Clustering Peer-to-Peer Networks

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*L. Ramaswamy, B. Gedik, and L. Liu, "A Distributed Approach to Node Clustering in Decentralized Peer-to-Peer Networks," *IEEE Transactions on Parallel and Distributed System*, Vol. 16, No. 9, Sept. 2005.

Outline

- Observations of P2P models
- Node Clustering
  - Connectivity-based Decentralized Node Clustering (CDC)
  - Two Hop Return Probability (THP)
- Handling Node Dynamics
- Performance Analysis
- Conclusions & Discussions

Characteristics of P2P Systems

- Network and data management are completely decentralized.
- Individual nodes have limited knowledge about the structure of the network.
- Networks are highly dynamic, with frequent entry and exit of nodes.

- P2P computing systems
  - File-sharing applications, mobile ad hoc networks, sensor networks

P2P Computing Model

- Benefit
  – Alleviating the scalability problem of client-server systems
- Challenges
  – Scalable techniques for data discovery and peer look-up
  – Efficient mechanisms for communication among nodes in the network

P2P Structure

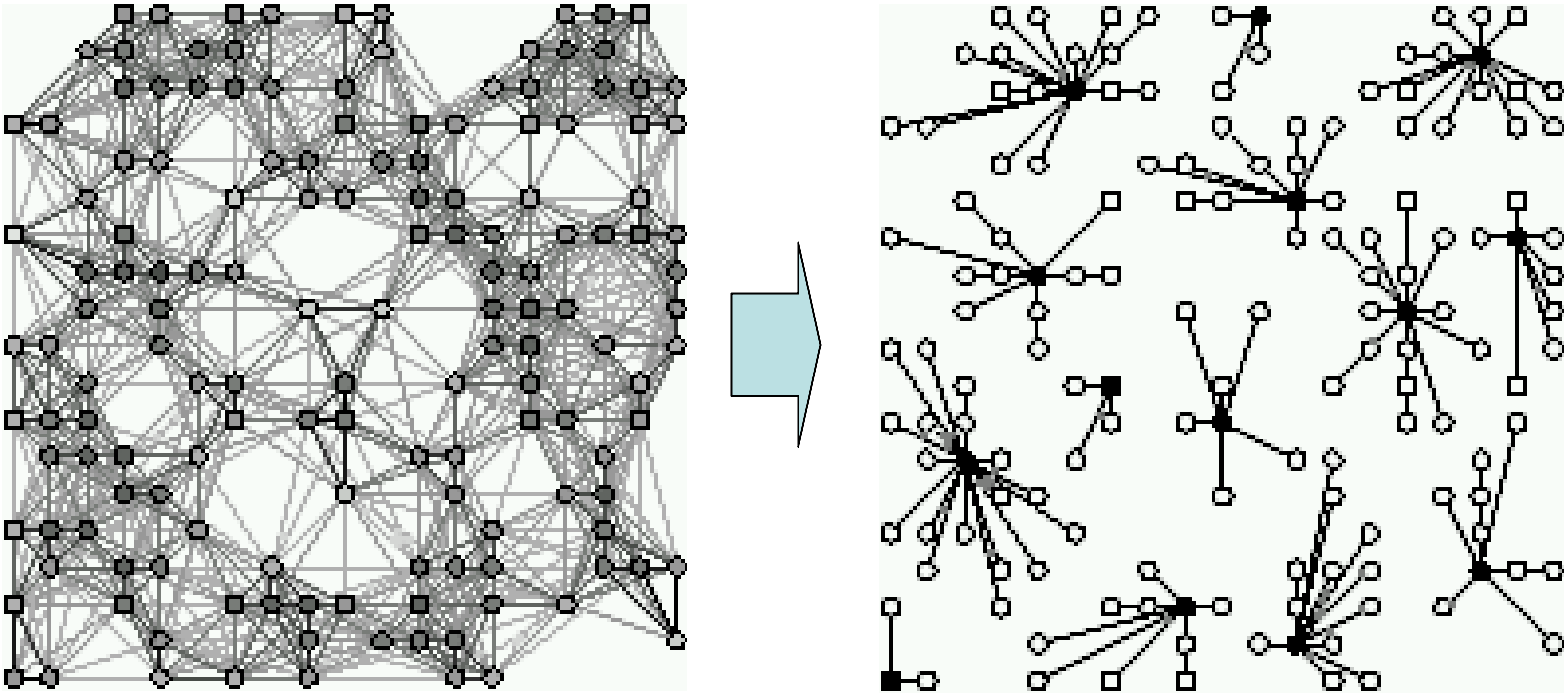
- The absence of any knowledge of the network structure is proving to be a stumbling block in utilizing the full capabilities of P2P networks.
- Discovering network structures is crucial to efficient data discovery, node look-up, and communication.

Node Clustering

- Node clustering is a partition of network nodes into one or more groups (based on their connectivity).

- Clustering helps on file replication
  - Replicas at each node on the delivering path (too much)
  - Replicas at node that downloaded the file (too little)
  - Replicas in each cluster to some value

Node Clustering Illustration



MCL: Markov Cluster Algorithm, PhD thesis by Stijn van Dongen, at http://micans.org/mcl/lit/

Connectivity-based Decentralized Node Clustering (CDC)

- CDC is proposed to discovering good quality clusters and handling the node dynamics.
  - Clustering the nodes of a network in a completely distributed and decentralized manner
  - Incorporating newly entering nodes into the cluster structure and gracefully handle the exit of existing nodes in the network

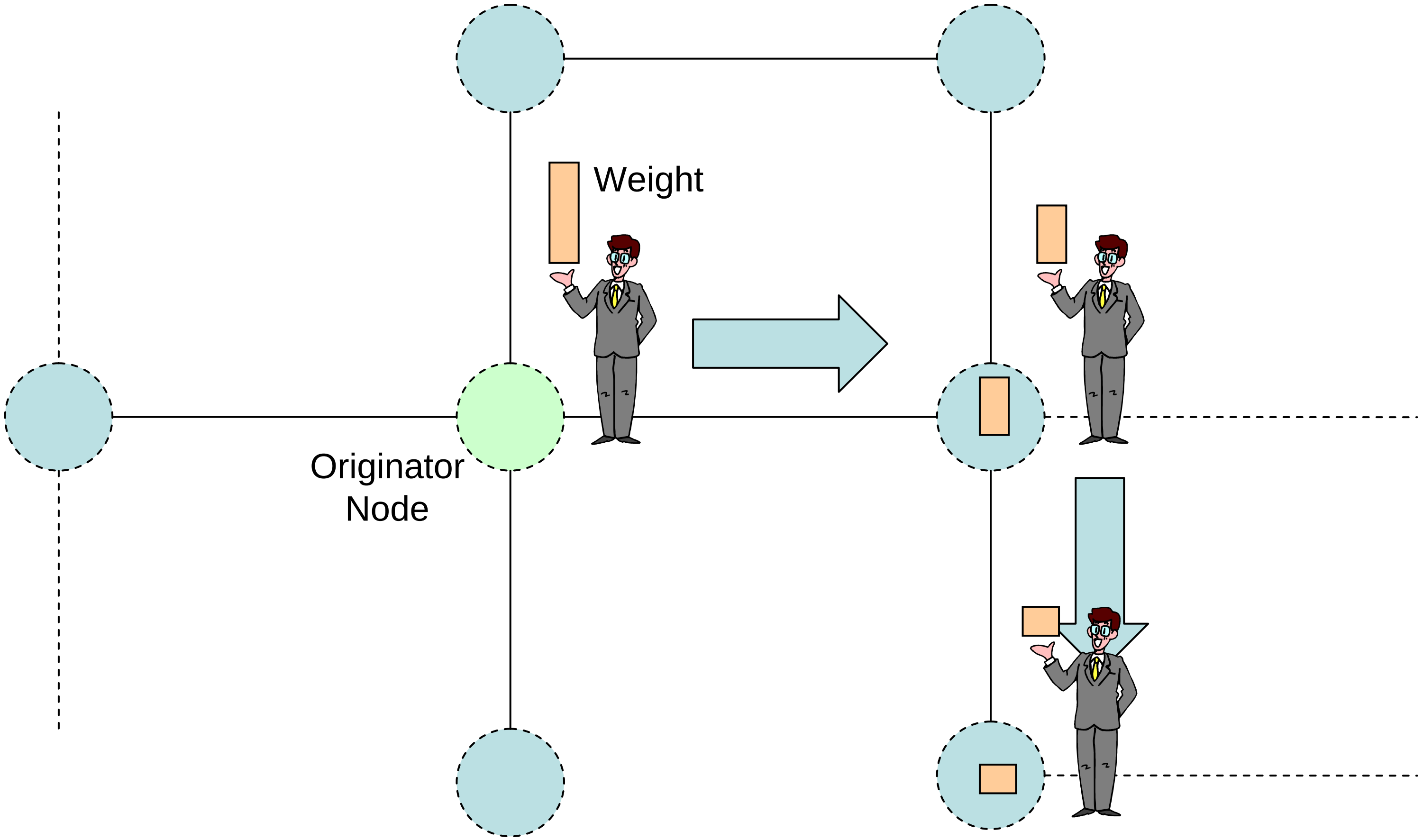
Definitions

- $G = (V, E)$; $V = \{V_1, V_2, \ldots, V_N\}$; $E = \{E_1, E_2, \ldots, E_M\}$
- *Degree*: # of edges incident on a node
- *Neighbor*: V_i and Vj are neighbors iff $E(Vi, Vj)$ exist
- *Clustering* $Cl = \{Cl_1, Cl_2, \ldots, Cl_Q)$ that:
  - each Cl_l is a nonempty subset of vertices $(\forall Cl_l, Cl_l \subseteq V)$ and $\bigcup_{l=1}^{l=Q} Cl_l = V$
  - any two nodes in Cl_l, $1 \leq l \leq Q$, are similar
  - any two nodes belonging to two different sets, say Cl_l and Cl_m, are dissimilar
- The similarity and dissimilarity functions may be appropriately defined according to the semantics of the graph under consideration and the application at hand.

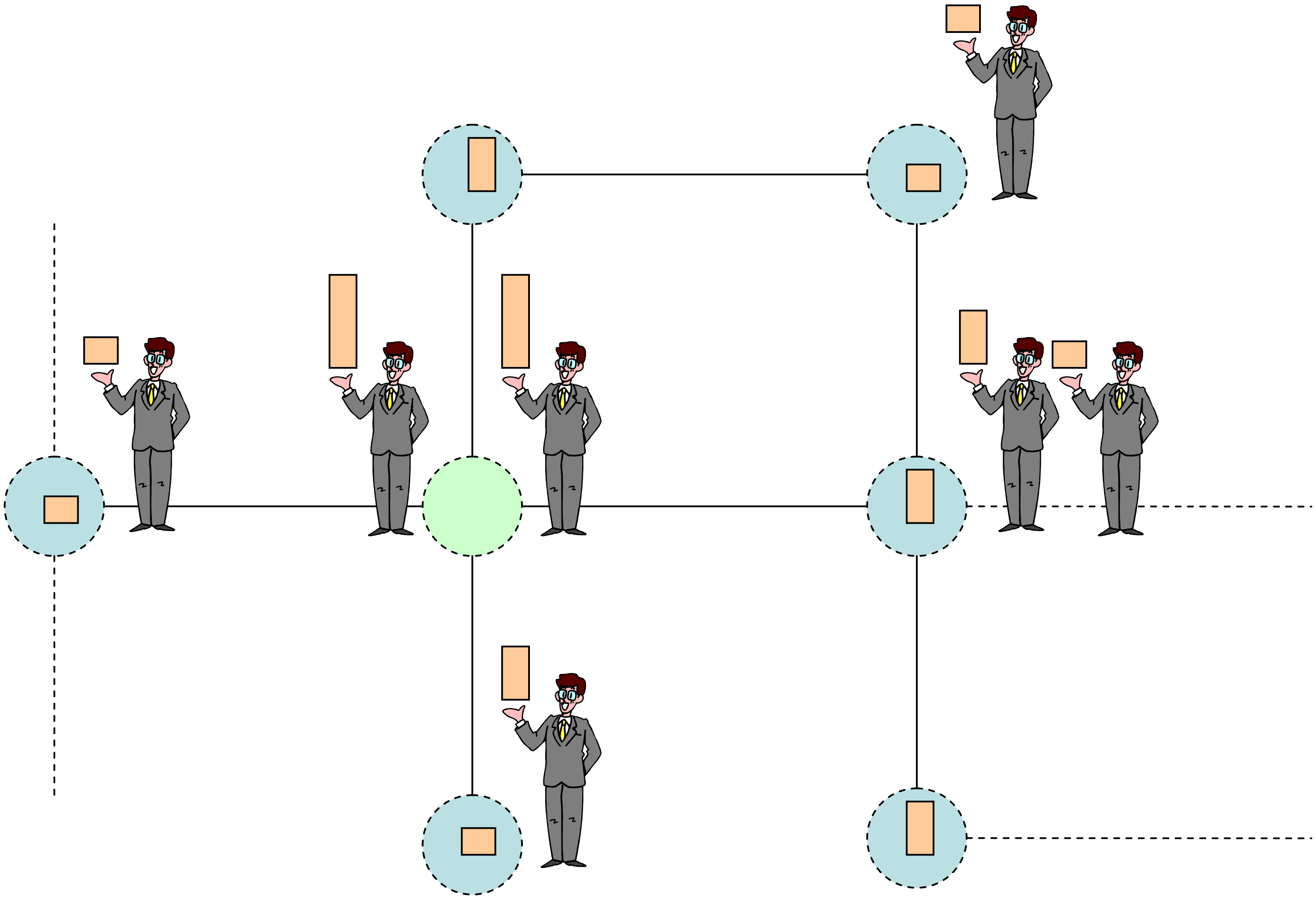
Properties of a Good Clustering

- In a graph *G*, for any two nodes V_i and V_j which belong to the same cluster Cl_l, there exists at least one path in *G* such that all intermediate vertices along that path lie in Cl_l.
- For a graph *G*, any two vertices lying in the same cluster tend to have a large number of paths connecting them.
- A random walk on the graph *G* tends to visit most of the nodes in a cluster multiple times before it leaves the cluster.

Random Walk on Intersecting Roads



Random Walk on Intersecting Roads



Observations

- If the graph structure has a densely connected graph structure around the originator node, then a high percentage of people can be observed in the nodes and edges that lie in the dense region around the originator.
- The nodes and edges that are not in the dense structure would have relatively few people in them.
- Nodes that lie inside the cluster would have accumulated a higher weight when compared with the nodes that are remotely approachable from the originator.

CDC Design

- Each peer would join a cluster from whose originator it received the maximum weight.

- Peer nodes -> intersection
- Connections between peers -> roads
- People moving about -> cluster messages

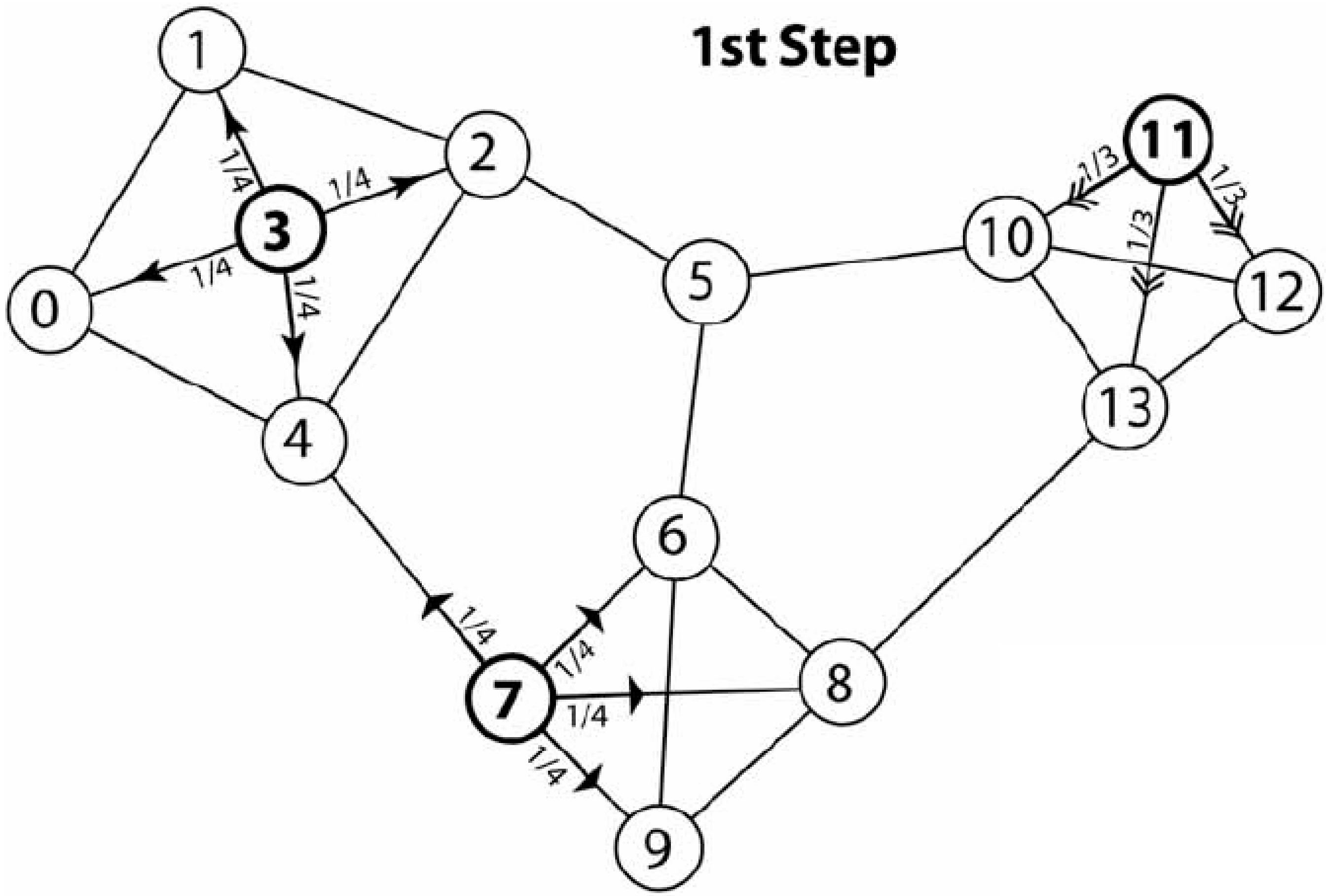
Cluster Message

- Originator ID
- Message ID
- Source ID
- Time-to-Live (*TTL*)
- Message Weight
  - $Msg.MWeight = 1/Degree(V_i)$
  - $TotalWeight(V_i, O_l) \mathrel{+}= Msg(O_l).MWeight$

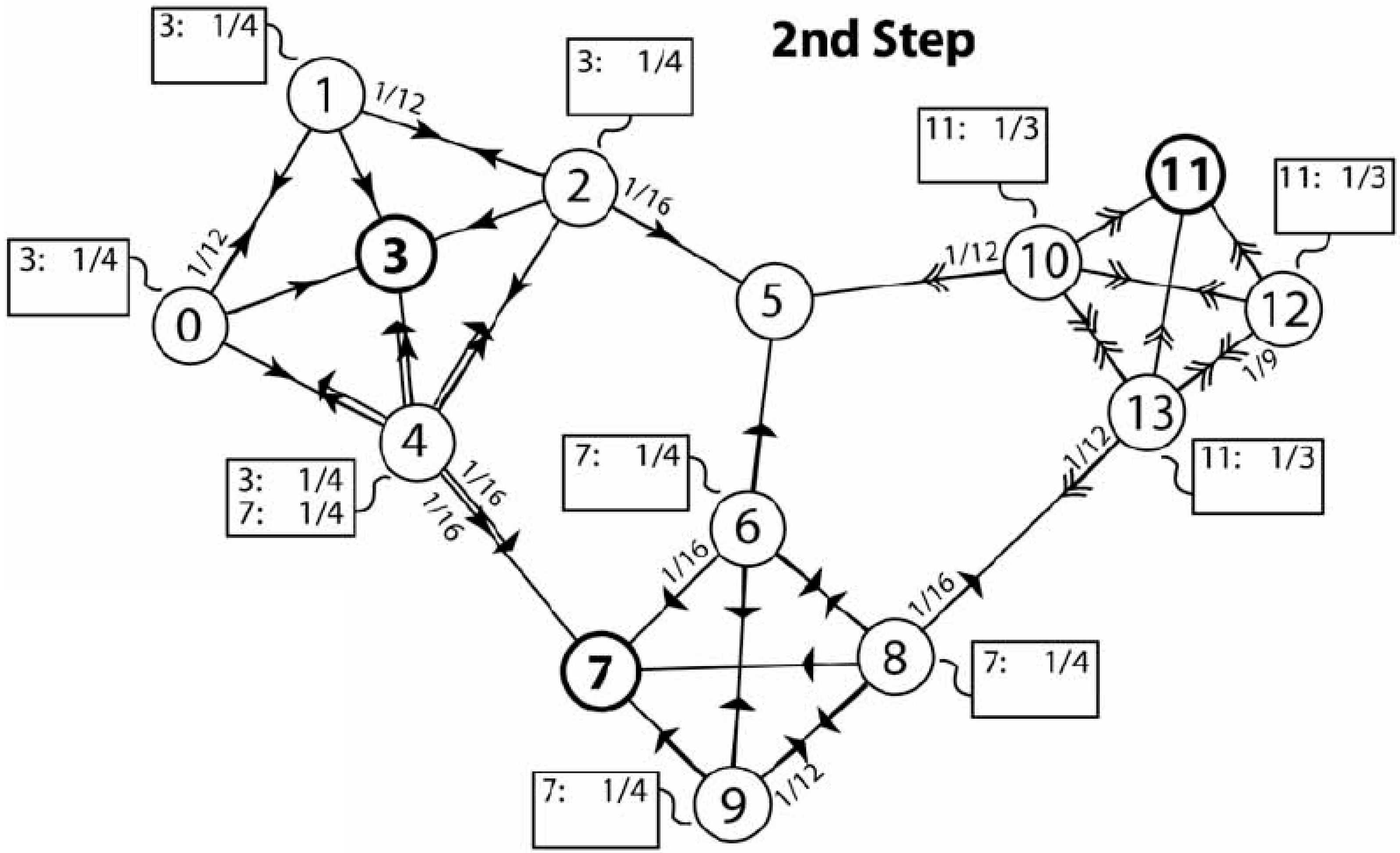
CDC Algorithm

- Originators broadcast cluster messages (*Msg*).
- On receiving *Msg*, the recipient *Vi* updates the *TotalWeight*(V_i, O_l) and check *TTL* whether to forward *Msg*.
- Before forwarding *Msg*, the recipient updates *Msg*.*MWeight* as *Msg*.*MWeight* ／ *Degree*(V_i) and decrements *TTL* by 1.
- After receiving the last *Msg*, the node joins the originator (cluster) whose *TotalWeight* is the maximum.
- If all *TotalWeight* lie below a predefined threshold, then the node remains an **outlier**.

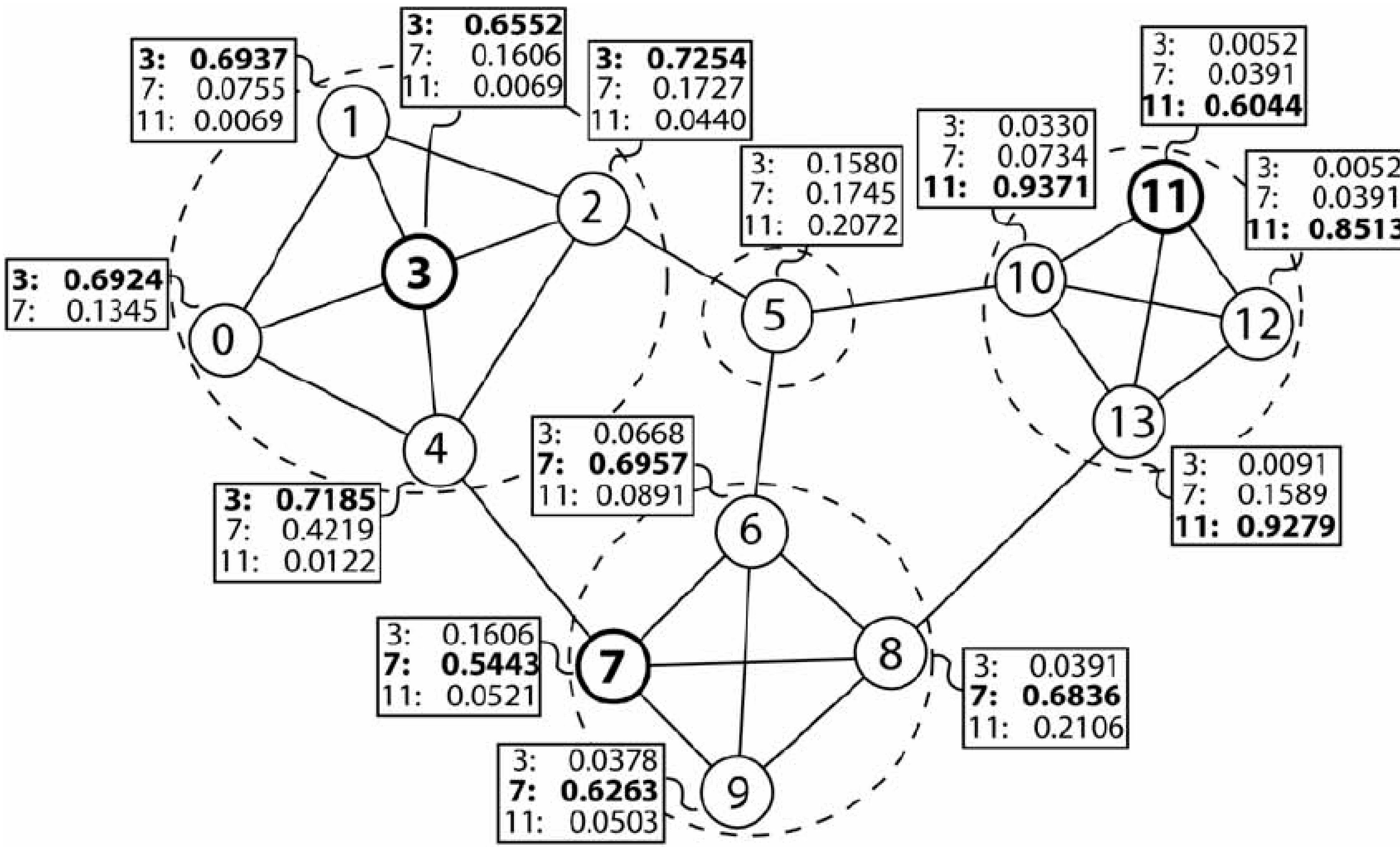
CDC Illustration – 1st Step



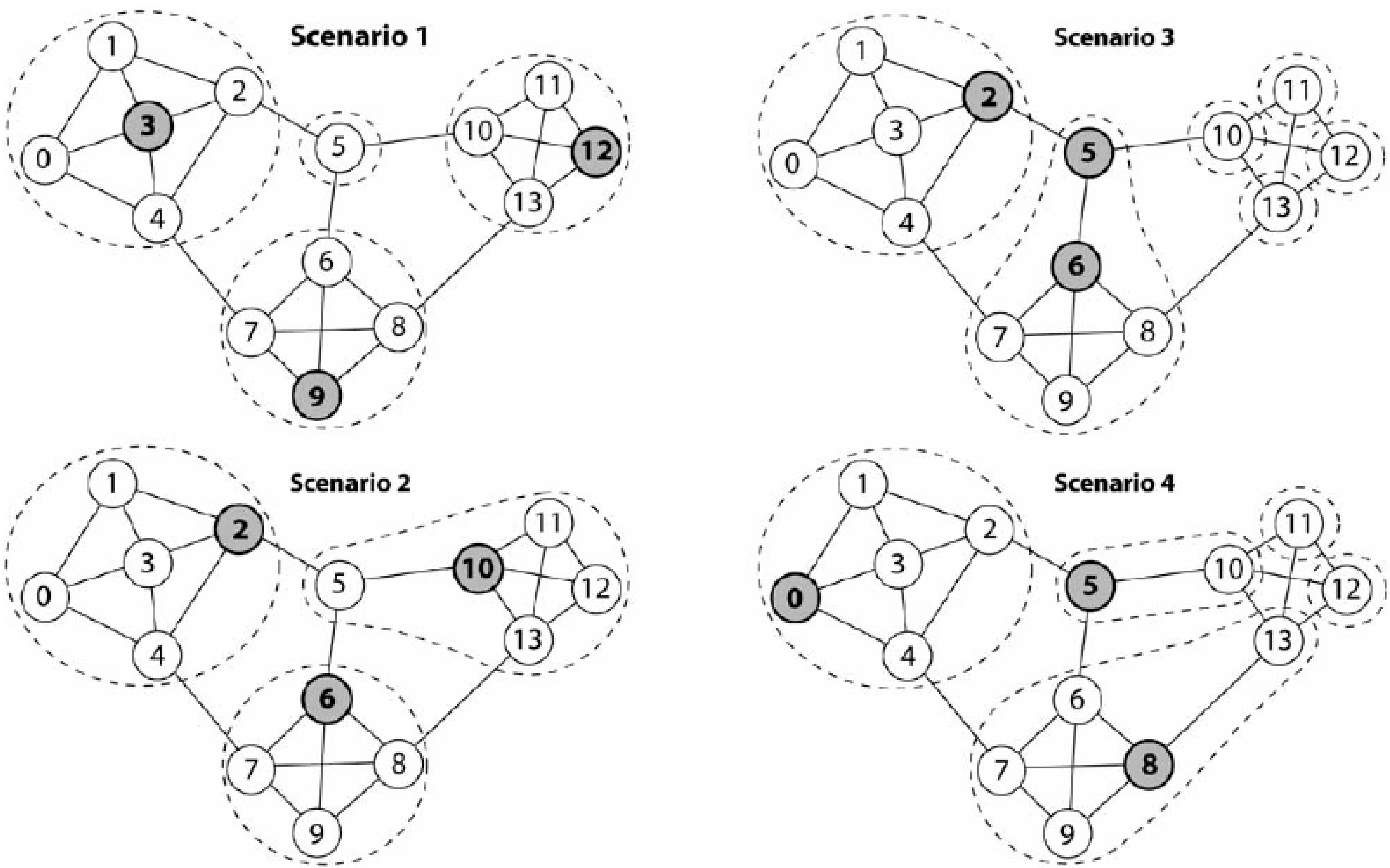
CDC Illustration – 2nd Step



CDC Illustration – Result for *TTL*=4



Originator Selection



Properties of Good Originator Selection

- The set of originators should be spread out in all regions of the graph.
- A node V_l is considered to be a good originator if it acquires more weight due to messages initiated by itself than the weight acquired by messages initiated by any other originator.
  - $TotalWeight(V_l, V_l) \geq TotalWeight(V_l, V_i), \forall V_i \in V$
- Two Hop Return Probability
  - $$TwoHopProb(V_l) = \sum_{V_i \in Nbr(V_l)} \left(\frac{1}{Degree(V_l) \times Degree(V_i)} \right)$$

THP Originator Selection

- When a node doesn't receives any clustering messages from other nodes, it start THP scheme.
  - *Msg.TTL* ≤ *InitialTTL-Vicinity*
- It obtains the degree of each of its neighbor.
- If the computed *TwoHopProb* is higher than a predefined *TwoHopThreshold*, the node become an originator.

Configurable Parameters

- Increasing the *WeightThreshold* parameter leads to an increase in the number of outliers and vice versa.
- Increasing the value of *Vicinity* and *TwoHopThreshold* parameters reduces the number of discovered clusters and vice versa.

Node Entry

- The new node joins a cluster which attracts it the most, provided its *ClustAttraction* is higher than a preset threshold.

- For each node $V_j \in Nbr(V_{N+1})$:
  - $$NbrAttraction_{V_{N+1}}(V_j) = \frac{1}{Degree(V_j)}$$

- $$ClustAttraction(Cl_l) = \sum_{V_i \in Cl_l \wedge V_i \in Nbr(V_{N+1})} NbrAttraction_{V_{N+1}}(V_i)$$

Node Exit

- When V_k exits the graph:
  - If neighbor V_{k+1} belong to a different cluster than V_k, it simply update its connectivity.
  - If they belong to the same cluster, then V_{k+1} acts as though it has just entered the system and adopt the same strategy as adding a new node.
- If V_k is an originator, the neighbor with the highest number of **in-cluster edges** are elected as the new originator.

Periodical Reclustering

- The algorithms of handling node dynamics are only approximations to the CDC scheme.
- Periodical reclustering is required to prevent degradation of clustering accuracy.
- The trade-off is between the accuracy of clustering and the clustering message load on the network.

Clustering Accuracy

$$ClustAccuracy(G, Cl) = \frac{\sum_{V_i \in V} ScalCov(V_i, Cl)}{\|V\|}$$

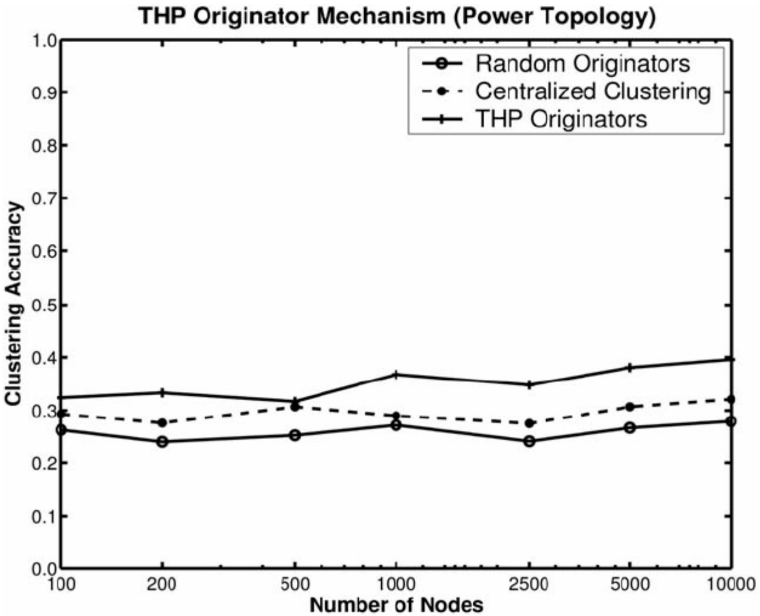
- Scaled Coverage Measure:
  - Nbr(Vi): the set of neighbors of Vi
  - Clust(Vi): the set of all nodes that beling to the same cluster as the of vertex Vi

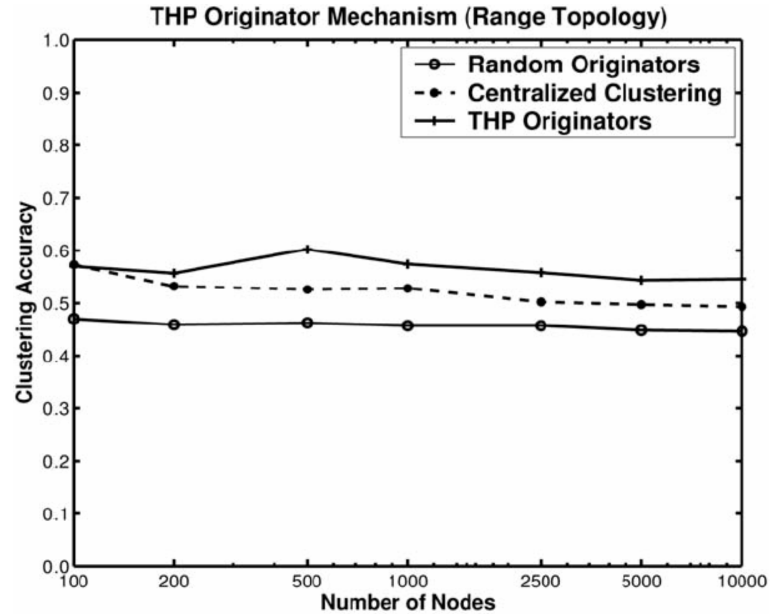
$$ScalCov(V_i, Cl) = 1 - \frac{\|FalsePositive(V_i, Cl)\| + \|FalseNegative(V_i, Cl)\|}{\|Nbr(V_i) \cup Clust(V_i)\|}$$

Simulation Topologies

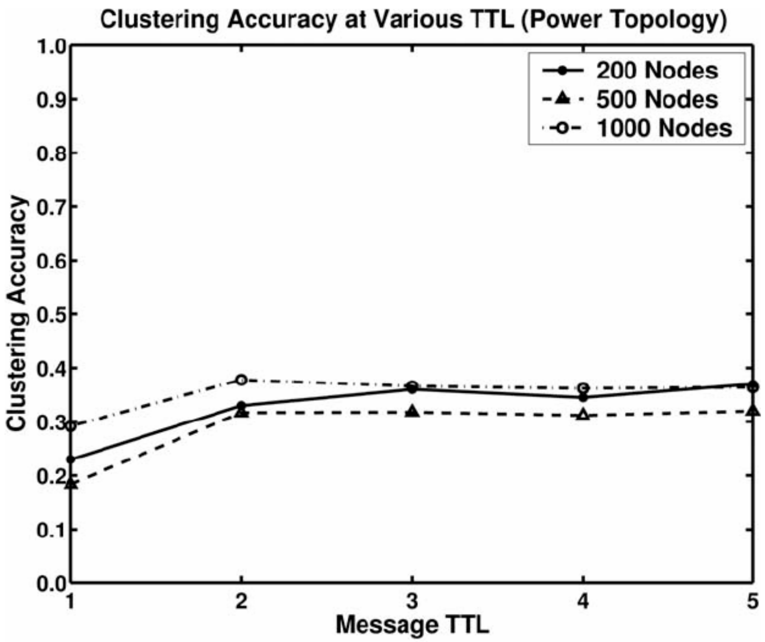
Parameter	Power Graphs	Range Graphs
Total Nodes	5000	5000
Total Edges	11446	27083
Average Degree	4.57	10.83
Maximum Degree	623	25
Minimum Degree	1	1
Variance in Degree	212.53	11.08

CDC w/ THP v.s. MCL[35]

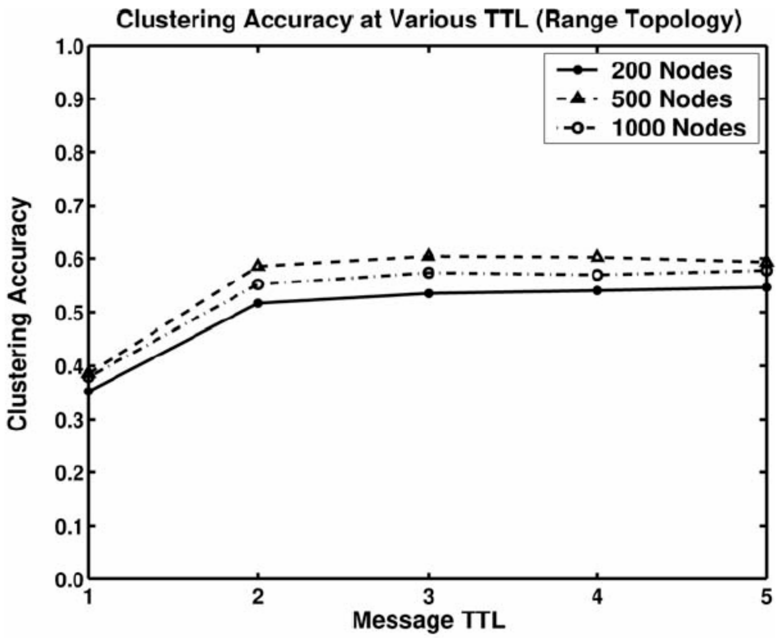




CA on TTL



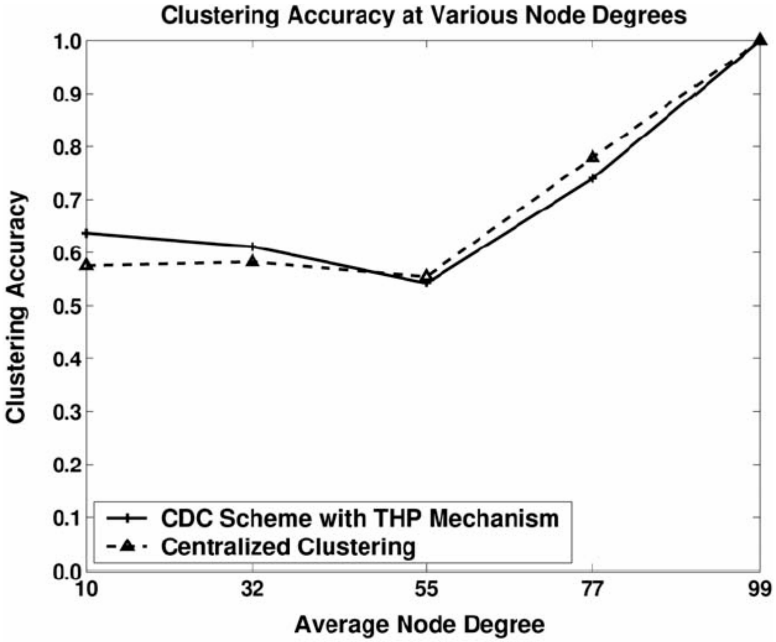
Clustering Accuracy at Various TTL (Power Topology)
200 Nodes
500 Nodes
1000 Nodes
Clustering Accuracy
Message TTL

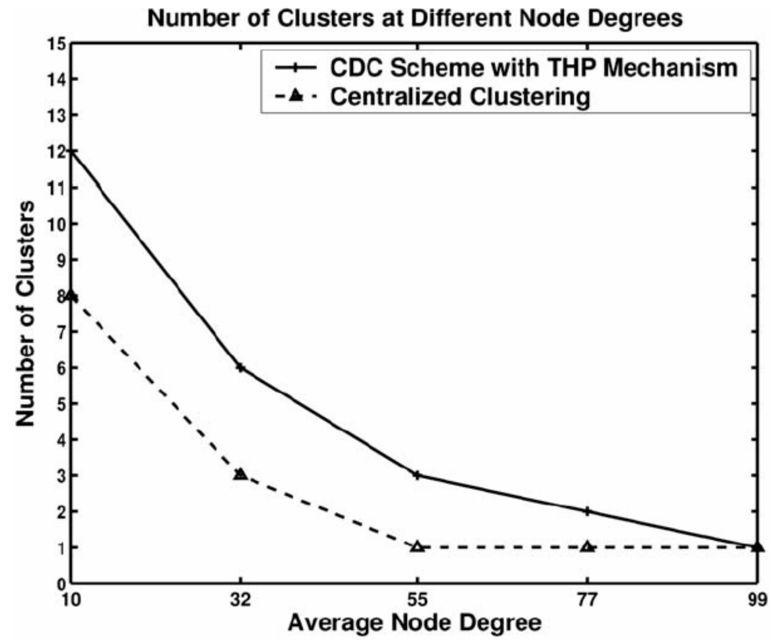


Clustering Accuracy at Various TTL (Range Topology)
200 Nodes
500 Nodes
1000 Nodes
Clustering Accuracy
Message TTL

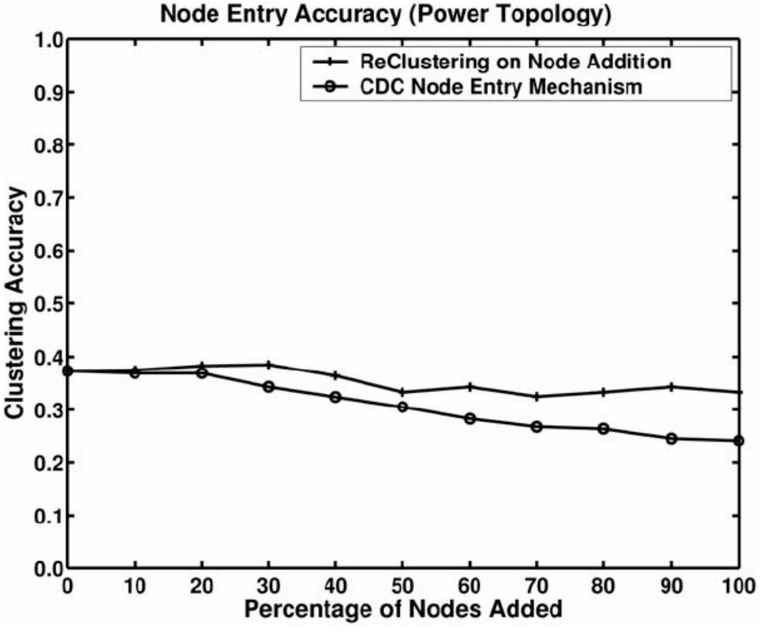
CA on Node Degree

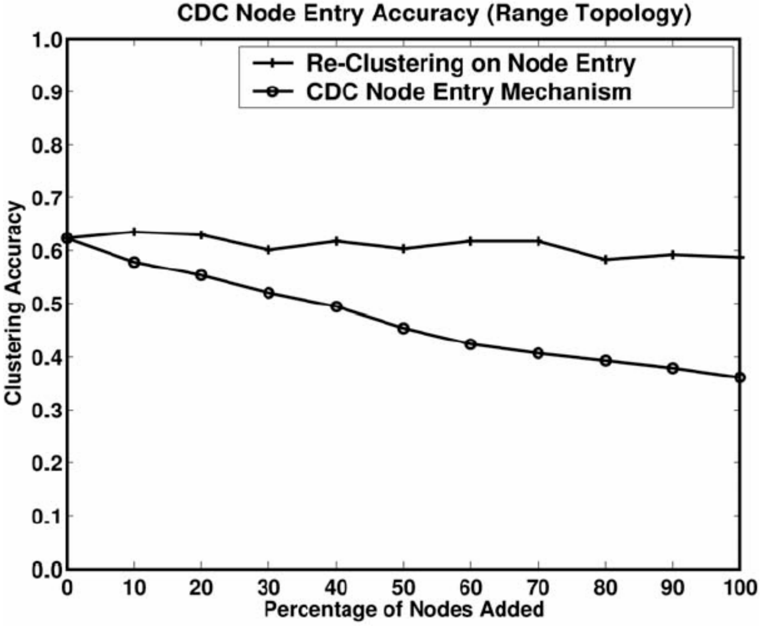
- 100 node



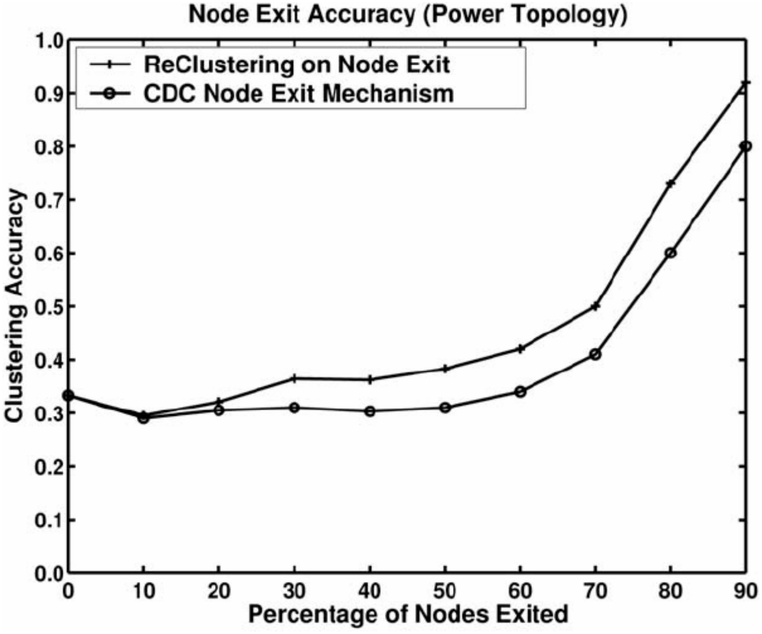


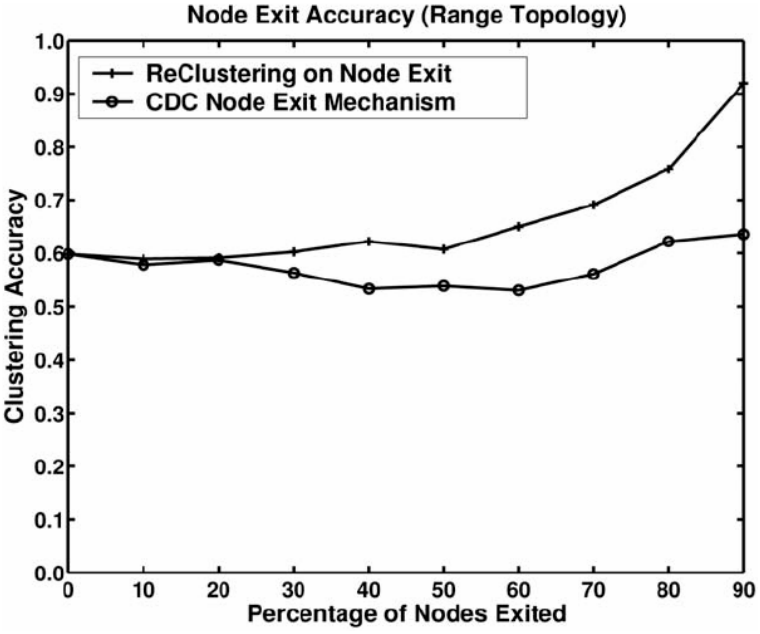
CA on Node Entry



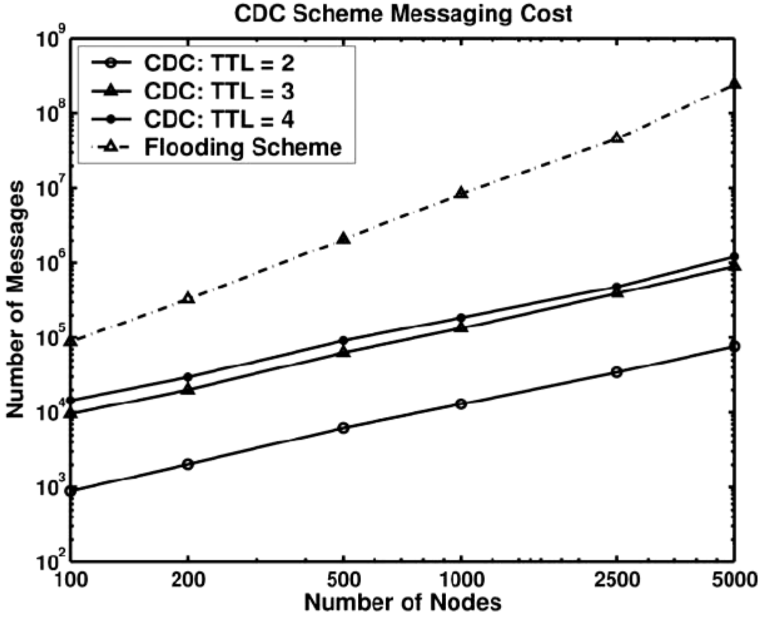


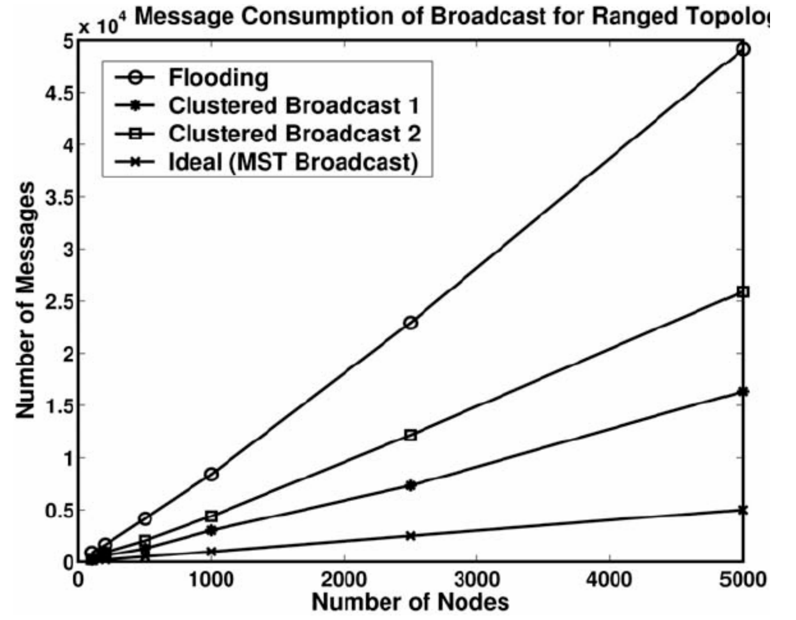
CA on Node Exit





Message Cost





Conclusions and Discussions

- CDC is completely decentralized and does not require a global view of the network structure.
- CDC incorporates new nodes into an existing cluster structure and handle the exit of nodes in the clusters.

- Originator (Superpeer) capacity?
- Degree based clustering?
  - Preferring High degree in P2P for superpeer structure
- Clustering on other systems?
  - Low bandwidth, low battery power, gateway as cluster head in ad hoc network, etc.