Wireless Broadcast with Network Coding
Dynamic Rate Selection

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Outline

- Motivation
- Broadcast with Network Coding
- Our approach: DRAGON
- Simulations
- Conclusion

Wireless Multi-hop Networks

Wireless Multi-hop Networks

- Wireless Ad-Hoc Networks, Mesh Networks, Sensor Networks, VANETs, . . .

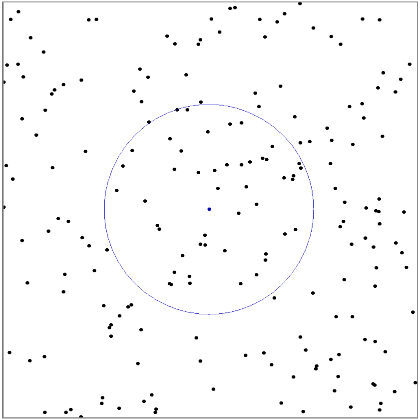
Specific Communication: Broadcast

- Broadcast: send same information from source(s) to several all nodes
- Use:
  - Information diffusion (emergency, software distribution, . . .)
  - Simplified multicast for multicast applications (conferencing, media distribution, . . .)

Motivation

Wireless Multi-hop Networks

- Wireless communication
- Limited capacity
- Specially for broadcast
- Issue: minimize the cost of broadcast



Goal

- Limit channel utilization ≊ decrease the total number of transmissions
- (ignore scheduling, spatial reuse, . . .)

Problem Statement

Considered Problem

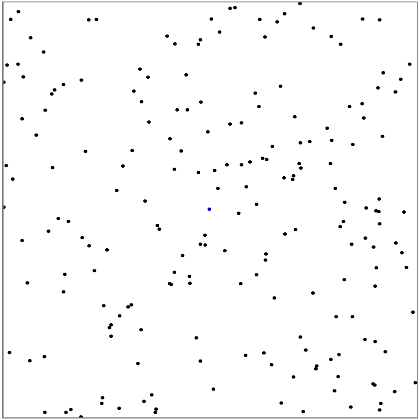
- Broadcast: from one source to all nodes in the network

Goal

- Minimize the total number of transmissions for broadcasting one message from the source
- $\longrightarrow$ Energy-Efficiency

Without Network Coding

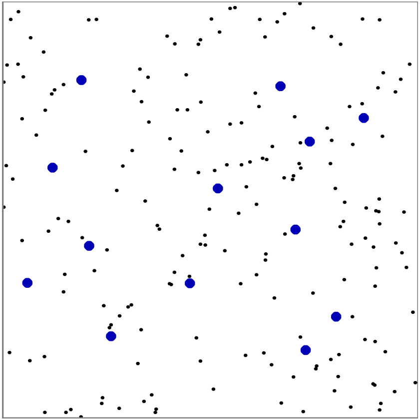
- Wireless case: heuristics exist



Efficient Broadcast

Without Network Coding

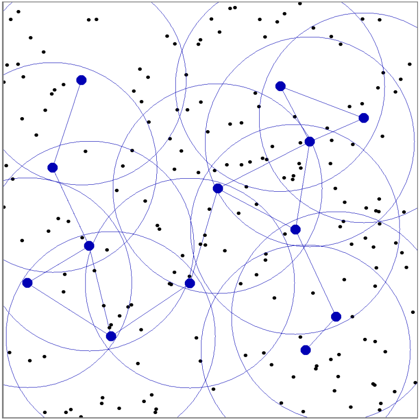
- Wireless case: heuristics exist
- Some subset of nodes retransmits messages



Efficient Broadcast

Without Network Coding

- Wireless case: heuristics exist
- Some subset of nodes retransmits messages
- Connected Dominating Set
- Energy-efficiency: minimizing the number of retransmitting nodes



Efficient Broadcast

Motivation for Network Coding

- In some cases, *network coding may outperform routing* for energy-efficient wireless broadcast
  - All to all broadcast:
    Fragouli et al. [Infocom'06]
  - *Asymptotic* optimality in the core of the network:
    in the core, essentially every transmission is useful to every receiver (network size and density $\rightarrow \infty$)
    C.A., S.Y Cho and P. Jacquet [WITS'07]
  - (large networks with density $\rightarrow \infty$ [INRIA RR-6547])
- In addition: natural error-recovery
  (compensation for packet loss, mobility, . . .)

Broadcast with Network Coding

- Random Linear Coding: coding using linear operations and random coefficients Ho et al. [ISIT'03]
- Without interferences, static network:
  - Performance (nb transm. per broadcast source packet): entirely defined by the average rate of each node
  - Rates for optimality may be found by linear program Lun et al. [IEEE Trans. Netw., June 2006]
- Even with interferences: linear program with constraints optimal rates (Park et al. [Milcom 2006])
- but what non-static network? or even simpler approaches?

Our approach

- An heuristic for finding the rates of each node
- Rate adjusted with a feedback control:
  D.R.A.G.O.N. (Dynamic Rate Adaptation from Gap with Other Nodes)
- Simple, dynamic, and generic
  - Simple: uses only information from the state of neighbors
  - Dynamic: allows for topology change, transient losses, . . .
  - Generic: actually no assumptions (interference, mobility, loss probability)

Basic Algorithm of Network Coding with Random Linear Coding

- Source generates packets P_1, P_2, P_3, ... (periodically)
- Every (re-)transmission in the network is a linear combination of some source packets:

$$Q = \alpha_1 P_1 + \alpha_2 P_2 + \ldots + \alpha_k P_k$$

- Every node v keeps a list of stored packets
- Every node regularly retransmits packets with a given rate:
  - creates a combination of all the stored packets
  - sends the coding coefficients
- Decoding at the end: linear algebra

Illustration of Random Linear Coding

Source packets: P_1, P_2, P_3

Node N_1

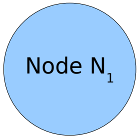
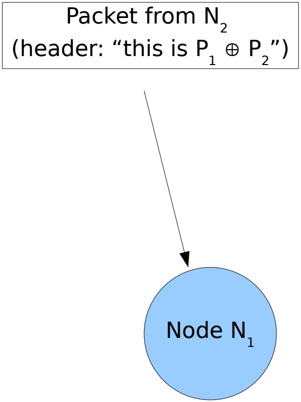


Illustration of Random Linear Coding

Source packets: P_1, P_2, P_3

Node N_1

- Receives $P_1 \oplus P_2$
  stores it as $\mathbf{Q_1} := P_1 \oplus P_2$



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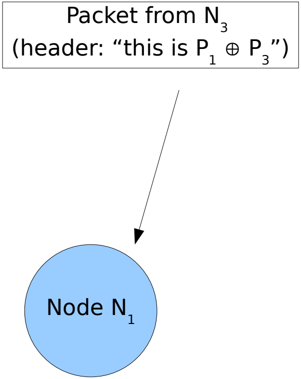
- Receives $P_1 \oplus P_3 \rightarrow \mathbf{Q_2}$



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- Receives $P_1 \oplus P_3 \to \mathbf{Q_2}$
- Receives $P_2 \oplus P_3 \to \mathbf{Q_3}$
  (**non-innovative** $= Q_1^{(N_1)} \oplus Q_2^{(N_1)}$)

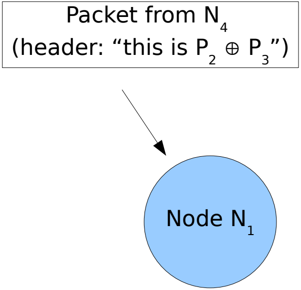

Illustration of Random Linear Coding

Source packets: P_1, P_2, P_3

Node N_1

- Receives $P_1 \oplus P_2$ stores it as $\mathbf{Q_1} := P_1 \oplus P_2$
- Receives $P_1 \oplus P_3 \to \mathbf{Q_2}$
- Receives $P_2 \oplus P_3 \to \mathbf{Q_3}$ (**non-innovative** $= Q_1^{(N_1)} \oplus Q_2^{(N_1)}$)
- Decides to send a packet (random coef.), ex: $Q_1^{(N_1)} \oplus Q_2^{(N_1)}$

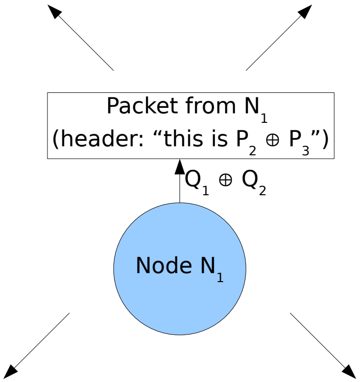

Illustration of Random Linear Coding

Source packets: P_1, P_2, P_3

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- Decides to send a packet (random coef.), ex: $Q_1^{(N_1)} \oplus Q_2^{(N_1)}$
- Receives $P_1 \oplus P_2 \oplus P_3 \rightarrow \mathbf{Q_4}$

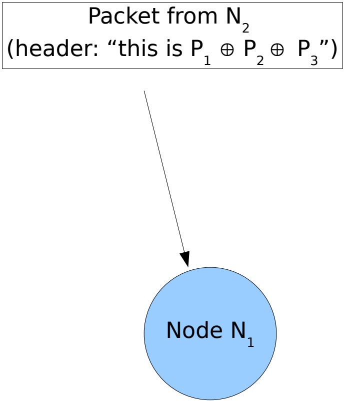

Illustration of Random Linear Coding

Storage of node N_1

- $Q_1^{(N_1)} = P_1 \oplus P_2$
- $Q_2^{(N_1)} = P_1 \oplus P_3$
- $Q_3^{(N_1)}$ redundant
- $Q_4^{(N_1)} = P_1 \oplus P_2 \oplus P_3$

Node N_1 may solve for the unknown source packets P_1, P_2, P_3

- Decoding: Gaussian elimination, possibly step at each arrival
- Possible when *rank* in a node is # coded source packets
- $P_1 = Q_1 \oplus Q_2 \oplus Q_4$
- $P_2 = Q_2 \oplus Q_4$
- $P_3 = Q_1 \oplus Q_4$

Illustration of Random Linear Coding

Storage of node N_1

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- $Q_2^{(N_1)} = P_1 \oplus P_3$
- $Q_3^{(N_1)}$ redundant
- $Q_4^{(N_1)} = P_1 \oplus P_2 \oplus P_3$

Evolution of rank after each arrival

- Rank of $\{Q_1\} = 1$
- Rank of $\{Q_1, Q_2\} = 2$
- Rank of $\{Q_1, Q_2, Q_3\} = 2$
- Rank of $\{Q_1, Q_2, Q_3, Q_4\} = 3$

Node N_1 may solve for the unknown source packets P_1, P_2, P_3

- Decoding: Gaussian elimination, possibly step at each arrival
- Possible when *rank* in a node is # coded source packets
- $P_1 = Q_1 \oplus Q_2 \oplus Q_4$
- $P_2 = Q_2 \oplus Q_4$
- $P_3 = Q_1 \oplus Q_4$

Our Approach

Normal behavior of network coding

- Assuming coded packets are propagated properly:
- The ranks in every node should increase homogeneously

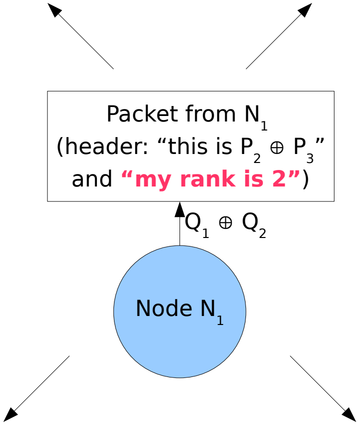
Idea

- Perform a control:
  - Detection: check if the ranks of two nodes are not sufficiently close to each other
  - If so: remedy the situation
- Acting locally: between neighbors

Mechanism for Detection

Rank advertisement in headers

- When sending a packet, the current rank of the node is set in the header
- As a result, the node gets (an estimate of) the rank of its neighbors:
  - $D_{N_2}, D_{N_3}, \ldots D_{N_k}$



Mechanism for Control

Principle of the Control

- When a node has a neighbor with a lower rank
- $\rightarrow$ It increases its rate
- $\rightarrow$ This will tend to close the gap
- Underlying property:
  - If a node u with higher rank transmits packets to a node v with lower rank, its packets will be innovative for v
  - Note: in the opposite direction, it may or may not be the case
  - This is an argument for energy-efficiency
- Heuristic: the increase of rate is proportional to the size of the gap
- Tends to equalize the ranks in each node globally

Details of DRAGON

Detail of the algorithm

- D.R.A.G.O.N - Dynamic Rate Adaptation from Gap with Other Nodes
- The node u memorizes the rank of the nodes of its neighbors: D_v for $v \in H_u$ (where H_u = neighbors of u)
- The node considers the largest gap between its rank D_u and the ranks of its neighbors:

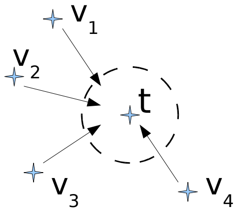
$$g'_u = \max_{u \in H_u} \frac{1}{|H_u|}(D_v - D_u)$$

- If $g_u > 0$: rate of the node is set to $C_v = \alpha g_u$
- Delay is approximated as $\frac{1}{C_v}$

Behavior of DRAGON

Behavior of the nodes

- Local Received Rate: total rate of from neighboring nodes
- In node v: `LocalReceivedRate`(v) is greater than $\alpha\times$ average gap with neighbors
- Gap would be closed in time $\approx \frac{1}{\alpha}$
- In linear network: exponential convergence to steady state



Simulations

Performance criterion

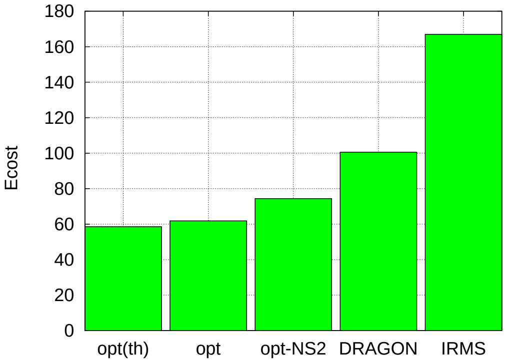
- $E_{\mathrm{cost}} =$ number of transmissions to broadcast one packet

Simulation Scenarios

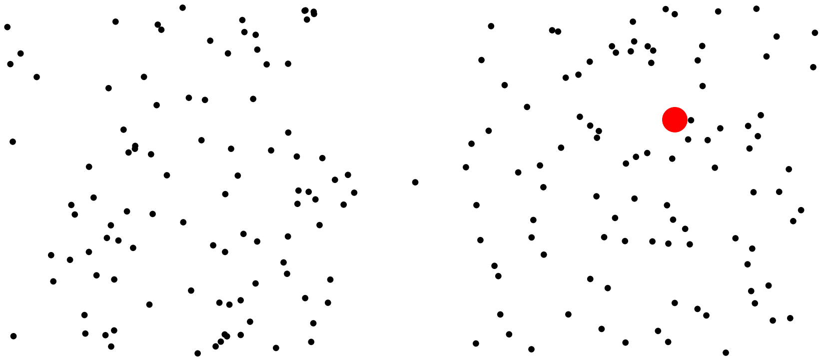
- Random unit disk graphs
- Ideal model or NS-2
- Comparison with:
  - Optimal rate selection (from linear program)
  - IRMS [Cho et al. WICON'07]: static algorithm with good results

Simulation Results

- Average of 6, relatively sparse networks (M=6)
- opt(th): theoretical optimal from linear program (no interference)
- opt, opt-NS2: more practical
- DRAGON: good performance

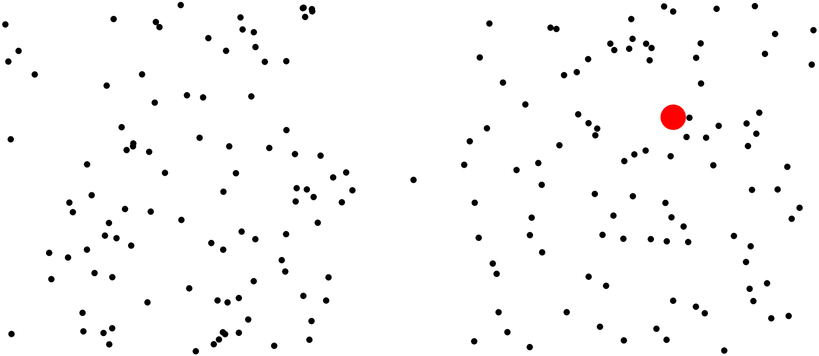


Simulation Results: Specific Topology



- Scenario difficult for static heuristics

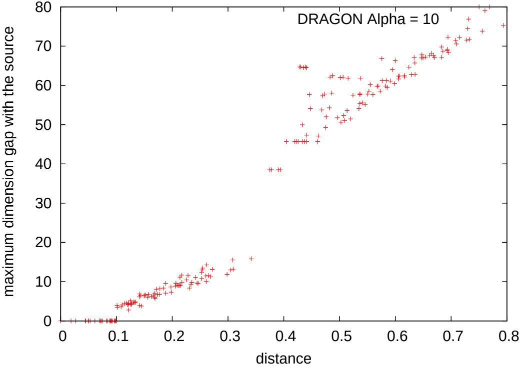
Simulation Results: Specific Topology



- Scenario difficult for static heuristics (ex: IRMS)
- DRAGON four times as efficient as IRMS

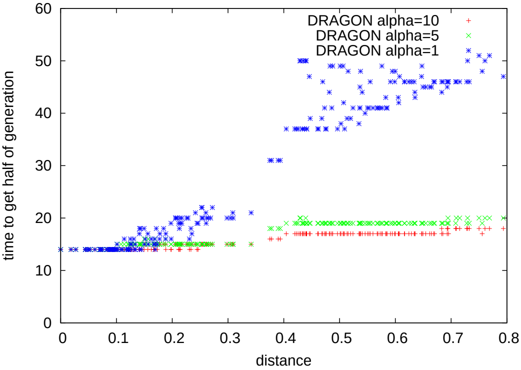
Simulation Results: Specific Topology

- Consider the distance to the source, and the rank of one node
- Illustrate the behavior



Simulation Results: Specific Topology

- Consider the delay to get half of the source packets (rank)
- Illustrate the impact of α



Conclusion and Future Work

Summary

- Proposed a new approach for energy-efficient broadcast: DRAGON
- Heuristic performing dynamic adaptation
- Hints and simulations results for its good behavior

Open Issues

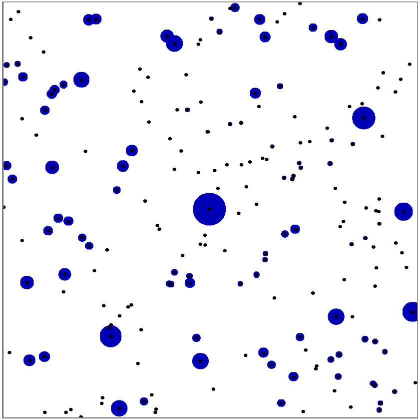
- What about interferences and capacity?
- Better control?
- Performance proofs in some scenarios?

Thank you for your attention

Optimal Solution with NC

Sample solution

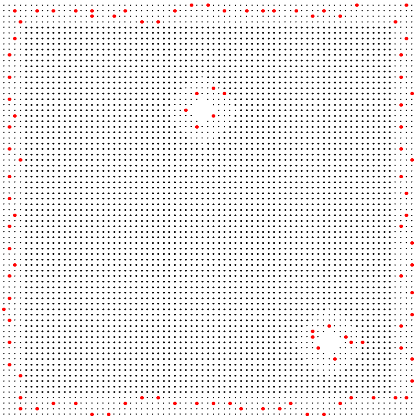
- Linear Program:
  - $\approx N^2 M$ variables (here sparse matrix with 3710156 coefs)
- Solution for the rate
  - Source rate $= 1$
  - Total rate $= 9.0625$



NC vs Routing: Scenario

Sample Rate Selection

- S. Y. Cho, C.A., *"Wireless Broadcast with Network Coding: A Connected Dominating Sets Approach"*, INRIA RR-6547, June 2008
- On this example: Outperforms any solution using routing



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