Throughput and Delay in Mobile Ad Hoc Networks with Network Coding: A Global Perspective

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Outline

- Research Background
- Challenges
- Introduction
- Mobility Model
- RLC-Scheme
- Main Results
- Analysis & Conclusion
- Future Work

Research Background

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- **Network coding for large scale wireless networks**
  - **Network coding (Ahlswede et al. [1])**
  - **Linear network coding (Li et al. [2])**
  - **Random linear network coding for multicast (Tracey et al.[3])**
  - **Algebraic approach to network coding (Koetter & Mdard [4])**

[1] R Ahlswede, N Cai, SYR Li, RW Yeung, “Network Information Flow,” IEEE Trans. on Inf. Theory, vol. 46, no. 4, pp. 1204-1216, Jul. 2000.

[2] SYR Li, RW Yeung, N Cai, “Linear Network Coding,” IEEE Trans. on Inf. Theory, vol. 49, no. 2, pp. 371-381, Feb. 2003.

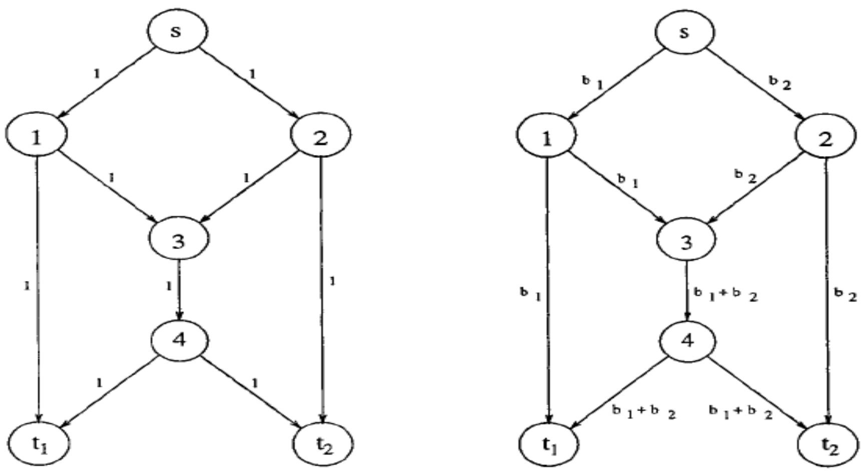
[3] Ho. T, M. Medard, R. Koetter, D.R. Karger, M. Effros, J. Shi, B. Leong, “A Random Linear Network Coding Approach to Multicast,” IEEE Trans. on Inf. Theory, vol. 52, no. 10, pp. 4413-4430, Oct. 2006.

[4] Ralf Koetter, Muriel Mdard, “An Algebraic Approach to Network Coding,” IEEE/ACM Transactions on Networking, vol. 11, no. 5, pp. 782-795, Oct. 2003.

Research Background

❑ Network coding (Ahlswede et al. [1])

- ➢ Save bandwidth
- ➢ Increase throughput
- ➢ Proved that relaying evidence of message can be more efficient than relaying message itself
- ➢ Leaves further problems of coding method for multi-source and multi-sink network

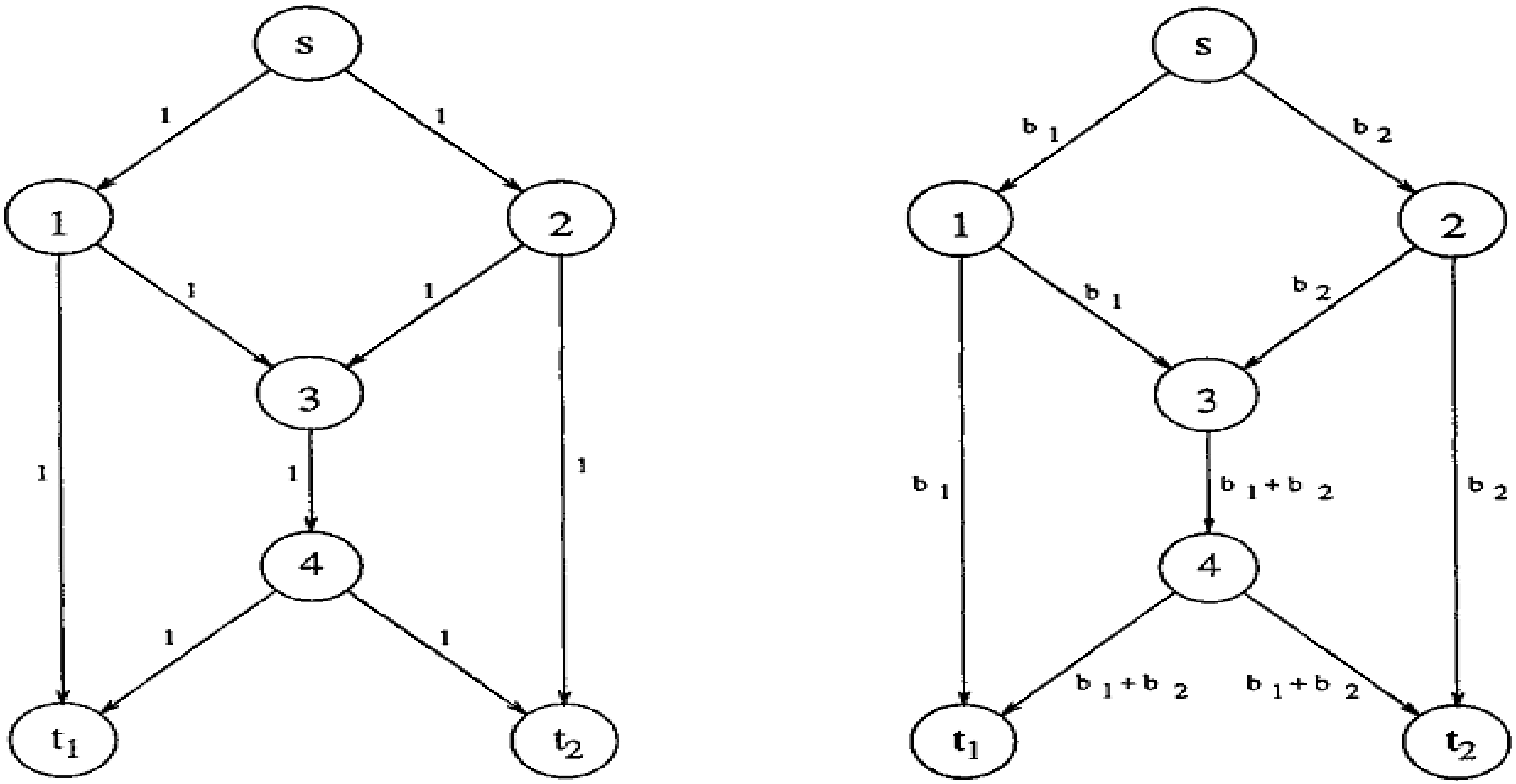


ground breaking work

[1] R Ahlswede, N Cai, SYR Li, RW Yeung, "Network Information Flow," IEEE Trans. on Inf. Theory, vol. 46, no. 4, pp. 1204-1216, Jul. 2000.

Research Background

- A one-source two-sink network with coding



(a) (b)

Research Background

- Traditional: regard the information to be multicast as a "fluid" which can simply be routed or replicated.

- Network coding: think of information as being "diffused" through the network from the source to the sinks.

Research Background

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- **The result can be regarded as the Max-flow Min-cut Theorem for network information flow.**

Conjecture 1: Let $G = (V, E)$ be a graph with source s and sinks $t_1, ..., t_L$, and the capacity of an edge (i, j) be denoted by R_{ij}. Then (R, h, G) is admissible if and only if the values of a max-folw from s to $t_l, l = 1, ..., L$ are greater than or equal to h, the rate of the information source.

Research Background

A Practical Work:

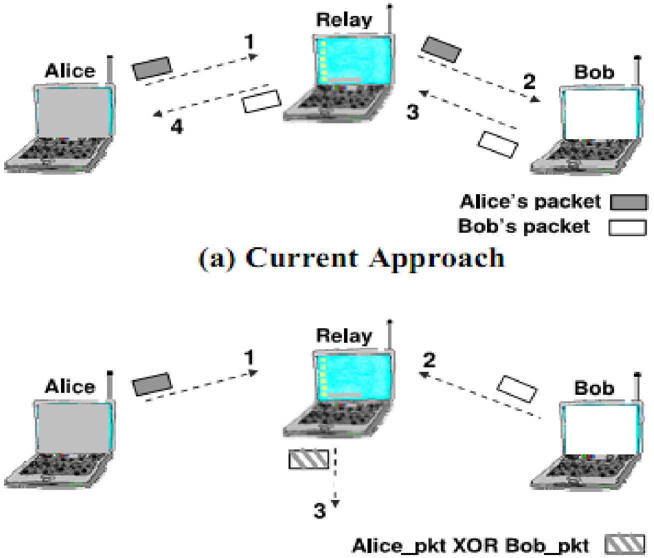
- S.Katti, H. Rahul, W. Hu, D. Katabi, M. Medard, and J. Crowcroft, “Xors in the air: Practical wireless network coding,” IEEE/ACM Trans. Netw., vol. 16, no. 3, pp. 497–510, 2008.

Contributions:

build up a wireless communication system named COPE utilizing network coding theory.

Example:

Decrease 4 transmissions to 3 transmissions



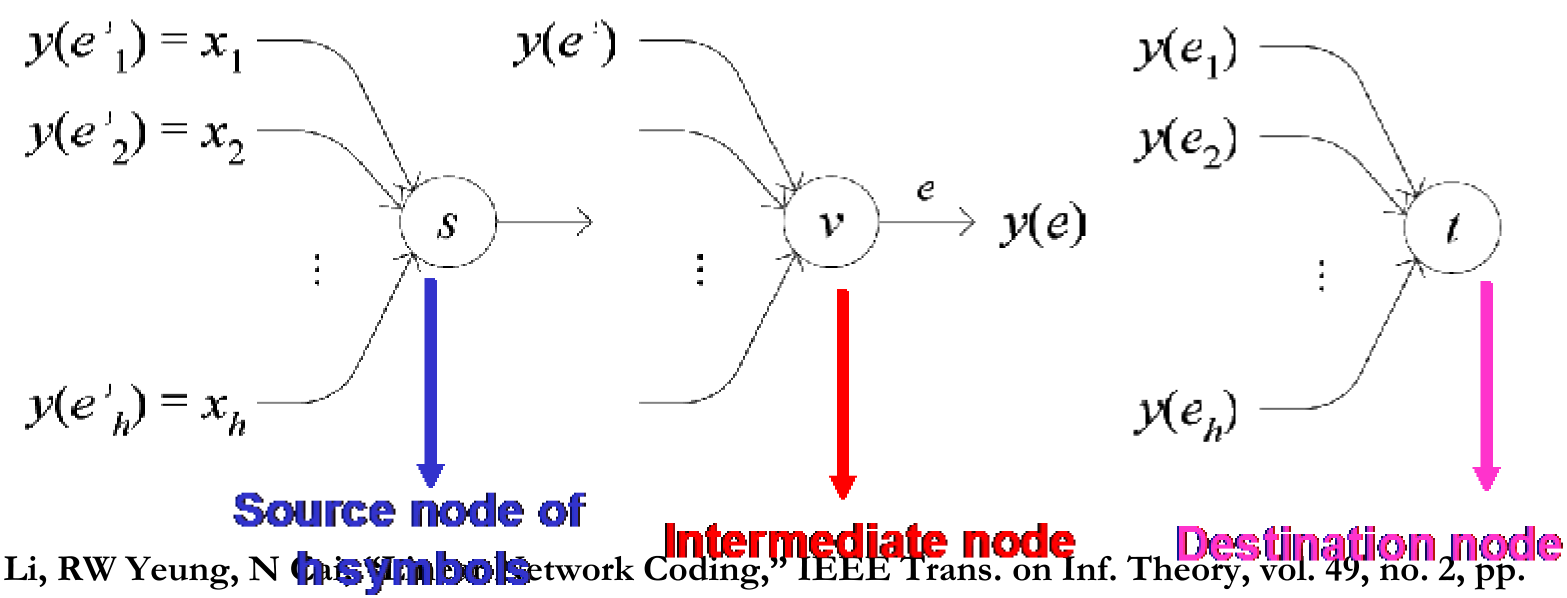
(a) Current Approach

(b) COPE

Research Background

Linear network coding (Li et al. [2])

- The output flow at a given node is obtained as a linear combination of its input flows
- Coding can be implemented at low computational cost
- The content of any information flowing out of a set of non source nodes can be derived from the accumulated information that has flown into the set of nodes



[2] SYR Li, RW Yeung, N Cai, "Linear Network Coding," IEEE Trans. on Inf. Theory, vol. 49, no. 2, pp. 371-381, Feb. 2003.

Research Background

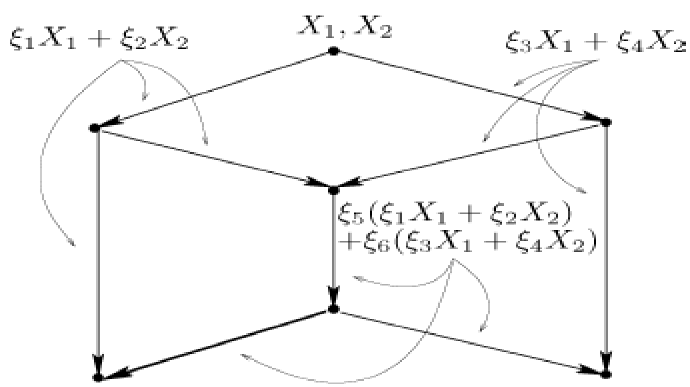
- Contribution: Design code and prove Network coding could achieve max-flow of network.

- The throughput capacity of the network with network coding is not studied

Research Background

- Random linear network coding for multicast (Tracey et al.[3])

- Network nodes form output packets by taking random linear combinations of corresponding blocks of bits in input packets
- Linear combination specified by the coefficient vector in the packet header
- Each sink receives with high probability a set of packets with linearly independent coefficient vectors, allowing it to decode

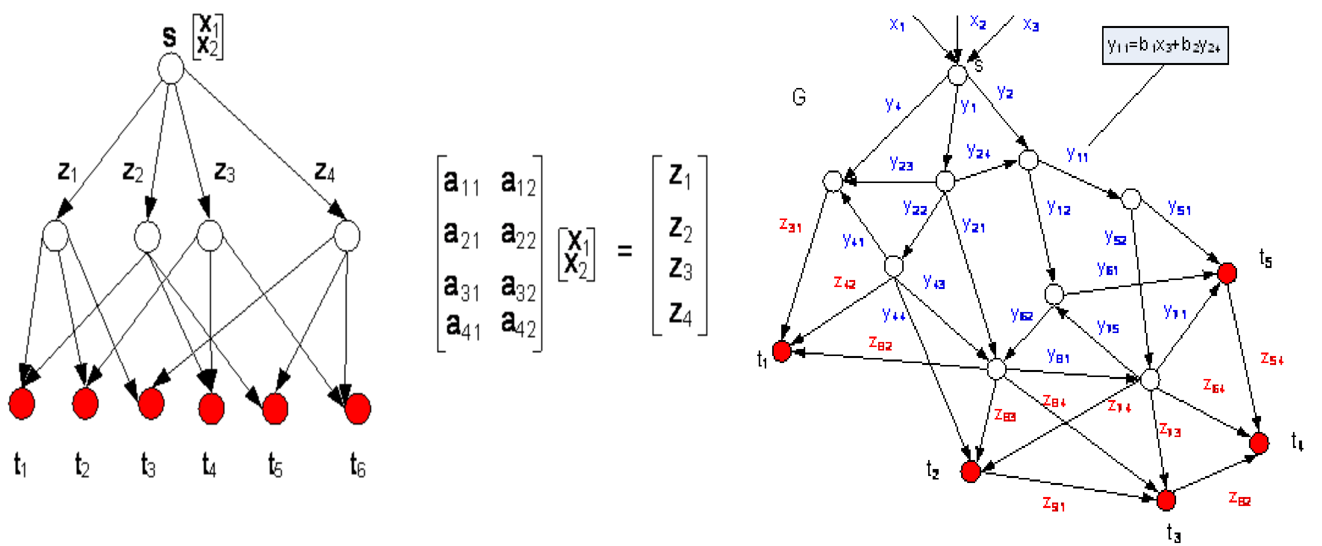


distributed random linear network coding

[3] Ho. T, M. Medard, R. Koetter, D.R. Karger, M. Effros, J. Shi, B. Leong, "A Random Linear Network Coding Approach to Multicast," IEEE Trans. on Inf. Theory, vol. 52, no. 10, pp. 4413-4430, Oct. 2006.

Research Background

- Algebraic approach to network coding (Koetter & Mdard [4])
  - Conditions that a given linear network coding problem is solvable
  - Efficiently find a solution to a given linear network coding problem
  - Static solution for a network that is subject to link failures



$$\begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \\ a_{31} & a_{32} \\ a_{41} & a_{42} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} z_1 \\ z_2 \\ z_3 \\ z_4 \end{bmatrix}$$

$$\begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} z_1 \\ z_2 \\ z_3 \end{bmatrix}$$

Illustration of algebraic approach to network coding

[4] Ralf Koetter, Muriel Mdard, “An Algebraic Approach to Network Coding,” IEEE/ACM Transactions on Networking, vol. 11, no. 5, pp. 782-795, Oct. 2003.

Research Background

Network capacity with network coding

- Network coding gain (Liu et al. [5])
- Network coding gain with different conditions (Zhang et al [6], Li et al [7].)
- etc

[5] J. Liu, D. Goeckel, D. Towsley, "Bounds on the Gain of Network Coding and Broadcasting in Wireless Networks," in Proc. IEEE INFOCOM, pp. 724-732, May 2007.

[6] Chi Zhang, Yuguang Fang and Xiaoyan Zhu, "Throughput-Delay Tradeoffs in Large-Scale MANETs with Network Coding," in Proc. IEEE INFOCOM, pp. 199-207, Rio de Janeiro, Brazil, April 2009.

[7] Zhongpeng Li, Baochun Li, and LC Lau, "A Constant Bound on Throughput Improvement of Multicast Network Coding in Undirected Networks," IEEE Transactions on Information Theory, vol. 55, no. 3, pp. 1016-1026, March 2009.

Research Background

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❑ Network coding gain (Liu et al. [5])

- show that network coding and broadcasting lead to at most a constant factor improvement in per node throughput

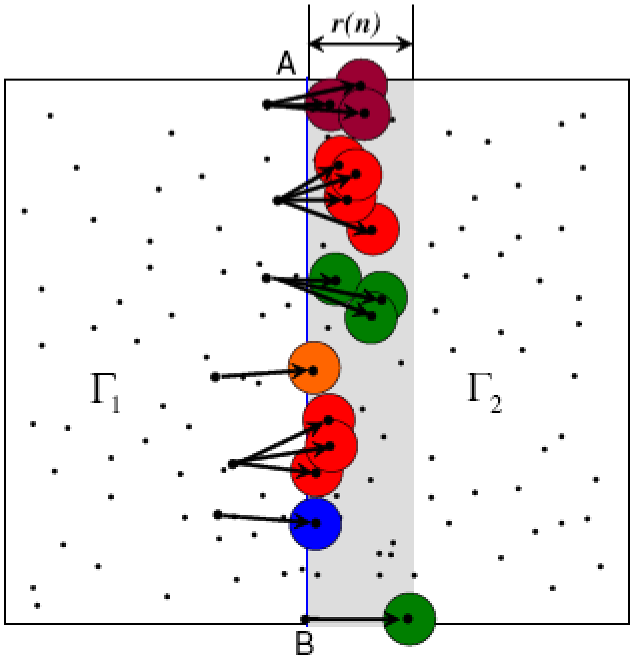
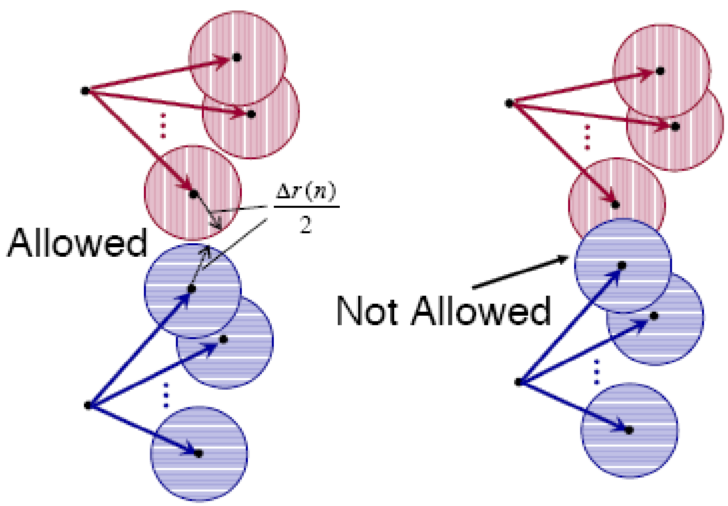


Illustration of cut capacity in 2D



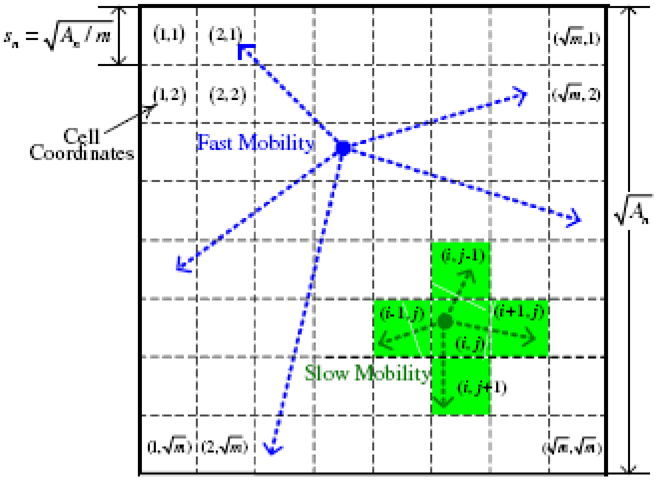
Interference of coding schemes in 2D

[5] J. Liu, D. Goeckel, D. Towsley, "Bounds on the Gain of Network Coding and Broadcasting in Wireless Networks," in Proc. IEEE INFOCOM, pp. 724-732, May 2007.

Research Background

- Network coding gain with different conditions (Zhang et al [6], Li et al [7].)

  - Optimal tradeoffs in different node mobility patterns
  - The ratio of achievable multicast throughput with network coding to that without network coding is bounded by a constant ratio of 2



Fast and slow mobility models for MANETs in [10]

[6] Chi Zhang, Yuguang Fang and Xiaoyan Zhu, "Throughput-Delay Tradeoffs in Large-Scale MANETs with Network Coding," in Proc. IEEE INFOCOM, pp. 199-207, Rio de Janeiro, Brazil, April 2009.

[7] Zhongpeng Li, Baochun Li, and LC Lau, "A Constant Bound on Throughput Improvement of Multicast Network Coding in Undirected Networks," IEEE Transactions on Information Theory, vol. 55, no. 3, pp. 1016-1026, March 2009.

Challenges

- How representative is the i.i.d mobility model in the study and in the industry application?
- Can the throughput-delay relationship be significantly different under some other reasonable mobility models, such as random walk mobility model, random way-point mobility model and Brownian motion model?

Introduction

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- **How does Network Coding improve the capacity and delay of Mobile Wireless Networks**
  - In the multi-hop manner, Random Linear Network Coding has a $\log n$ gain on the delay in some cases.
  - The Hybrid Mobility Models are representative, which cover a variety of mobility models.

Introduction

❑ Mobile Wireless Networks with Random Linear Network Coding

Hybrid Mobility Models	Relay Schemes
Hybrid Random Walk Mobility Models (i.i.d & random walk)	2-hop Relay with RLC
Discrete Random Direction Models (Brownian motion & random way point)	Multi-hop Relay with RLC

- **Main Results:** In 2-hop Relay with RLC scheme, there is $\log n$ gain on delay only when the mobility model is random walk. In multi-hop Relay with RLC scheme, there is $\log n$ gain on delay, whatever the mobility model is.

Related Works:

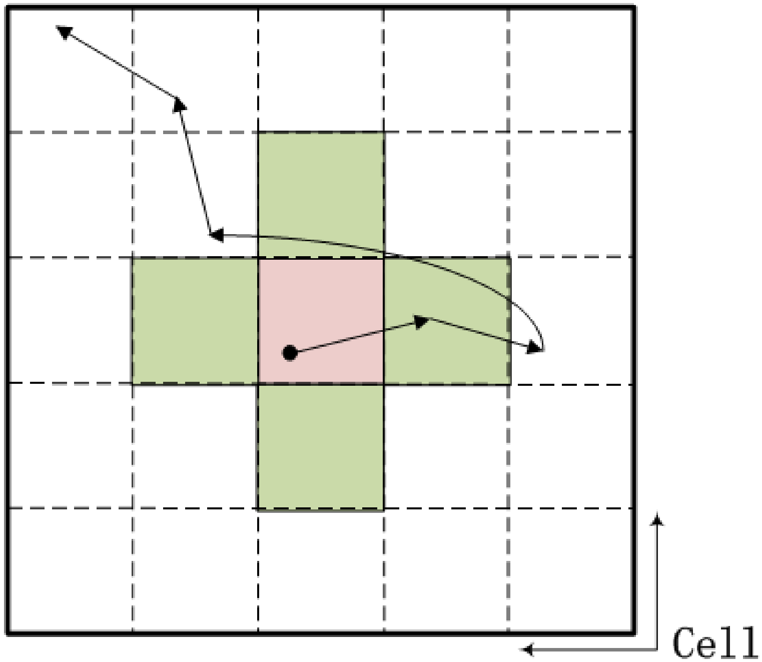
[8] C. Zhang, Y. Fang and X. Zhu, "Throughput-Delay Tradeoffs in Large-Scale MANETs with Network Coding," in Proc. IEEE INFOCOM, pp.199-207, Rio de Janeiro, Brazil, April 2009.

[9] G. Sharma, R. Mazumdar, and N. B. Shroff, "Delay and capacity trade-offs in mobile ad hoc networks: a global perspective," IEEE/ACM Trans. Netw., vol. 15, no. 5, pp. 981–992, 2007.

Mobility Model

Hybrid Random Walk Mobility Models(1)

- The unit square is divided into $n^{2\beta}$ cells, thus resulting in a discrete torus of size $n^{\beta} \times n^{\beta}$, where $0 \le \beta \le 1/2$.



- Here, when $\beta=0$, the model is essentially **the i.i.d mobility model**; when $\beta=1/2$, the model becomes the **random walk mobility model**.

Mobility Model

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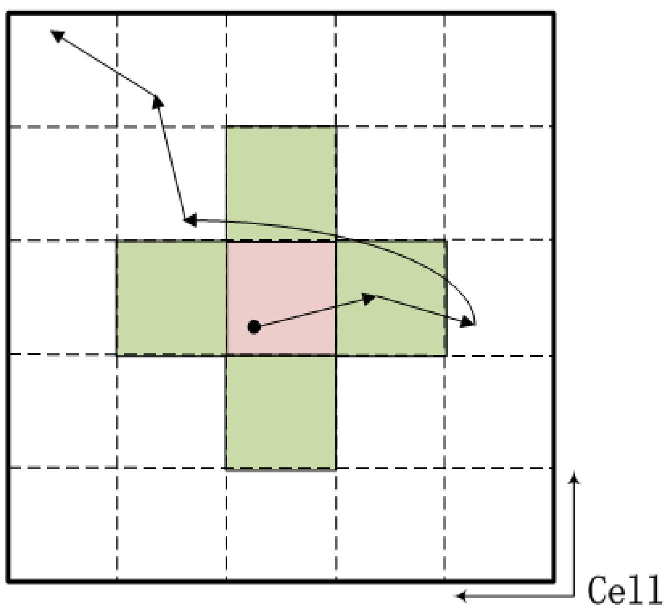
Hybrid Random Walk Mobility Models(2)

- At each time slot a node is assumed to be in one cell. And initially each node is equally likely to be in any of the n cells, independently of the other nodes.
- At the beginning of a slot, a node jumps from its current cell to an adjacent cell. Here the adjacent cell means: Let a node be in cell (l, j) where $l, j = 0,1,2,\ldots,n^{\beta}-1$ at time slot t, then at timeslot t+1, the node is equally likely to be in the same cell (l, j) or any of the four adjacent cells (i-1,j) (i+1,j) (I,j-1) (I,j+1).



Mobility Model

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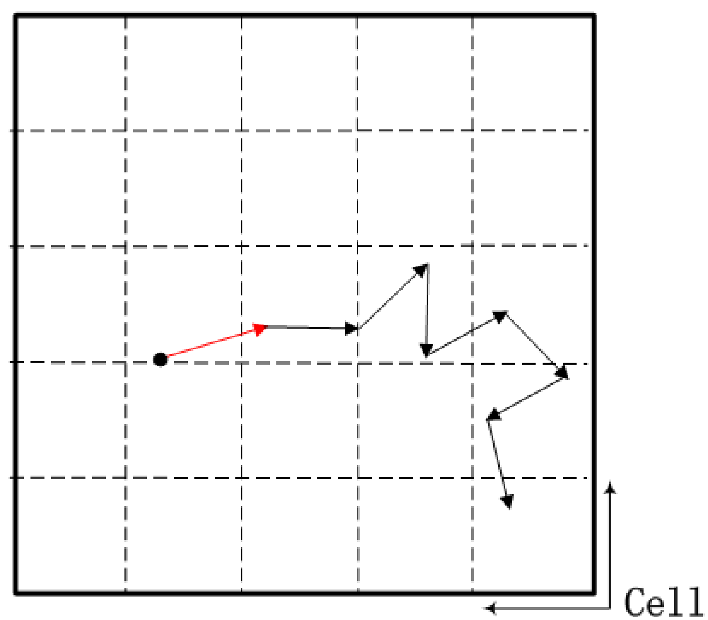
Discrete Random Direction Models（1）

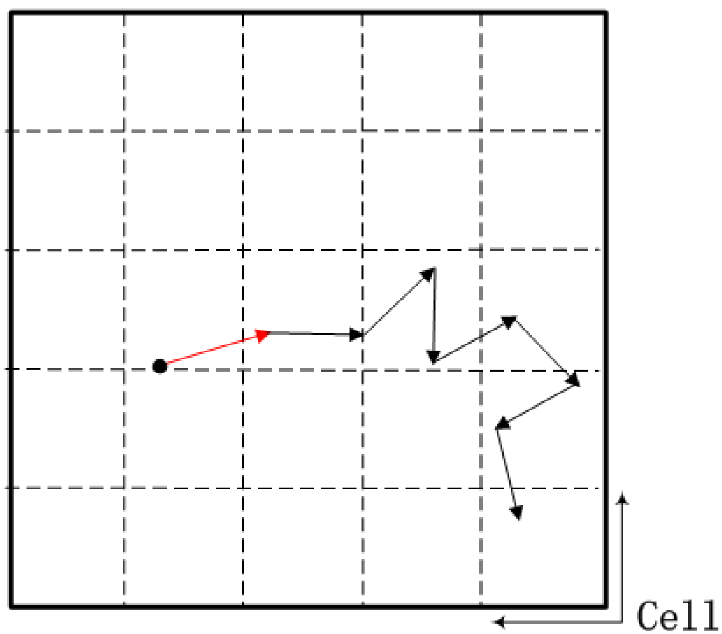
- The unit square is divided into $n^{2\alpha}$ squares of which area is called a cell, thus resulting in a discrete torus of size $n^{\alpha} \times n^{\alpha}$, where $0 \le \alpha \le 1/2$.
- The motion of a node is divided into multiple trips. At the beginning of a trip, the node chooses a direction θ uniformly between[0,2π], and moves a distance of $n^{-\alpha}$ in that direction with the speed v_n .



Mobility Model

Discrete Random Direction Models（2）

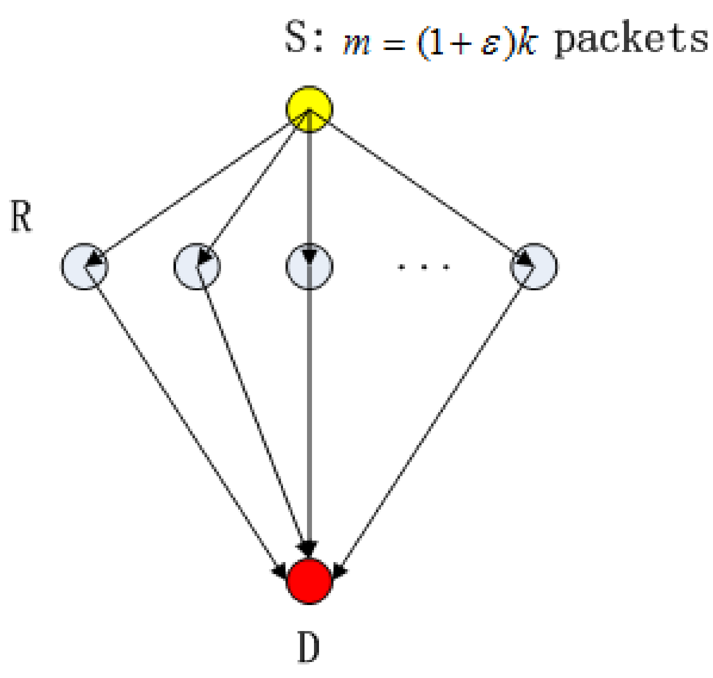
- Here we choose $v_n = \Theta(n^{-1/2})$, therefore a time slot should be $\Theta(n^{1/2-\alpha})$.
- Here, the discrete random direction model with α=1/2 degenerates into the **random walk model**, which is the discrete time version of the Brownian motion model. When α=0, this is **random way point model**.



RLC-Scheme

RLC-Based Relay Schemes: 2-hop Relay with RLC(1)

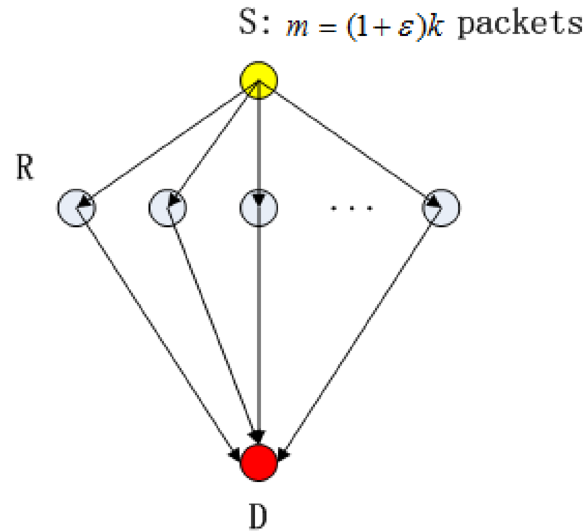
- k original packets in each source node will be grouped into one generation(transmission task). Each source will operate RLC and send $m=(1+\varepsilon)k$ coded packets for each generation, where ε is a constant.
- In one time slot, only one node in a cell can be active.



RLC-Scheme

RLC-Based Relay Schemes: 2-hop Relay with RLC(2)

- For an active cell with at least two nodes, randomly assign a node as sender and choose another node in the cell as a receiver.
- When the relay nodes have received the coded packet, it will store it in the buffer, when all the destinations have received the coded packet, it will be deleted from the buffer.
- When destinations receive enough coded packets, they will decode the k original packets.



RLC Scheme

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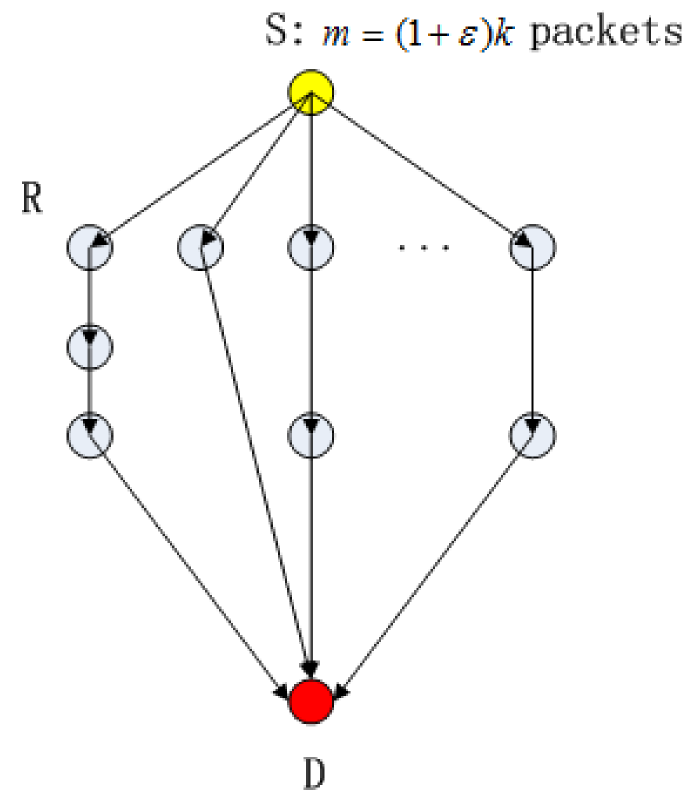
RLC-Based Relay Schemes: Multi-hop Relay with RLC

- The transmission way for the source and relay node is similar to the 2-hop relay scheme with network coding.
- The difference is that relay nodes can transmit packets to other relay.



Main Results

Throughput and Delay with RLC under Hybrid Random Walk Models

- Theorem 1: When 2-hop relay with RLC scheme is used and $k = \Theta(n^{2\beta})$, we have $T(n) = \Theta(1)$ and $D(n) = \Theta(n^{2\beta})$ for hybrid random walk models, here $0 < \beta \le 1/2$. When $\beta=0$, the mobility model is i.i.d and we have $T(n) = \Theta(1)$, $D(n) = \Theta(n)$.

- Theorem 2: When multi-hop relay with RLC scheme is used, under hybrid random walk model with $k = \Theta(n^{\beta})$, we have $T(n) = \Theta(1)$ and $D(n) = \Theta(n^{\beta})$.

Main Results

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Throughput and Delay with RLC under Hybrid Random Walk Model: Comparison

- There is no gain under 2-hop delay algorithm compared to Gaurav Sharma's work[9] when $\beta=0$. And there is a $\log n$ gain on delay when $\beta=1/2$. This is the same with the conclusion Chi Zhang[8] has made.

- Compared to the network without NC under multi-hop delay algorithm, there is a $\log n$ gain on delay. When we take $\beta=0$ and $1/2$, that are the i.i.d. and random walk mobility model, and the result is the same with Chi Zhang's work[8].

Main Results

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Throughput and Delay with RLC under Discrete Random Direction Model

- Theorem 3: Under the discrete random direction model, 2-hop relay with RLC scheme is adopted and $k = \Theta(n^{2\alpha})$, then we get $T(n) = \Theta(n^{\alpha-1/2})$ and $D(n) = \Theta(n^{1/2+\alpha})$,here $0 \le \alpha < 1/2$. When $\alpha=1/2$,we have $D(n) = \Theta(n)$.

- Theorem 4: When multi-hop relay with RLC scheme is used, $k = \Theta(n^{\alpha})$ then we have $T(n) = \Theta(n^{\alpha-1/2})$ and $D(n) = \Theta(n^{1/2})$.

Main Results

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Throughput and Delay with RLC under Discrete Random Direction Model: Comparison

- From Theorem 3, we can see that there is no gain under 2-hop delay algorithm compared to Gaurav Sharma's work[9] when $\alpha=0$ and there is a log n gain on delay when $\alpha=1/2$.

- From Theorem 4, we can see that compared to the network without NC, there is a $\log n$ gain in delay.

Main Results

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- Comparasion with Gaurav Sharma's work[9] in capacity and delay (2-hop)

Scheme	Condition	Capacity	Delay
Hybrid Random Walk Models w.o. NC 2-hop	β<1/2 β=1/2	$\omega(1/\sqrt{n})$	$\Theta(n)$ $\Theta(n \log n)$
Hybrid Random Walk Models w. NC 2-hop	β=0 $k = \Theta(n^{2\beta})$ 0<β≤1/2	$\Theta(1)$	$\Theta(n)$ $\Theta(n^{2\beta})$
Discrete Random Direction Models w.o. NC 2-hop	0≤α<1/2 α=1/2	$\omega(1/\sqrt{n})$	$\Theta(n)$ $\Theta(n \log n)$
Discrete Random Direction Models w. NC 2-hop	$k = \Theta(n^{2\alpha})$ 0≤α<1/2 α=1/2	$\Theta(n^{\alpha-1/2})$	$\Theta(n^{1/2+\alpha})$ $\Theta(n)$

Main Results

- Comparasion with Gaurav Sharma's work[9] in capacity and delay (multi-hop)

scheme	condition	capacity	delay
Hybrid Random Walk Models w.o. NC multi-hop	0≤β≤1/2	$\omega(1/\sqrt{n})$	$\Theta(n^{2\beta}\log n)$
Hybrid Random Walk Models w. NC multi-hop	$k=\Theta(n^{2\beta})$	$\Theta(1)$	$\Theta(n^{2\beta})$
Discrete Random Direction Models w.o. NC multi-hop	0≤α≤1/2	$\omega(1/\sqrt{n})$	$\Theta(n^{1/2+\alpha}\log n)$
Discrete Random Direction Models w. NC multi-hop	$k=\Theta(n^{2\alpha})$	$\Theta(n^{\alpha-1/2})$	$\Theta(n^{1/2+\alpha})$

Analysis & Conclusion

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Result Analysis

- **Main Results:** In 2-hop Relay with RLC scheme, there is only a $\log n$ gain on delay when the mobility model is random walk mobility model.

- **Main Results:** In multi-hop Relay with RLC scheme, there is a $\log n$ gain on delay, which is independent of mobility models.

- The property of NC utilized in Mobile Wireless Network: **make more information redundancy to decrease the delay.**

Analysis & Conclusion

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Summary

- **Network Coding in Mobile Wireless Networks:**
  - In the multi-hop manner, Random Linear Network Coding has a $\log n$ gain on the delay.
  - **Effective property of NC:** make more information redundancy to decrease the delay.

Future Work

- We will add the base station to the network and analyze the impact of BS to the throughput and delay with NC.

Thank you !