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Scalability Problems and Clustering

- What happens to protocols when the number of network nodes grows?
  - Especially crucial in WSNs
- A traditional networking solution: Hierarchical organization of the nodes
- Network nodes are grouped into clusters
- Some nodes, locally the "best," are selected to coordinate the clustering process: Clusterheads

How to Select the Best Nodes

- Independence of the clusterheads
- Dominance of the clusterheads
- Possibility to express "preferences"
- Distributed operations
- Fast and simple implementation

Previous Approaches

- Heuristics based on Independent Sets
  - Minimum ID approach (Gerla & al.)
  - Maximum degree (Ephremides & al.)
- Heuristics based on Dominating Sets
  - The concept of "spine"
  - Minimum connected dominating set

Maximum Independent Set (MIS)

- A subset V’ of the vertices V of a graph G=(V,E) is independent when for each u,v $\in$ V’ the edge {u,v} $\notin$ E
- MIS is an Optimization Problem
- Input: A Graph G=(V,E) with n vertices
- Output: A subset V’ of V that is independent and has maximum size

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MIS: Hardness

- No known algorithm computer a MIS in polynomial time
- Need for approximate solutions
- And approximation algorithm is an algorithm that produces a solution that is not optimal, but that approximates it
- We sacrifice optimality in favor of a "good" solution that can be computed efficiently

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MIS is HARD to Approximate

- Bad news
  - Not only MIS is computationally hard
  - It is also hard to approximate:
    - ✓ Approximate solutions are not so good
    - ✓ They are "unboundedly" far from the optimum
- We consider the simple greedy heuristic for the MIS

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Greedy Heuristic for MIS, 1

- Select the vertex with minimum degree and put it in the MIS
  - The degree of a vertex is the number of its neighbors
    - ✓ Cardinality of its adjacency list
  - Keep going till all the vertices are either in the MIS or COVERED by a vertices in the MIS

Greedy Heuristic for MIS, 2

```
MIS(V,E,d) // d is the vector of degrees
  mis = Ø
  while V ≠ Ø do
    v = vertex with min degree
    mis = mis U {v}
    V = V – {{v} U  N(v)}
  return mis
```

On MDS—what if we look at UDG graphs?

- Bad news: Still computationally hard
- Better news: Minimum DS It is approximable “up to a constant”
  - It means that the ratio between the size of a DS computed by MIS greedy on UDGs and the size of a MDS is < c, c a constant
- This constant is 5

Greedy MIS: Maximal Solution

- The greedy solution provides a maximal independent set
  - An independent set is maximal when, if you add a vertex, the set is no longer independent
    - ✓ You cannot make an maximal independent set bigger
- This solution is also a minimal dominating set
  - A dominating set D subset of V is a set such that a vertex v ∊ V is either in D or it has a neighbor in D
- Solutions we will see are variant of this approach

Greedy MIS for MDS on UDG is 5-approximable, 1

- Key fact: In a UDG disk (radius 1) there are at most 5 independent nodes
- Consider an Optimal solution and a Greedy solution
- Since Opt is dominant, it dominates Greedy
- Assign every vertex of Greedy to one dominator in Opt (choose one if more)

Greedy MIS for MDS on UDG is 5-approximable, 2

- For each u in Opt consider its assigned vertices $v_1(u)$, $v_2(u)$, …, $v_k(u)$ of Greedy
- How big is k?
- Well, all $v_i(u)$ must be distant 1 from u and they also have to be independent
- Greedy: at most 5 times bigger than Opt

- UDGs model ad hoc networks
- IS and DS are useful for clustering ad hoc networks
  - Gives the network a hierarchical organization
  - Decreases the amount of information at each node
  - Enhances scalability
  - Helps in “resource assignment”

Advantages of hierarchical organization

- routing always through the clusterhead
- data aggregation at the clusterhead
- easy to locally synchronize nodes within the cluster, using TDMA MAC protocol for intra-cluster communication and different MAC protocols (e.g. CDMA) for inter-cluster communications

MWIS-Based Clustering

- MWIS = Maximal Weight Independent Set
- Clustering selection based on generic **weights** (real numbers > 0)
  - Mobility/node related parameters
  - Generalizes previous “Independent Set” solutions

Two Protocols

- Distributed Clustering Algorithm (DCA)
  - Quasi-mobile networks, periodical reclustering. Allow complexity analysis, fast and simple
- Distributed and Mobility-Adaptive Clustering (DMAC) Algorithm
  - Same rules/procedures for clustering set up and maintenance, adaptive to nodes mobility and node/link failures

DCA: Distributed Clustering Algorithm, 1

- Assumptions
  - Knowledge of IDs and weights of one-hop neighbors
  - Broadcast transmission of a packet in finite time (a "step")
  - Nodes do not move during clustering

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DCA, 2

- (Only) Two messages:
  - CH(v): Sent by a clusterhead v
  - JOIN(u,t): Sent by ordinary node u when it joins the cluster of clusterhead t
- Three (simple) procedures:
  - Init (start up)
  - OnReceivingCH(v), OnReceivingJOIN(u,v) (message triggered)

DCA

- Ogni nodo conosce i suoi vicini ed il loro peso
- Un nodo è init se ha il peso più grande dei pesi dei suoi nodi vicini
- Gli init node diventano clusterhead e invitano i loro vicini a far parte del loro cluster
- Un nodo x aspetta di ricevere messaggi dai vicini di peso maggiore prima di prendere una decisione
  - Se un vicino di peso maggiore lo invita a far parte del suo cluster allora x entra a far parte del cluster del vicino di peso maggiore che lo contatta (inviando un messaggio di Join) → nodo ordinario
  - Altrimenti diventa clusterhead lui stesso e invia un messaggio di CH

- Due tipi di messaggi
  - CH(v) è usato da un nodo v per rendere consapevoli i suoi vicini del fatto che ha assunto il ruolo di clusterhead
  - JOIN(v,u) è usato dal nodo v per comunicare ai suoi vicini che sarà parte di un cluster il cui clusterhead è il nodo u

- Variabili
  - Cluster(v) indica l’insieme dei nodi che fanno parte del cluster di cui è clusterhead v
  - Clusterhead è una variabile che identifica il clusterhead del mio cluster
  - Ch(u) è vero quando o ha mandato un messaggio CH (u==v) oppure quando ha ricevuto un messaggio di CH dal nodo u
  - La variabile booleana Join (u,t) è vera se il nodo v ha ricevuto un JOIN(u,v) dal nodo u

DCA-Procedure (eseguite dal nodo v)

- Init

```
Se tutti i nodi vicini hanno un peso minore di v
    invia CH(v);
    Cluster(v)=Cluster(v)U{v};
    Ch(v)=true;
    Clusterhead=v;
```

DCA-Procedure (eseguite dal nodo v)

- On receiving CH(u)

  Ch(u)=true;

  Se u ha un peso maggiore di me e i vicini di peso maggiore di v con peso maggiore di u hanno tutti mandato un Join, allora

    Clusterhead=u;

    invia JOIN(v,Clusterhead);

DCA-Procedure (eseguite dal nodo v)

```
•   On receiving JOIN(u,t)
    Join(u,t)=true;
    Se v è un clusterhead allora se t==v
        {Cluster(v)=Cluster(v)U{u};
        Se ho ricevuto Join da tutti i vicini più                piccoli EXIT}
    Altrimenti se tutti i vicini di peso maggiore hanno preso una decisione sul ruolo.
        {e tutti i vicini di peso maggiore hanno mandato JOIN
                {mandiamo un CH(v);
                Cluster(v)=Cluster(v)U{v};
                Clusterhead =v;
                Se si è ricevuto JOIN da tutti i vicini minori EXIT.}
        Altrimenti se uno o più vicini di peso maggiore hanno mandato un CH
                {Clusterhead=il vicino con peso più grande tra quelli che sono
            diventati clusterhead e mi hanno invitato.
                manda JOIN(v,Clusterhead);
                EXIT;}
            }
  }
```

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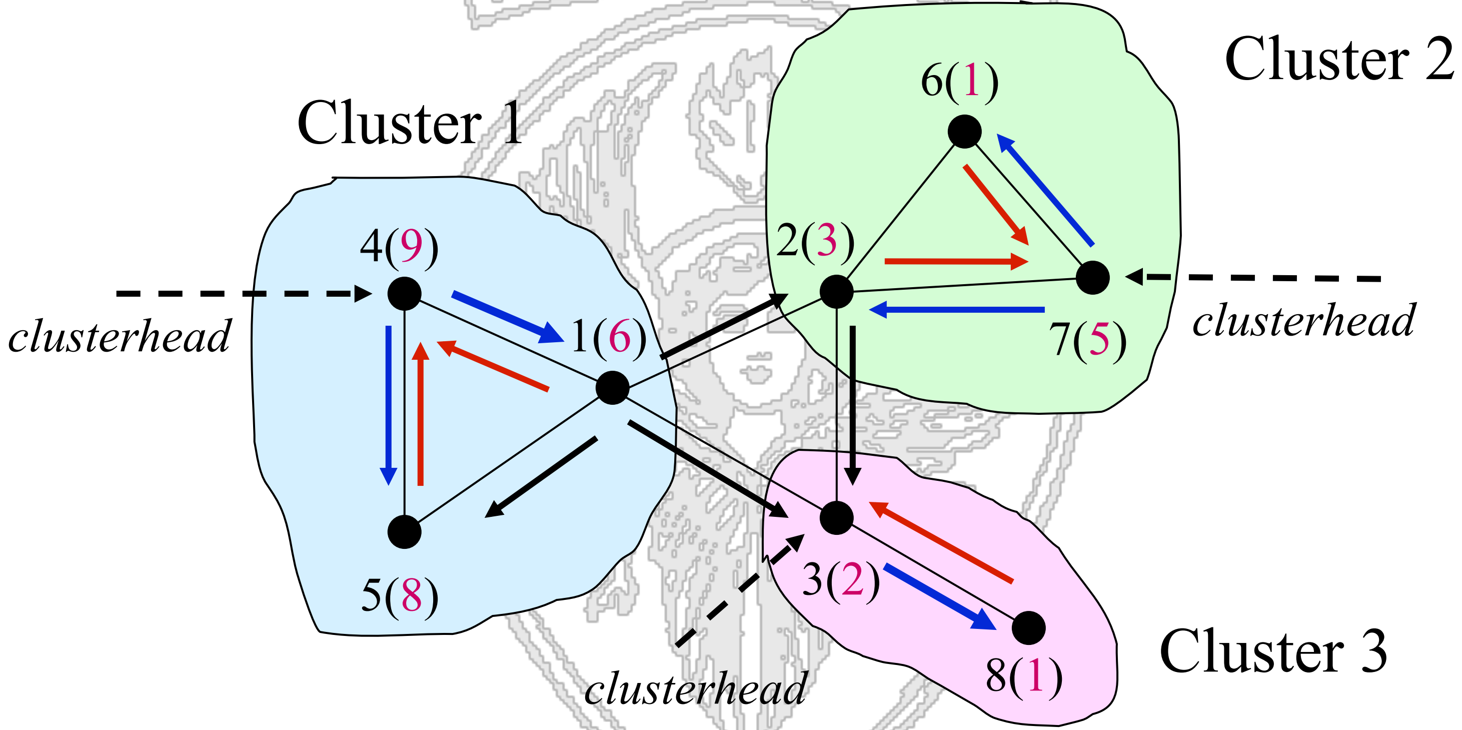
Example



I Step II Step III Step IV Step V Step

DCA: Provable Properties

- Consider

$$\tau: V \rightarrow \{1,2,3, \ldots , 2k\}$$

V = set of network nodes, k = number of clusters

- **Proposition**: Each node v in V sends exactly one message by $\tau(v)$ steps
- **Corollary 1**: DCA message complexity is $n = |V|$
- **Corollary 2**: DCA terminates correctly in at most 2k steps ($<= 2n$)

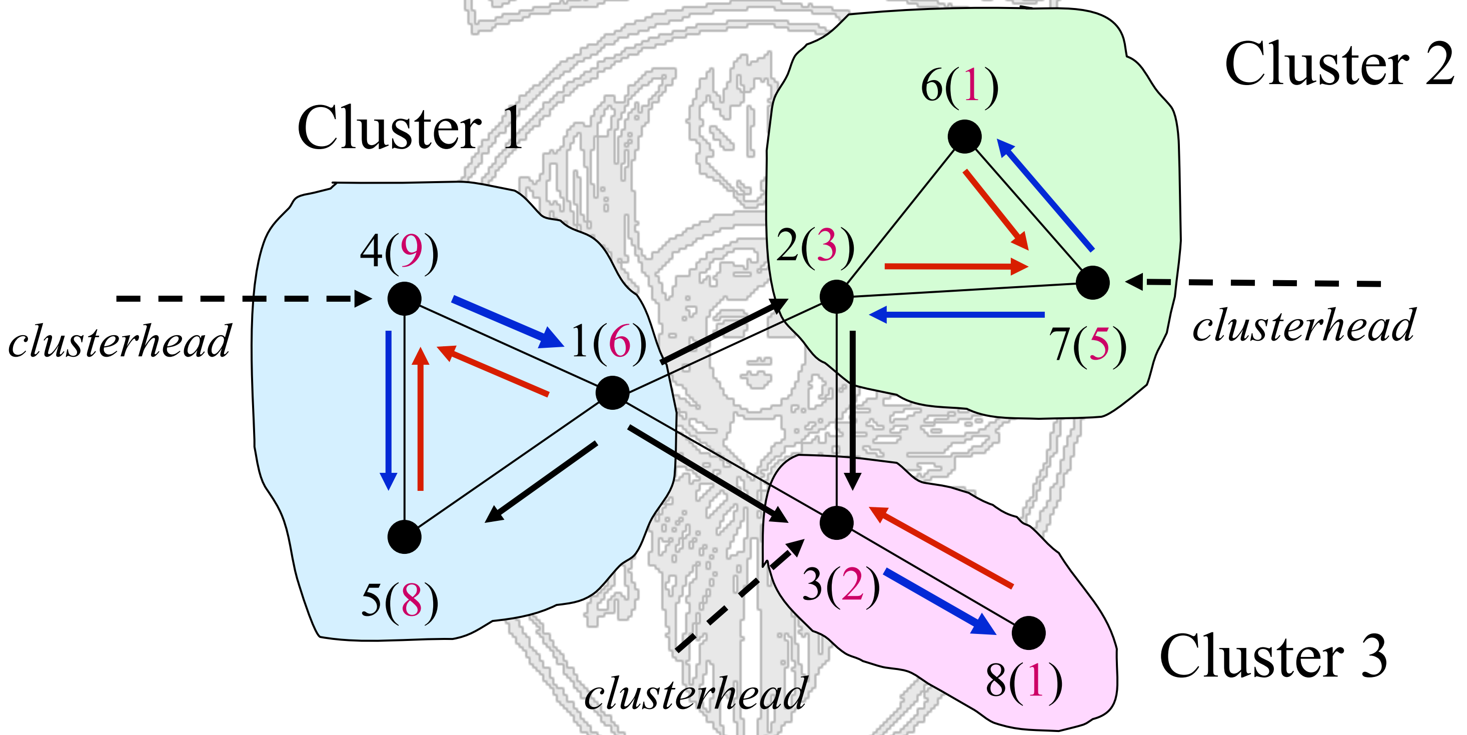
Joining Clusterheads: Dynamic Backbone

- A theorem from Chlamtac and Farago:

  If a network is connected, and DCA is used, then if and only if each clusterhead is linked to all the clusterheads at most three hops away, the resulting backbone network is guaranteed to be connected

PROVATE A DIMOSTRARLO

Example



I Step II Step III Step IV Step V Step

4 Backbone Formation Protocols

- 3 representatives of major approaches
  - Selection of independent set of nodes and backbone construction (DCA)
  - Rich dominating set formation and pruning (WuLi)
  - Two-phase algorithm with theoretical guarantees (WAF)
- 1 proposal after the performance comparison (DCA-S)

Distributed Clustering Algorithm (DCA)

- Distributed and localized implementation of the greedy for independent set
- Takes node status into account for node selection
- Independent nodes are joined into a connected backbone (connectivity is guaranteed) via gateways
- Low degree of parallelism (“dependency chains”)

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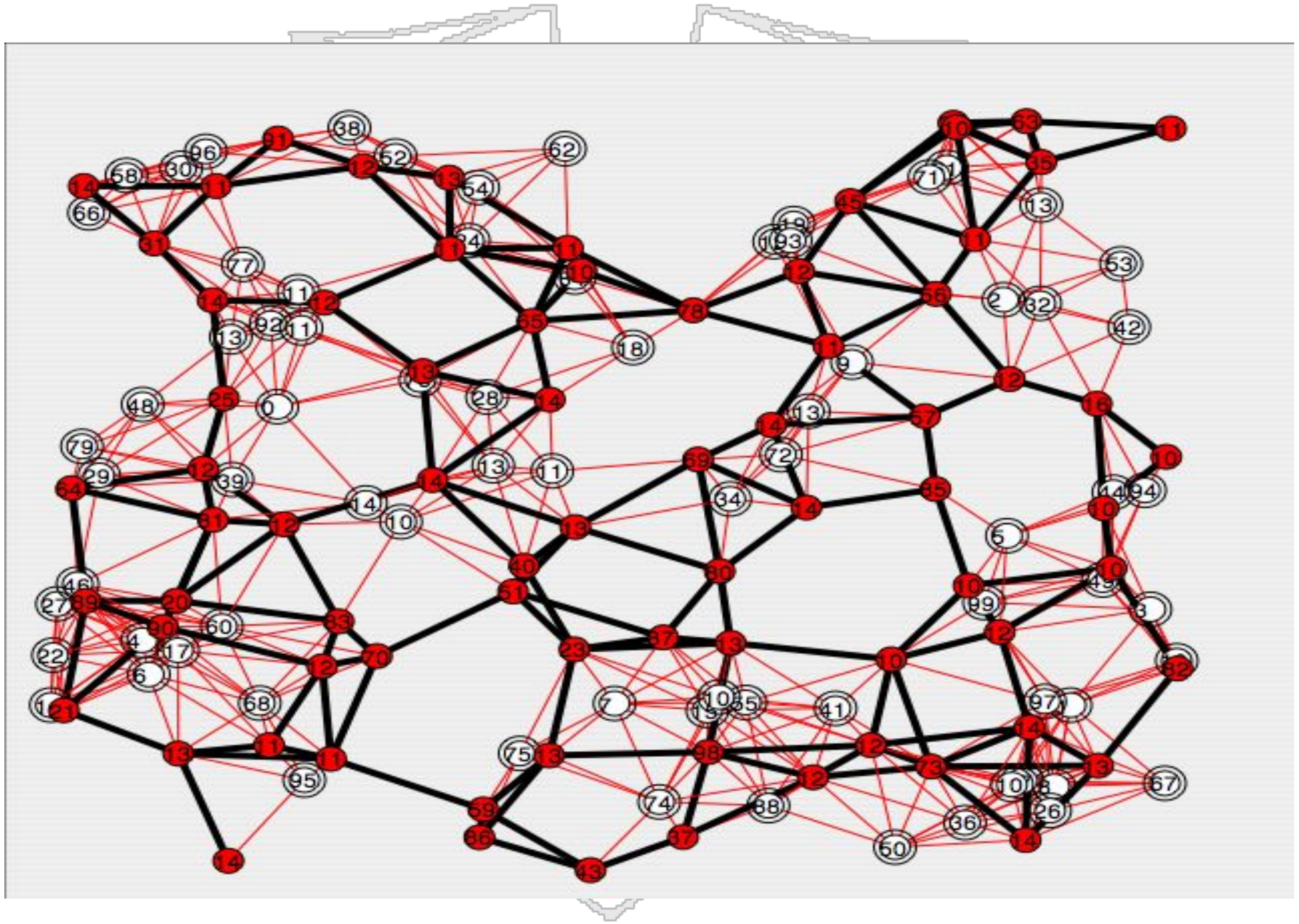
A DCA Backbone



WuLi: Wu and Li protocol

- Distributed and localized protocols for forming a connected dominating set
- Build a rich connected dominating set
- Applies localized rules for pruning unnecessary nodes/ links
- High degree of parallelism ("all localized")

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WuLi: Wu and Li protocol

- Distributed and localized protocols for forming a connected dominating set
- Build a rich
- Applies localized rules for pruning unnecessary nodes/ links
- High degree of parallelism ("all localized")

If a vertex v has two neighbors which are not in visibility range it enters the set C

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WuLi: Wu and Li protocol

- Distributed and localized protocols for forming a connected dominating set
- Build a rich connected dominating set
- Applies localized rules for pruning unnecessary nodes/ links
- High degree of parallelism ("all localized")

What is needed is, from the neighbors, whether they are in C and their list of neighbors.

WuLi-dominance property

da 'On Calculating Connected Dominating Set for Efficient Routing in Ad Hoc Wireless Networks', Wu and Li

Assume V' is the set of vertices that are marked T in V, i.e., the set of vertices which initially enter the CDS since they have at least two neighbors which are not neighbors of each other. The reduced graph G' is the subgraph of G induced by V'. The following two theorems show that G is a dominating set of G and it is connected.

- THEOREM 1: Given a G = (V, E) that is connected, but not completely connected, the vertex subset V', derived from the marking process, forms a dominating set of G.
- PROOF: Randomly select a vertex v in G. We show that v is either in V' (a set of vertices in V that are marked T) or adjacent to a vertex in V' . Assume v is marked F, if there is at least one neighbor marked T, the theorem is proved. When all its neighbors are marked F, we consider the following two cases: (1) All the other vertices in G are neighbors of v. Based on the marking process and the fact that m(v)=F, all these neighbors must be pairwise connected, i.e., G is completely connected. This contradicts to the assumption that G is not completely connected. (2) There is at least one vertex u in G that is not adjacent to vertex v. Construct a shortest path, {v,vi,v2, ... u}, between vertices v and u. Such a path always exists since G is a connected graph. Note that v2 is u when v and u are 2-distance apart in G. Also, v and v2 are not directly connected; otherwise, {v, v2,. .. u} is a shorter path between v and u. Based on the marking process, vertex vi, with both v and v2 as its neighbors, must be marked T. Again this contradicts the assumption that v's neighbors are all marked F. CVD

WuLi (first step produces a CDS)

- THEOREM 2: The resulting DS C=G’ is a connected graph.
- PROOF: We prove this theorem by contradiction. Assume G’ is disconnected and v and u are two disconnected vertices in G’. Assume $dis_G(v,u) = k+1 > 1$ and{v,v1,v2,...,vk,u} is a shortest path between vertices v and u in G. Clearly, all v1,v2, ...vk are distinct and among them there is at least one vi such that m(vi) = F (otherwise, v and u are connected in G’). On the other hand, the two adjacent vertices of vi, vi-1 and vi+i, are not connected in G (otherwise, {v, ..vi, vi+1, ... vk,u} would be a shorter path). Therefore, m(vi) =T based on the marking process.

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- Distr
  conn
- Build
- Appl
  links
- High degree of parallelism ("all localized")

Rule 1: for each pair of nodes u and v in C
the one with the smallest ID, say v, can be removed
from C if v and all its neighbors are covered by u
Rule 2: Assume nodes u,v, and w are in C and
assume that v's ID is the smallest. If u and w are
neighors of v and are in each other transmission
range and if each neighbor of v is covered by u
and w, then v can be removed from C.

Mantengono la proprietà di connessione e di dominanza

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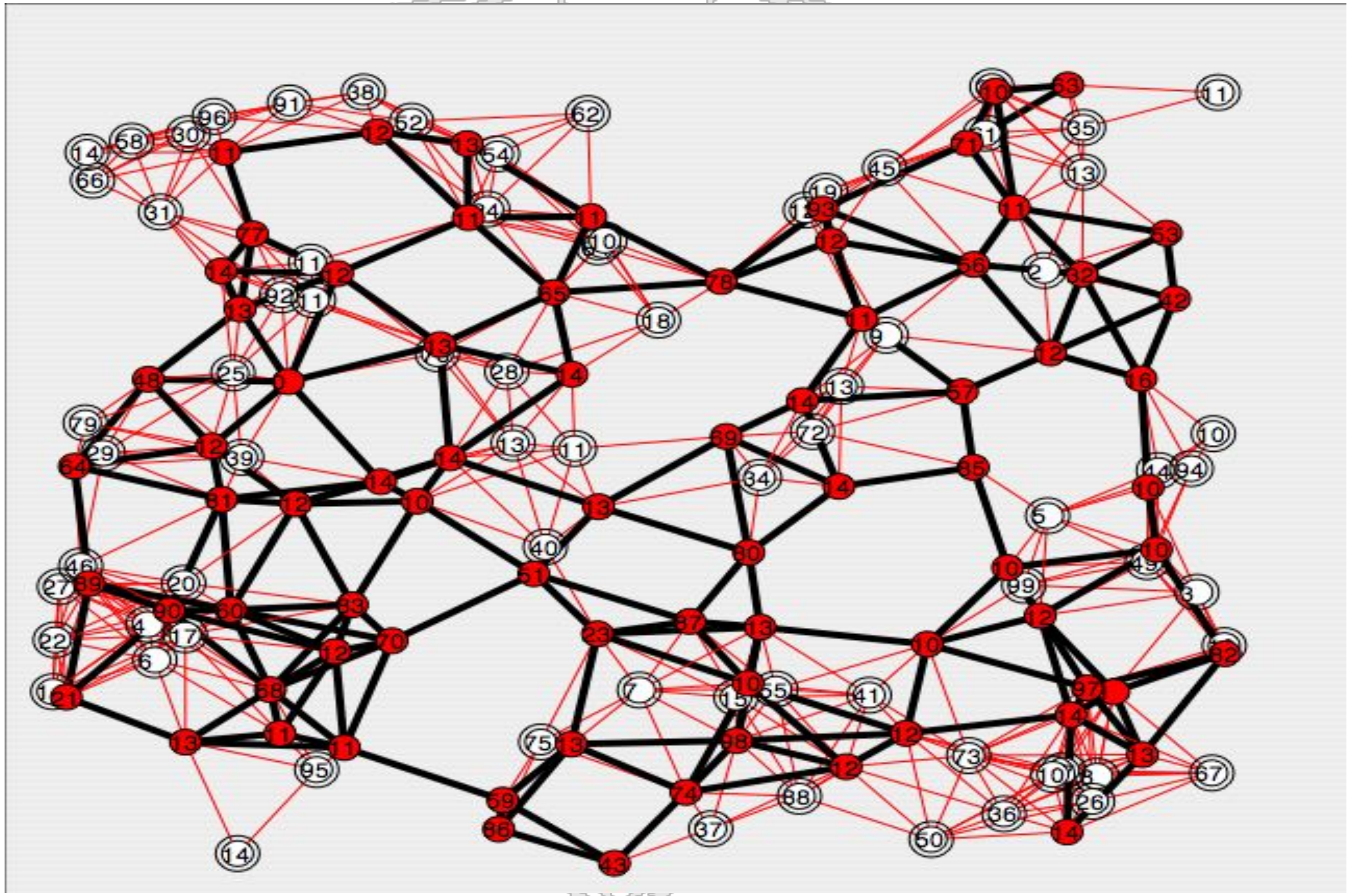
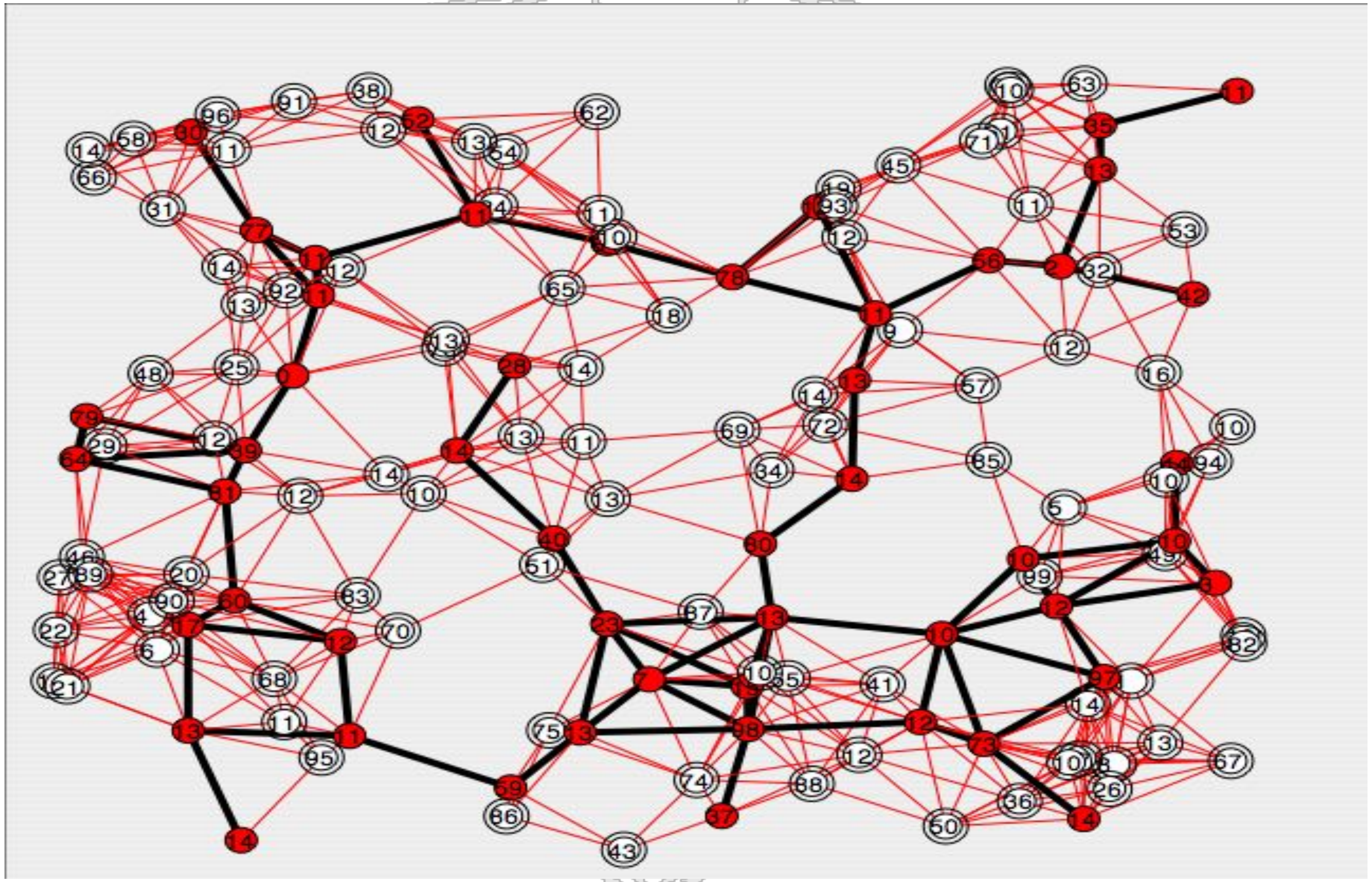
A WuLi Backbone



WAF: Wan, Alzoubi and Frieder

- Two phases
  - Leader election: One node is chosen among all network nodes to be the root of a tree
  - Nodes at different levels of the trees can be chosen to form a connected dominating set
- The “leader election tree” is quite expensive
- Very low degree of parallelism

A WAF Backbone



DCA-S: DCA Sparsified

- Build a connected dominating set (say, with DCA) and consider its spanned sub-graph H (include gateways)
- Erdös: If a graph does not have small cycles then it is sparse
- Find and break small cycles (small=log n)
  - In practice we search and break cycles with 3 and 4 links
- Breaking cycles does not compromise connectivity

Simulation Results

- Metrics (all averages)

1. Protocol duration
2. Operation overhead (in bytes)
3. Energy consumption (per node)
4. Backbone size
5. Route length
6. Backbone robustness (node deaths for disconnections)

Simulation Results, 2

- Parameters of ns2-based simulations
  - Nodes: ≤ 300, IST EYES prototype
    - ✓ Tx range: 30m
    - ✓ Initial (residual) energy: 1J
    - ✓ Tx, Rx, idle power: 24, 14.4, 0.015 (mW)
  - Area: 200 x 200m
  - Six scenarios with increasing densities (avg. degrees: 3.5 to 20)

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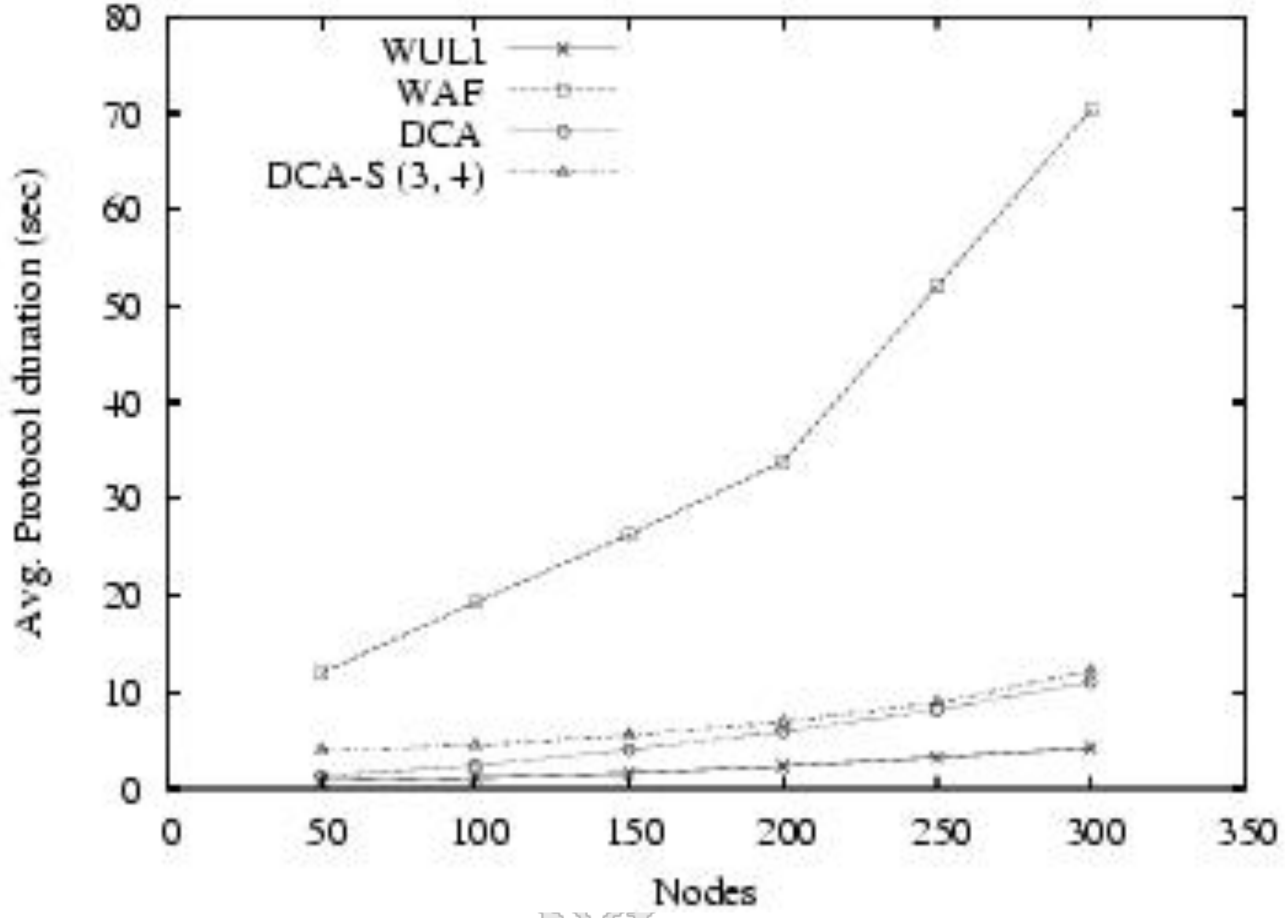
Protocol Duration

- WuLi is fastest
  - Simple operation; parallelism
- DCA: Reasonably fast
  - Possible dependencies and gateway selection
- DCA-S: As DCA
  - The sparsification phase is executed by fewer nodes and requires little info exchange
- WAF: Slower
  - Non-trivial leader election

Protocol Duration, 2



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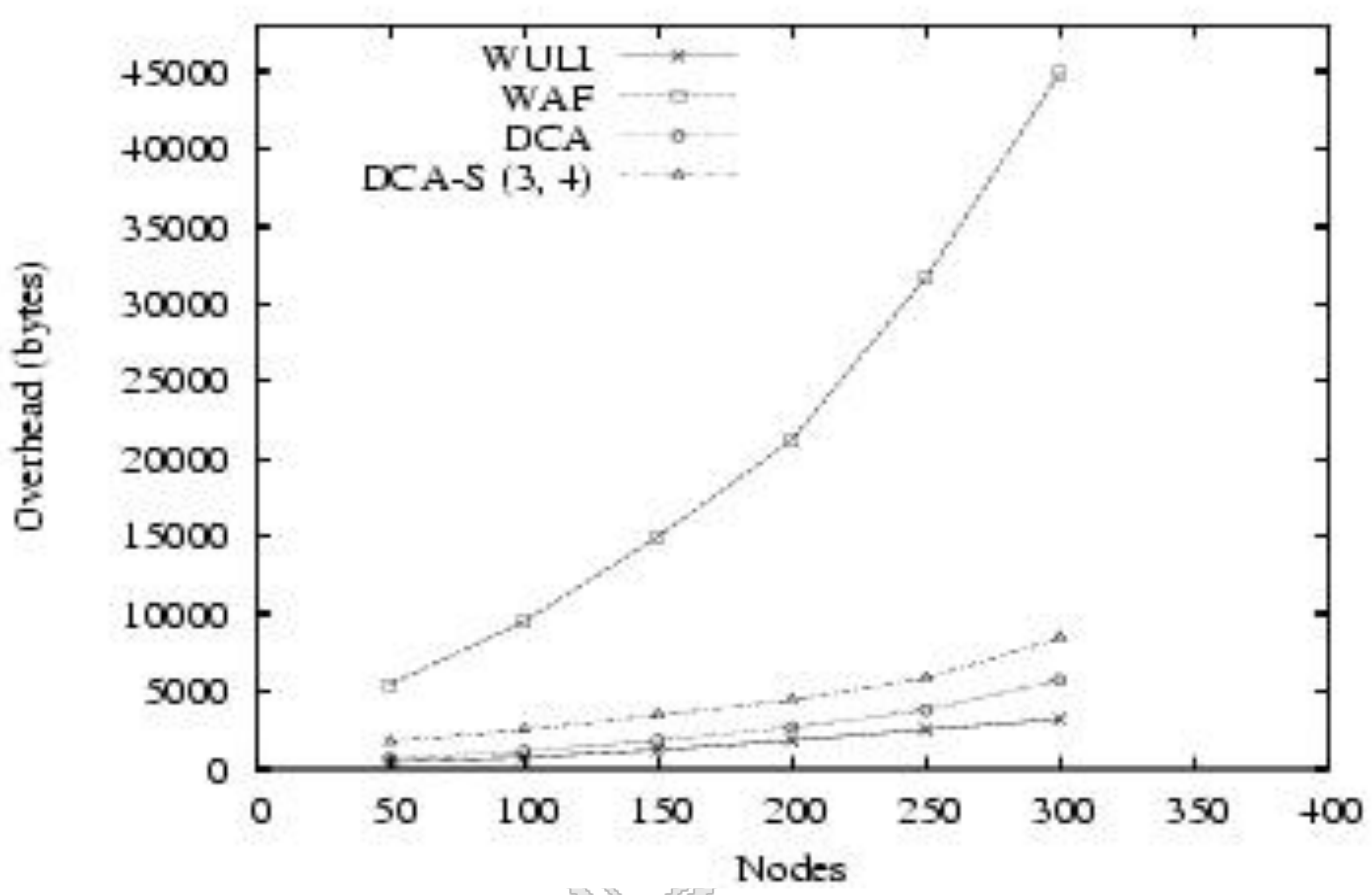
Protocol Overhead



Protocol Overhead, 2

- Average number of protocol bytes per node
- WuLi: Best performing
  - Simple list exchange
- DCA(-S): Almost twice as much
  - Bit more info needed (weight, IDs, …)
- WAF
  - Leader election complexity

Energy Consumption

- Important metric per backbone set up and maintenance
- Similar to overhead results
- WuLi and DCA perform quite well
- DCA-S performs similarly: No difference in breaking cycles with 3 or 4 links
- WAF: High consumption due to first phase

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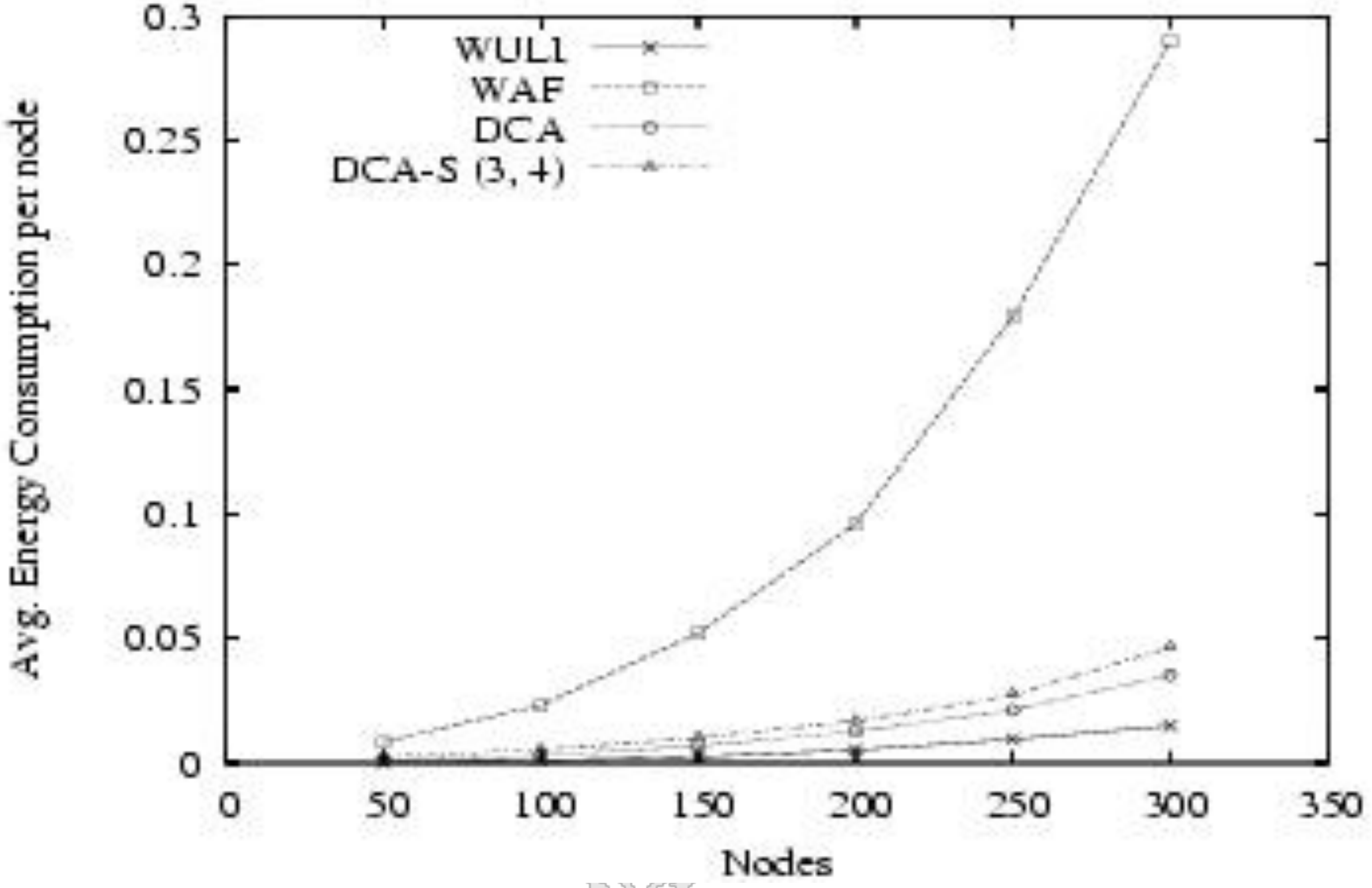
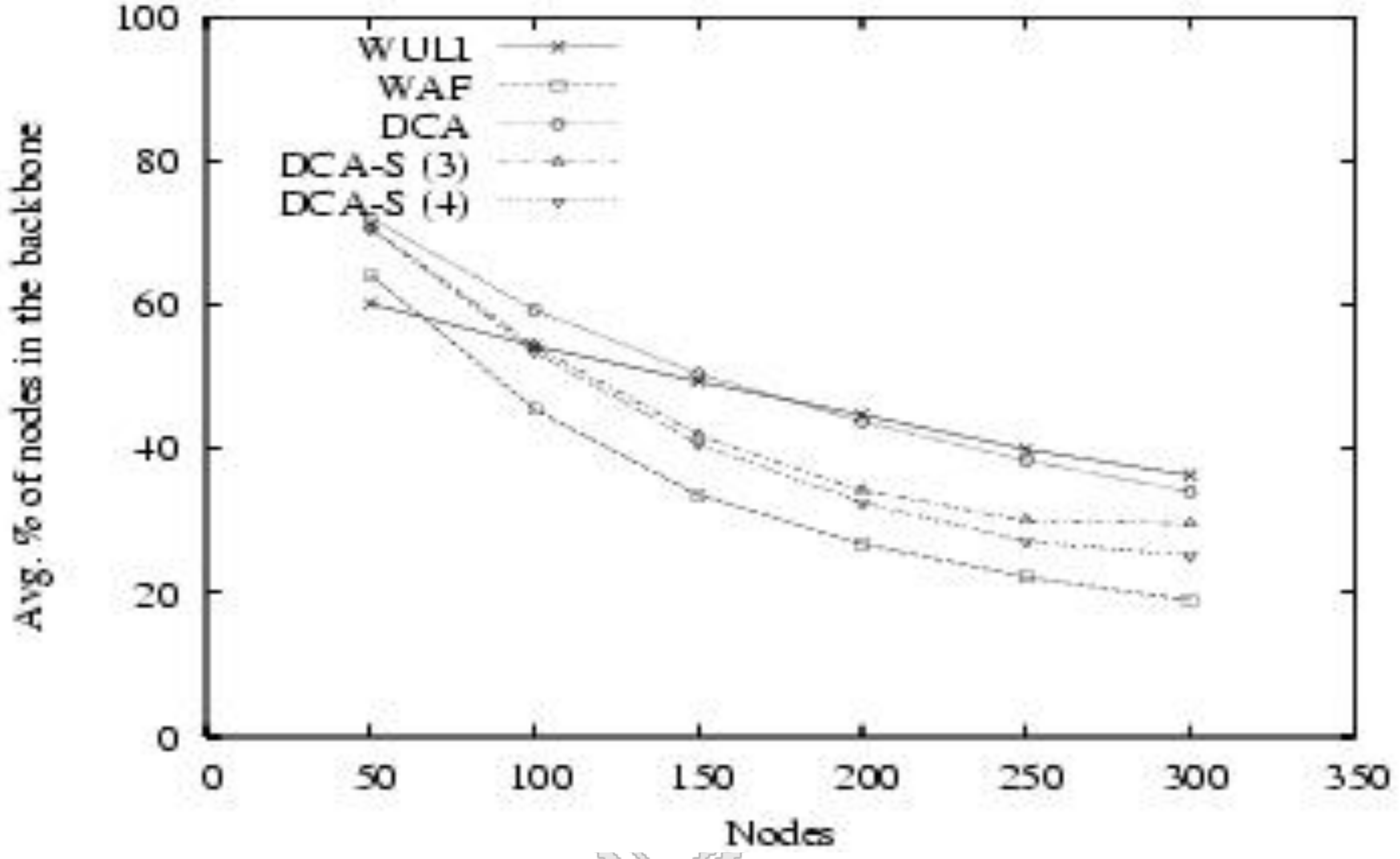
Energy Consumption, 2



Backbone Size

- Important metric: Routing info and awake/asleep cycles
  - Small backbone + role rotation: key for WSNs
- Decrease with n increasing (bigger clusters)
- WAF: “Slimmer” backbone (tree like)
- DCA-S, 4 < DCA-S, 3 < DCA < WuLi

Backbone Size, 2



Backbone Robustness

- Number of nodes needed to disconnect the backbone
- Useful for planning backbone re-orgs
- Increases with network density
- WuLi and DCA: More robust
  - Resilient to up to 25 “death” when n = 300
- WAF: Quite a disaster (tree-like topologies)
- DCA-S: In the middle

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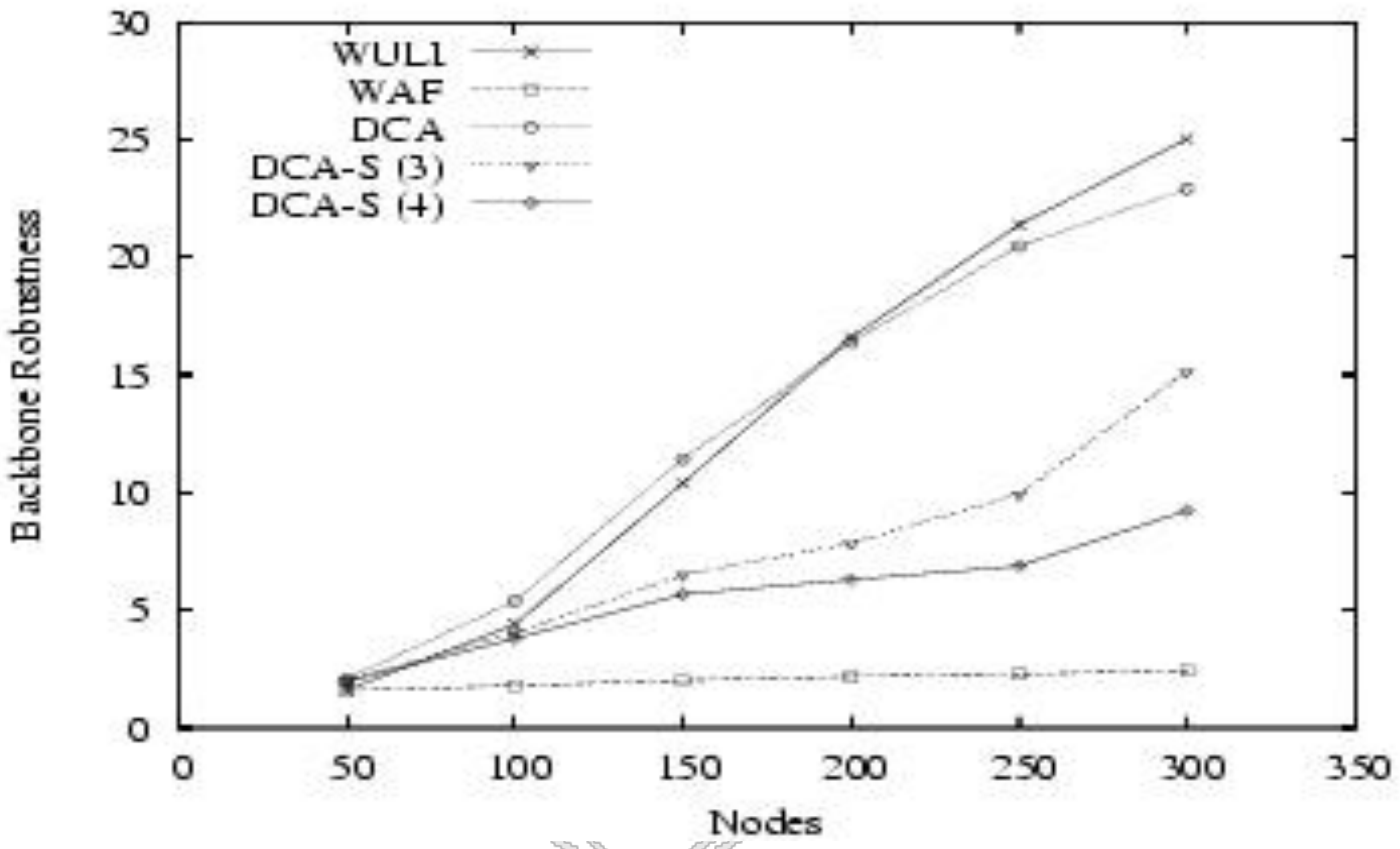
Backbone Robustness, 2



Route Length

- Flat topology (“visibility graph”) as a base
- Expected increase: Hierarchy routes are longer
- DCA & WuLi: 7 to 34.7% longer routes
- DCA-S: Up to 9% more than DCA
- WAF: Up to 33.4% longer than DCA

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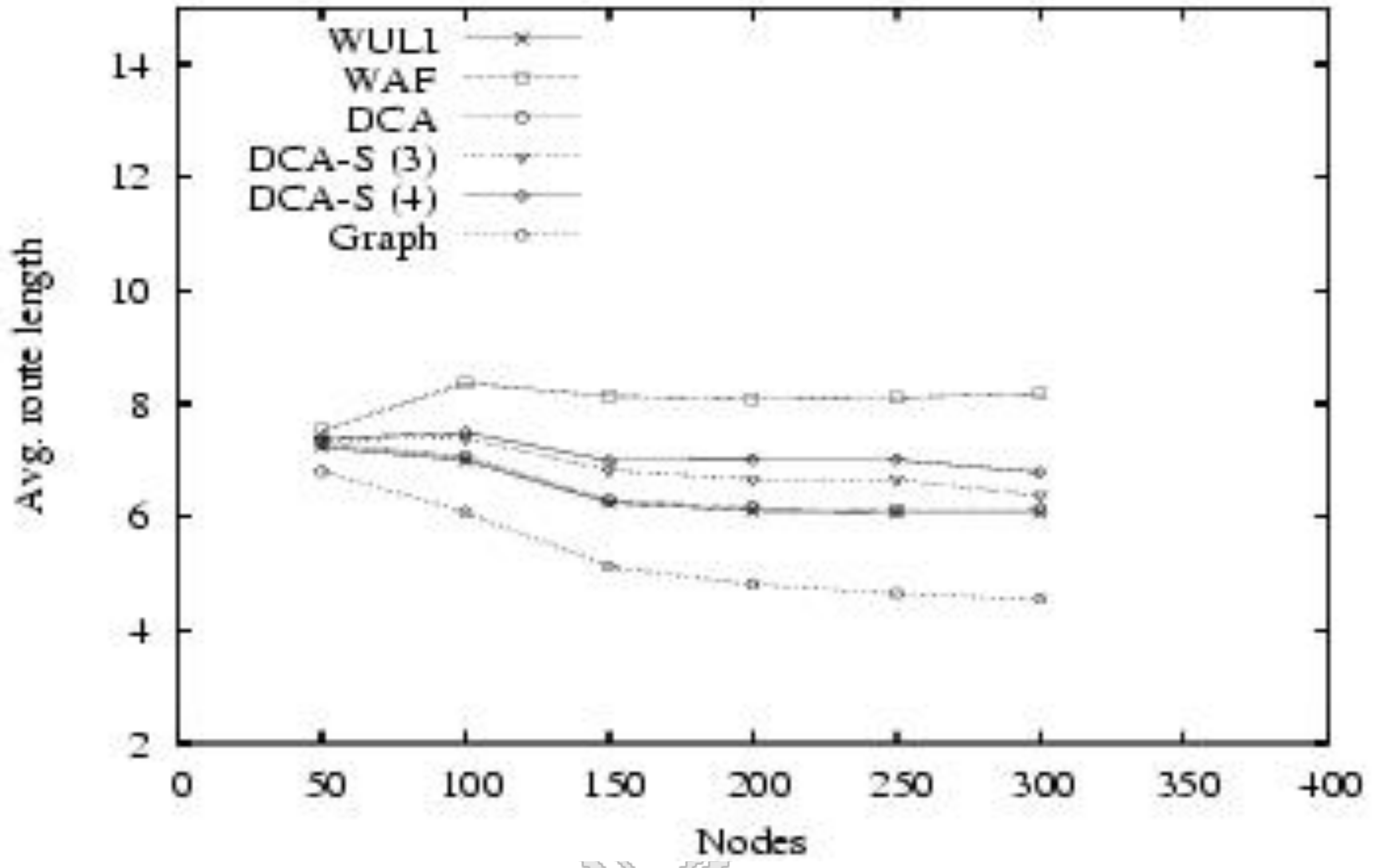
Route Length, 2



“To Go”

- Hierarchical organization is effective for prolonging network lifetime
- Four protocols for backbone formation:
  - DCA, WuLi, WAF and DCA-S
- Nice theoretical features → hard to implement
- Simple solutions (WuLi, DCA): Good starting point for efficient implementations
- DCA-S: “Slimmer” backbone at a reasonable cost

Highly Dynamic Destination-Sequenced Distance-Vector (DSDV) Routing-Correctness

- Assuming routing tables are stable and a change occurs
  - let G(x) denotes the routes graph from the sources to x BEFORE the change (assume no loop)
  - change occurs at *i* when 1) the link from *i* to its parent p(*i*) in G(x) breaks → *i* sets to inf that route (no loop can occur) 2) node *i* receives from one of its neighbors k a route to x with sequence number SN^x_k and metric m which is selected to replace the current metric *i* has to reach x (this occurs only if SN^x_k greater than the previous SN I had stored Sn^x_i or if the two SN are equal but the new route has a lower hop cost → in the first case if selecting k leads to a loop then $SN^x_k <= Sn^x_i$ which is a contradiction, in the second case comes from the observation reduction in the costs do not bring to loops).

Adapting to Mobility and Node/Link Failures: DMAC

- DMAC is for clustering set up AND maintenance

Quando muore un nodo ordinario se ne tiene solo traccia
Quando muore un gw bisogna riselezionare un nuovo gw
Quando muore un CH un nodo che stava in quel clusterhead
vede se c'è un altro vicino CH a cui riaffiliarsi ed in caso
si affilia a quello di peso maggiore
Altrimenti se ha il peso maggiore tra i vicini restanti diventa CH
L'arrivo di un nuovo nodo o la comparsa di un link puo'
Costringere a manutenzioni del backbone (per mantenere la
proprieta' che il nodo di peso maggiore è CH)

DMAC: The Procedures

- INIT
- Link-dependent procedures:
  - Link_Failure
  - New_Link
- Message-triggered procedures:
  - OnReceivingCH(v)
  - OnReceivingJOIN(u,t)