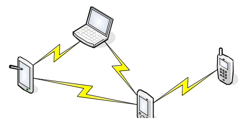
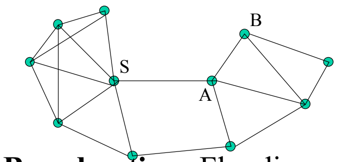
Broadcasting and dominating sets in ad hoc and sensor networks

Tutorial



Ivan Stojmenovic

Multi-hop wireless networks



Unit graphs
radius

Broadcasting = Flooding =

sending message from one node S to all other nodes

Blind flooding = message retransmitted once by each node

Power efficiency ? Retransmission by A and B suffices

Broadcasting - applications

- Alarm signal
- Route discovery in non-GPS routing
- Paging
- Destination search in GPS routing:
  - Source S *broadcasts* short message that will search for destination D
  - Destination D will *route* back to S with a short message location report
  - S will *route* full message to D
- Location updates for routing, geocasting, …

Criteria for broadcasting protocols

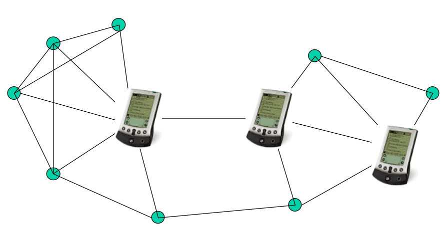
- *Counting retransmissions* or *minimum total energy* ?
- Centralized vs. **localized** decisions ?
- **Average** or worst case performance analysis ?
- **Localized maintenance** or chain effect ?
- **Deterministic** or stochastic decisions ?
- Guaranteed delivery **yes= reliable** (if MAC ideal) or no ?
- Set of transmitting nodes depends on source?
  yes / **no** (stable sets allow scheduling active periods)

# of messages between neighbors ? **Few** ? O(degree) ? More?

Assumptions about local knowledge:

1-hop neighbors, 1-hop neighbors + degree of neighbors, location of 1-hop neighbors, 2-hop neighbors

Connected dominating sets



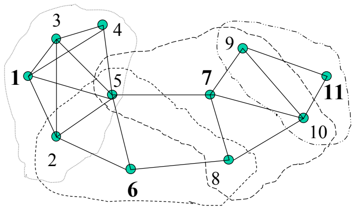
Each node either in *dominating set* or has a neighbor from dominating set

Flooding reduced if only nodes in ***connected dominating set*** nodes retransmit

Dominating set = transmitting nodes

- Broadcasting by retransmitting from nodes in a *connected dominating set*
- Each node receives the message if retransmissions are collision-free
- Finding (connected) dominating sets of minimal size is NP-complete problem (centralized)
- Find connected dominating set of small size locally
- Deterministic broadcasting (counting retransmissions): *Clustering, covering, forwarding neighbors*

Broadcasting via clustering one-to-all



Lauer 1988

Pagani, Rosi 1999

Lowest ID clustering

Lin, Gerla 1997

Clusterheads: 1,6,7,11

Borders: 2,5,8,9,10

Maintenance overhead

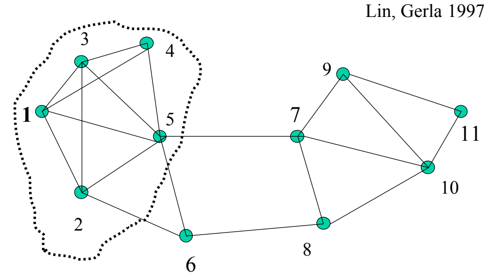
Broadcasting:

clusterheads and borders retransmit:

9 out of 11 nodes (one-to-all)

Lowest ID clustering – first cluster

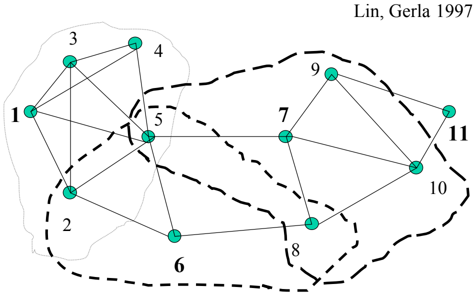
Lin, Gerla 1997



Clusterhead = lowest ID among undecided neighbors next?

Lowest ID clustering – second and third clusters

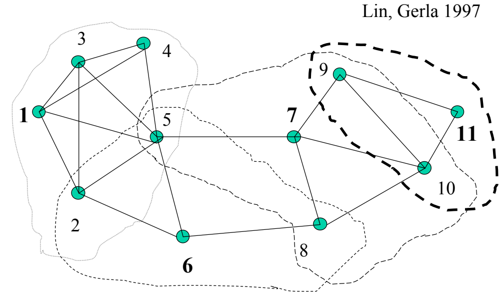
Lin, Gerla 1997



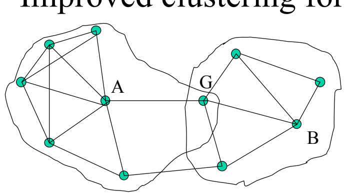
next ?

Lowest ID clustering – fourth cluster

Lin, Gerla 1997



Improved clustering for broadcasting



ConID=(*degree, id*) Clusterheads=

higher *degree* nodes, lower *id* if degrees same

Clusterheads: A, B; border: G - Retransmission by 3 out of 11 nodes

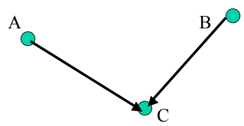
Garcia, Solano, Stojmenovic 2003

Chain effect with clustering

- Mobility or change in the activity status of a single node may trigger global update of cluster structure
- Localized algorithm but not localized maintenance
- ***Quazi-localized*** protocol
- Localized maintenance is preferred
- Localized clustering maintenance exists but the structure quality becomes low
- Set of border nodes in cluster structure can be reduced (with some overhead)

Broadcast storm problem

Ni, Tseng, Chen, Sheu MOBICOM 1999



Hidden terminal problem: collision at C

Blind flooding is unreliable at MAC layer, and has increased latency due to Redundancy, collision, contention

Probabilistic, counter, distance, location and cluster based broadcasting

Ni, Tseng, Chen, Sheu MOBICOM 1999

(delivery not guaranteed even for collision free broadcasting!)

Probabilistic: retransmit with fixed probability p

Counter-based: retransmit if <C copies received

Distance-based: retransmit if distance to each transmitting neighbor >D

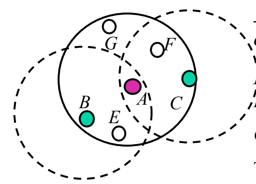
Location-based: retransmit if additional area ratio > A best (GPS advantage) but SRB low for RE>80%

Cluster based: reduce above methods to clusterheads and borders

Stochastic flooding broadcast

- Cartigny, Simplot and Carle 2002, 4 schemes:
- Probability *p* for retransmitting is inversely proportional to local density
- Distance between two nodes is evaluated by comparing their neighbor lists; *p* increases with the distance, in favor of nodes at the border of senders
- *p* depends on both local density and distance
- Plus *neighbor elimination* is applied: no retransmission if no neighbor exists that did not hear the same message already

Neighbor elimination



Wait and see whether someone else will do the job

Does A transmit after B and C?

B retransmits → *A* eliminates *E* and *B*

C retransmits → *A* eliminates *F* and *C*

Timeout at *A* expires

A retransmits because of *G*

August 2000: independently

Stojmenovic, Seddigh

Peng, Lu

Lim, Kim

Waiting time? e.g. proportional to 1/(# of uncovered neighbors)

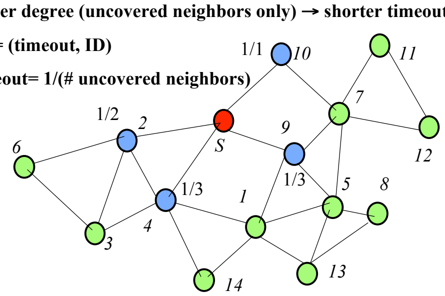
Dynamic timeout extension with more neighbors covered

Neighbor elimination - example

Higher degree (uncovered neighbors only) → shorter timeout

Key= (timeout, ID)

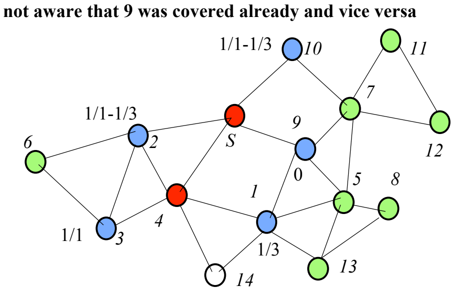
Timeout= 1/(# uncovered neighbors)



S*= source, timeouts after transmission of *S

Neighbor elimination - example

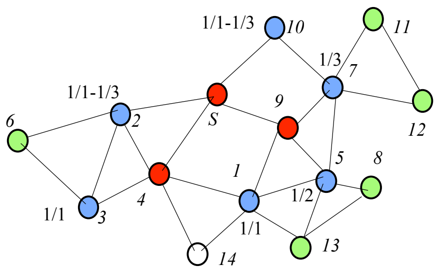
1 is not aware that 9 was covered already and vice versa



4*= first retransmission, timeouts after transmission by *4

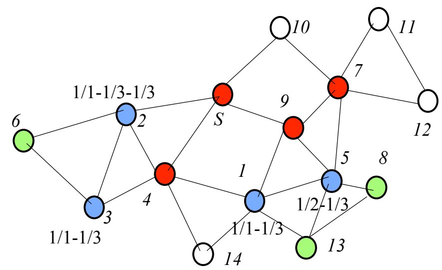
Neighbor elimination - example

Node 7 is not aware that 10 received the message



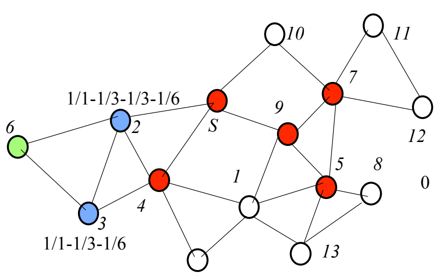
9*= second retransmission, timeouts after transmission by *9

Neighbor elimination - example



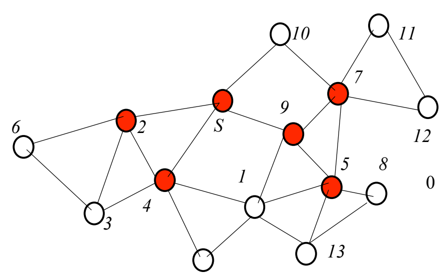
7*= third retransmission, timeouts after transmission by *7

Neighbor elimination - example



5 = fourth retransmissions, timeouts afterwards

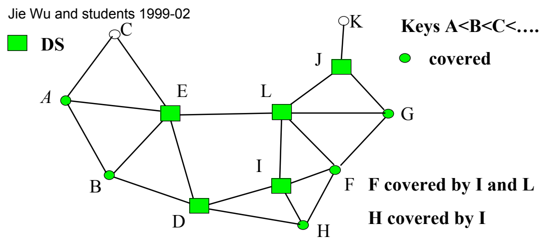
Neighbor elimination - example



***2*= the last retransmission**

Dominating sets by *covering*

Jie Wu and students 1999-02

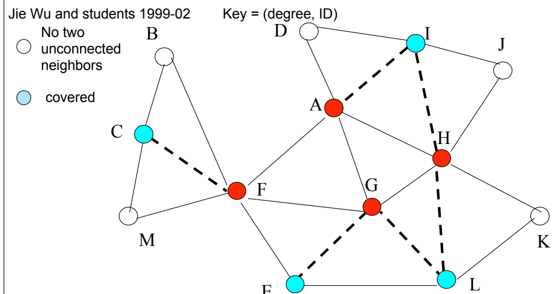


○ **Not intermediate** (no two unconnected neighbors)

F covered by I, L, … ← I, L, … connected and any neighbor of F is neighbor of one of I, L,.. and key(F) < min (key(I), key(L),…)

Dominating sets by *covering*

Jie Wu and students 1999-02 Key = (degree, ID)

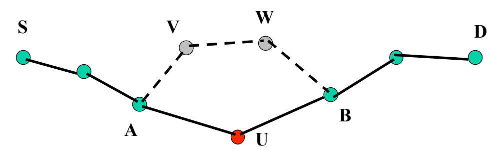


I covered by A, H, … ← A, H,.. connected and any neighbor of I is neighbor of one of A, H,.. and key(I) < min (key(A), key(H),…)

Generalized covering rule

- Dai and Wu 2002
- Covering **A** by few *connected* neighbors
- Construct subgraph G of higher ***key*** neighbors
- If G empty or disconnected then ***A*** in DS
- If G connected but exists neighbor of ***A*** which is not neighbor of any node from G then ***A*** in DS
- Otherwise A is covered and not in DS
- Dijkstra's shortest path to test connectivity
- No message exchange to decide DS status !!
- Localized maintenance

DS by covering is connected



S was connected to D: S → … → A → U → B → … → D

U covered by V, W, … and is not in DS

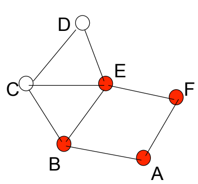
A connected to one of V, W,… B connected to one of V, W, ..

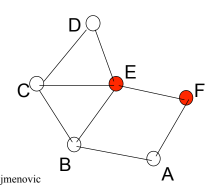
⇒ A → U → B replaced by A → V → W → B

⇒ S and D remain connected

Enhanced Dominating sets

- Wu and Dai 2003; Ingelrest, Simplot-Ryl, Stojmenovic, 2005
- 2-hop neighbors may be used to cover 1-hop neighbors
- Overhead reduction: 15% topological 30% positional info
- Generalized rule: Enhanced rule:



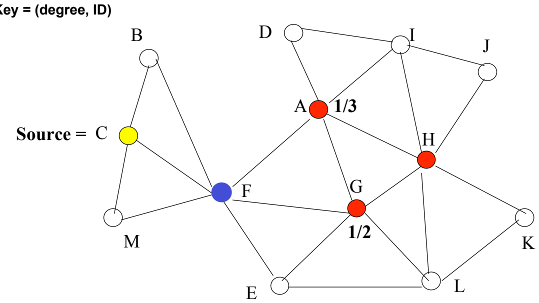


Broadcasting by covering DS

- Stojmenovic, Seddigh, Zunic, August 2000, IEEE Trans. Parallel Distr. Syst. January 2002,
  Fast breaking paper in computer science for October 2003 (Thomson ISI – citations early 2003)
- Nodes not in DS do not retransmit message
- Nodes in DS:
  when first copy received, set timeout,
  when any copy received, *eliminate neighbors* receiving same copy
  timeout expired →retransmit if any neighbor left
- Key = (# of neighbors, ID)
- RANA (Retransmit After Negative Acknowledgement)

Broadcasting by *covering DS and NE*

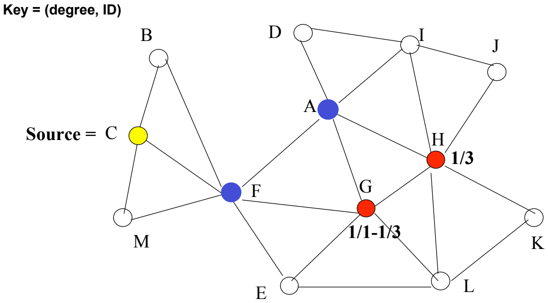
Key = (degree, ID)



First retransmission =F, timeouts at A and G

Broadcasting by *covering DS and NE*

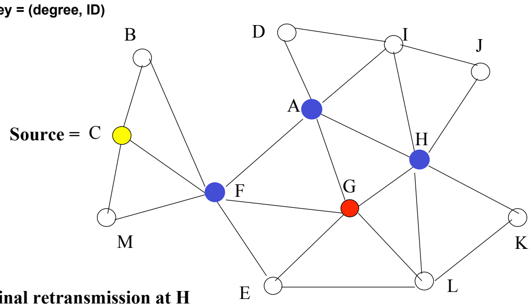
Key = (degree, ID)



Second retransmission =A, timeouts at H and G

Broadcasting by *covering DS and NE*

Key = (degree, ID)

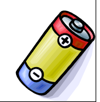


Final retransmission at H

G does not transmit

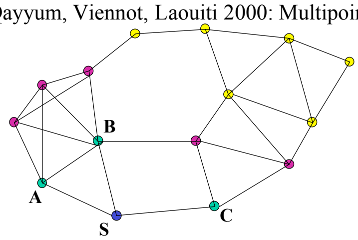
Power-aware connected DS

- Wu, Dai, Gao, Stojmenovic, Wu 2001-3
- *Key=(energy, degree, x, y, id)*
- Nodes with more energy are preferred in dominating set, which may change in time
- Routes through nodes in DS only
- Broadcasting by nodes in dominating set
- Nodes in dominating set are active = *scheduling node activity*



Broadcasting by forwarding neighbors

Qayyum, Viennot, Laouiti 2000: Multipoint relaying MPR



Lim & Kim 2000

Calinescu, Mandoiu, Wan, Zelikovsky 2001

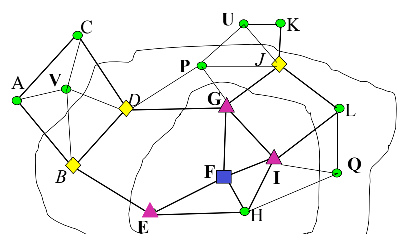
Sun & Lai 2001

S: source or relay of retransmitting node

Find minimal set of 1-hop ● neighbors that *covers* all 2-hop ● neighbors of **S**: **B** and **C** (relays of S)

Heuristics: B: 4●, A: 2●, C:2●, choose *B*; A:0●, C: 1●, choose *C*

Forwarding neighbors



G, I, E* for node *F, D* and *J* for *G,* and *B* for *E

Induced DS is source dependent ⇒ not for activity scheduling

Area Based Beaconless Reliable Broadcasting in Sensor Networks

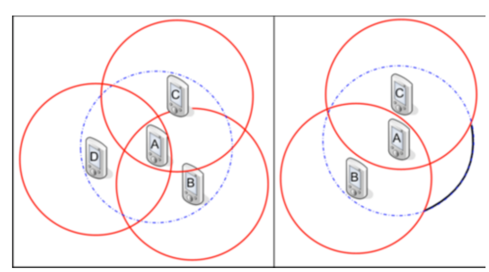
Ovalle-Martínez, Nayak, Stojmenović, Carle, Simplot-Ryl 2006

Heissenbuttel, Braun, Wälchli, Bernoulli INFOCOM 2006 - independently similar protocol 2D only

- Each sensor know its own **geographic position** but has no knowledge of existing neighbors: ***beaconless***
- Algorithm should be **localized**
- **Reliable** = *guaranteed delivery if MAC layer is ideal*
- **Average** case performance

ABBA: main idea

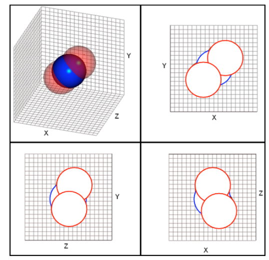
no retransmission iff circle (perimeter suffices) covered by previous retransmissions



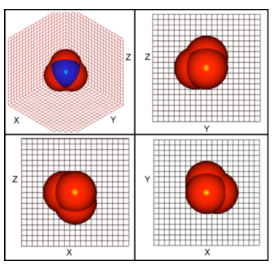
2D ABBA protocol

- After receiving the first copy of message, node decides about waiting period and evaluates coming transmissions
- At end of timeout, if its circle is not fully covered, it retransmits. Otherwise it remains silent.
- Timeout can de decided in different ways: at random, or based on portion of covered perimeter etc.

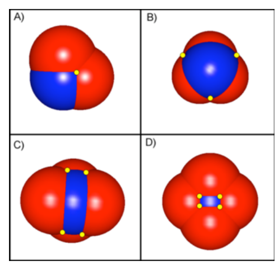
3D-ABBA-1: coverage in three projections



3D-ABBA-1: blue node covered in all three projections, but not in space



3D-ABBA-3: Covering intersection points of 3 spheres

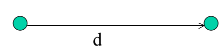


Theorem: if all intersection points with two other spheres covered then sphere covered

- Proof: by contradiction.
- Assume not covered. Then portion of sphere not covered, let Y be point there. 'Walk' from Y around sphere until heating a covered edge from a circle. 'Walk' along that edge until heating another such edge. This point of intersection of three spheres is not covered by any sphere, a contradiction.

Minimal energy broadcasting

- power =u(d)= $ad^{\alpha} + c$, $2 \leq \alpha$



- Choose transmission radius at each node so that network is connected and sum of transmission powers is minimized
- Topology control (source independent undirectional)
- Broadcast oriented (source dependent directional)
- Globalized solutions in two dozens of articles
  Wieselthier, Nguyen and Ephremides 2000 (BIP)
- First localized solution:
  Cartigny, Simplot, Stojmenovic INFOCOM 2003

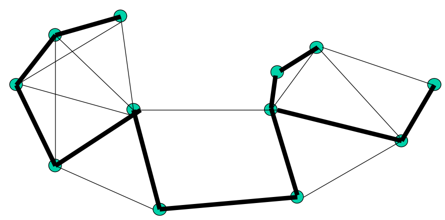
Broadcast Incremental Power

- BIP Wieselthier, Nguyen and Ephremides 2000
- Add one node at a time so that the additional power is minimized
- Options: add new transmission, or increase transmission radius of existing transmitting node
- BIP and other proposed methods in practice behave like MST since $2 \leq \alpha$ in $d^{\alpha} + c$, unless c is significant with respect to density
- centralized algorithm: significant overhead to collect information, making energy saving claims invalid

LBIP: Localized BIP

- Ingelrest and Simplot-Ryl, Wireless Networks, 2006.
- Each node maintains two-hop neighbors info
- BIP protocol is followed as is, where each node makes decisions based on local knowledge available
- Performance very close to BIP
- Overhead: collect 2-hop knowledge, forwarding neighbors in packet

Cover neighbors in connected structure

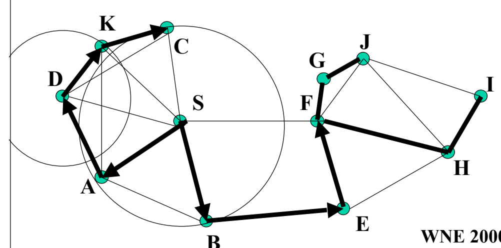


MST= minimal spanning tree, global information, overhead ??

Average degree 1.99 (n-1 edges for n nodes)

Choose transmission radius to cover remaining neighbors + **neighbor elimination** (some nodes may not transmit at all)

Cover neighbors in connected structure



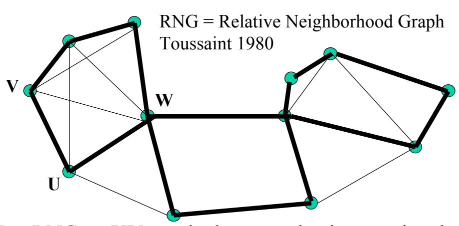
WNE 2000

S→A,B,C; A→D; B→E; D→K; K→C; E→F; F→ H,G,J; H →I; G does not transmit (neighbor elimination **F→ J**)

Broadcast oriented MST based; **best for reasonable density**

Localized structures: RNG

RNG = Relative Neighborhood Graph
Toussaint 1980

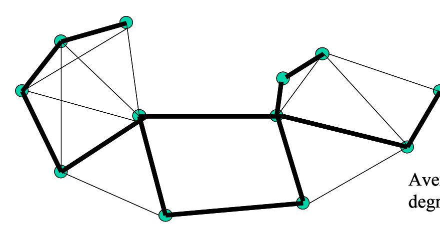


UV ∈ RNG → UV not the longest edge in any triangle UVW

Average degree ≈2.5 RNG vs MST : ≈ twice more energy, but MST spends also energy on communication overhead

RNG based broadcasting: Cartigny, Simplot, Stojmenovic 2003

Localized structure: LMST



Average degree 2.04

LMST= Localized Minimal Spanning Tree: Li, Hou, Sha 2003

Each node constructs MST of subgraph of its neighbors; keep edge if both endpoints have it in their MSTs

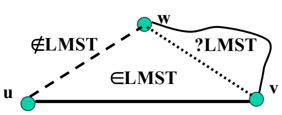
MST ⊆ LMST ⊆ RNG LMST ≈50% more energy than MST

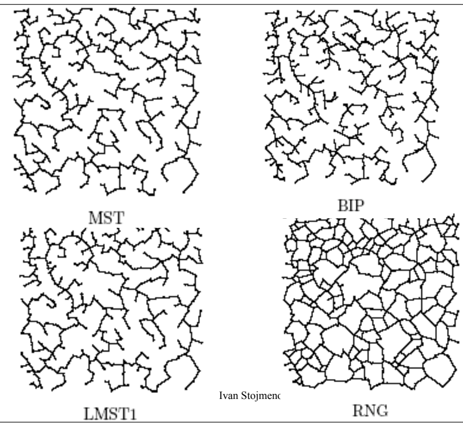
LMST ⊆ RNG

Suppose $uv \in LMST$ but $uv \notin RNG$.

$\exists$ w, $uw < uv$, $vw < uv$ (unique edge lengths)

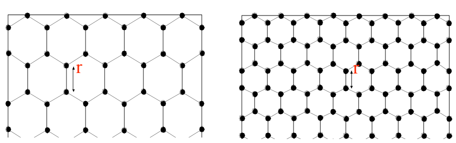
uv can be replaced by uw in $MST(n(u))$, giving a spanning tree with lower overall weight (total sum of all edge lengths) than the minimal one ($MST(n(u))$), which is a contradiction.





Target Radius: TR-LBOP

- Ingelrest, Simplot, Stojmenovic 2004
- For large c in $r^{\alpha} + c$ many transmissions over short edges are expensive due to multiples of c
- Large radius is also power expensive
- Consider energy consumption in honeycomb mesh with variable edge length over fixed area



TR-LBOP

$PC(r) = r^{\alpha} + c$

- There exists target radius for broadcasting $r^2 = 2c/(\alpha - 2)$
- The energy overhead of TR-LBOP over BIP remains below 50% for all densities
  - Each node manages two lists of neighbors, L and L'
    - →L contains LMST-neighbors
    - →L' contains the rest of the neighborhood (***new***)
  - At the end of the NES
    - →If L is empty, the retransmission is canceled
    - →Otherwise, the radius is chosen long enough to reach:
      - The furthest neighbor in L
      - The neighbor in L' that is the nearest one to the target radius (***new***)

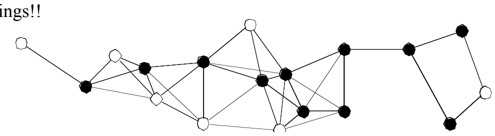
A Dominating Sets and Target Radius Based Localized Activity Scheduling and Minimum Energy Broadcast Protocol

- Ingelrest, Simplot, Stojmenovic 2004
- Construct subgraph where each node considers only neighbors whose distance is no greater than the *target radius* and neighbors in *RNG* or *LMST*.
- A connected dominating set (CDS) is constructed using this subgraph.
- Next, nodes not selected for CDS are sent to sleep mode (they periodically wake up for sending and receiving messages from associated closest dominating set nodes).
- Nodes in selected CDS remain active and apply TR-LBOP

Example

- Each node chooses a radius that covers its LMST-neighbors and the target radius
- The generalized covering rule for CDS is applied
- Each passive node is attached to its nearest dominant neighbor

Performance similar to TR-LBOP in energy need for broadcasting, plus many nodes are placed to sleep mode for additional energy savings!!



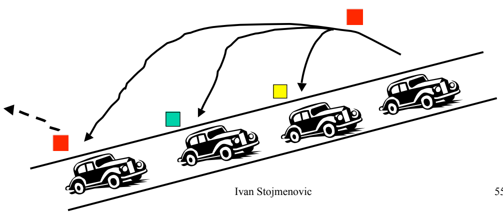
Inter-vehicle communication

Sun, Feng, Lai, Yamada, Okada 2000

-Learn neighboring cars on the same highway and direction

-include ID of furthest neighbor in the transmitted message

-furthest neighbor retransmits



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Inter-vehicle communication with GPS

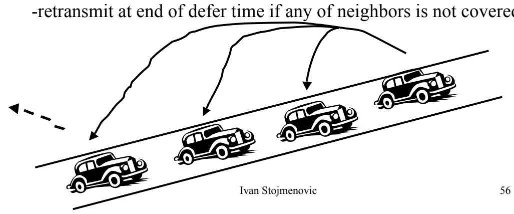
Sun, Feng, Lai, Yamada, Okada 2000

-Include LOCATION with the message

-defer time inversely proportional to distance from vehicle

- discard neighbors covered by any of transmissions

-retransmit at end of defer time if any of neighbors is not covered



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Parameterless Broadcasting from Static to Mobile networks (PBSM)

Khan, Stojmenovic, Zaguia 2008

Features

- Has two versions: 1-hop positional, 2-hop topological.
- Dominating sets is calculated after each periodic hello message.
- Each node knows only about its 1- or 2-hop neighbors (local knowledge).
- Each node maintains a **N** list (neighbors who didn't receive message) and **R** list (nodes which received message).
- Seamless transition of behavior from static to mobile without using threshold parameter.

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Proposed Broadcasting method (PBSM)

Description

When a node, x, receives message from y:

- $R_x = R_x + y + \text{Neighbor}(y)$
- $N_x = \text{Neighbor}(x) - R_x$

If a node receives message, it starts or adjusts timeout. (Timeout ≈ 1/ |N|).

Non-DS nodes set up longer timeout so that DS nodes can transmit first.

If timeout expires and N is non-empty, then node broadcasts (NES).

When a node discovers new neighbor(s) after hello msg, it updates R and N.

- If N becomes nonempty, timeout restarts.
- If timeout expires with N non-empty then retransmit (possibly again).

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Example showing operation of PBSM

N | R | N
B | S,F, **M**, **A**, **G**, **E**, D, **I** |
F | A,S,B, M, G, E ,**D**,**I**,**H**
A | F,**S**,**B**, **M**, G, **E**, D,I,H, **J**,**K**,**L**
H | A, **F**, G, **D**,I, J,K,L
D | A,I,**H**, **G**, **F**, B |
I | A,D,H,**G**,**F**, J,**K**,**L**,**B** |
G | F,**S**,**B**,**M**,A,E,**D**,H,**I**, L,**J**,**K**