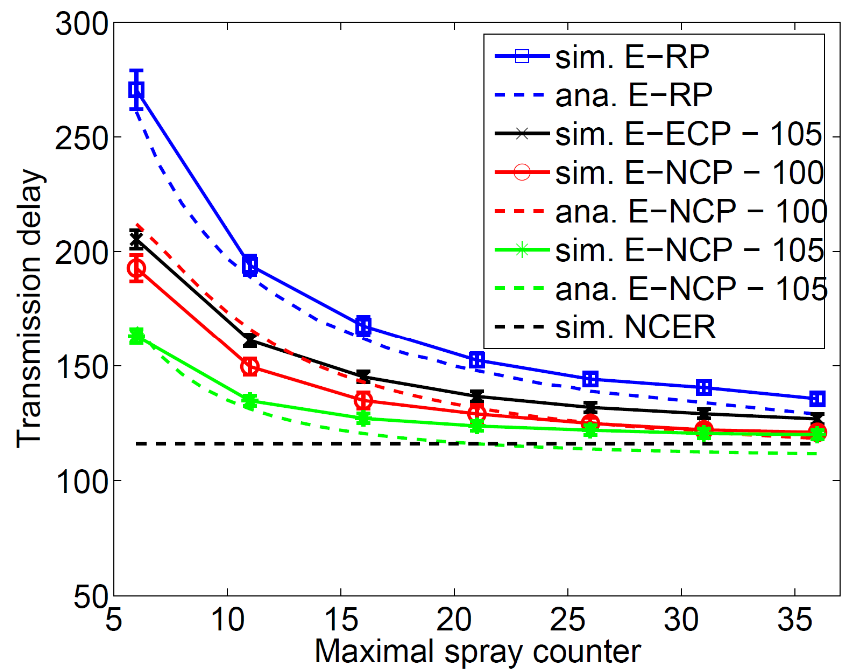
DESTINATION:

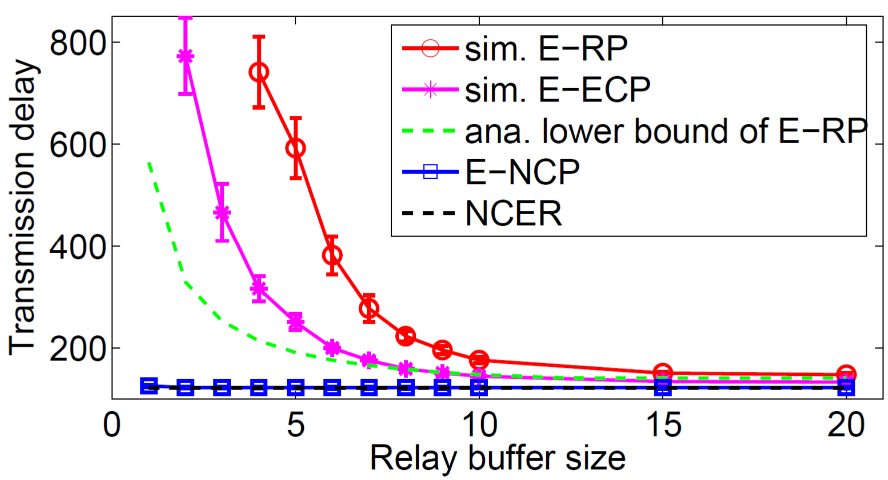
```
do
{
    if(got a packet)
    {
        add to packet list
        try to decode list of packets;
        if(decode possible)
        {
            exit loop;
        }
    }

}while(true);
```

Performance







Some Limitations

- Destination has to wait till minimum of K encoded packets are received
- Some packets which have linear dependence could arise during encoding at relays.