Colorado State University

CNRL Computer Networking Research Laboratory

# Top-Down Clustering Based Self-Organization of Collaborative Wireless Sensor Networks

M.Sc Final Exam


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July 21, 2008

**Graduate Committee**

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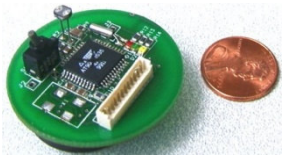
- This work is supported in part by the grant from Environmental Sciences Division, Army Research Office

# Overview

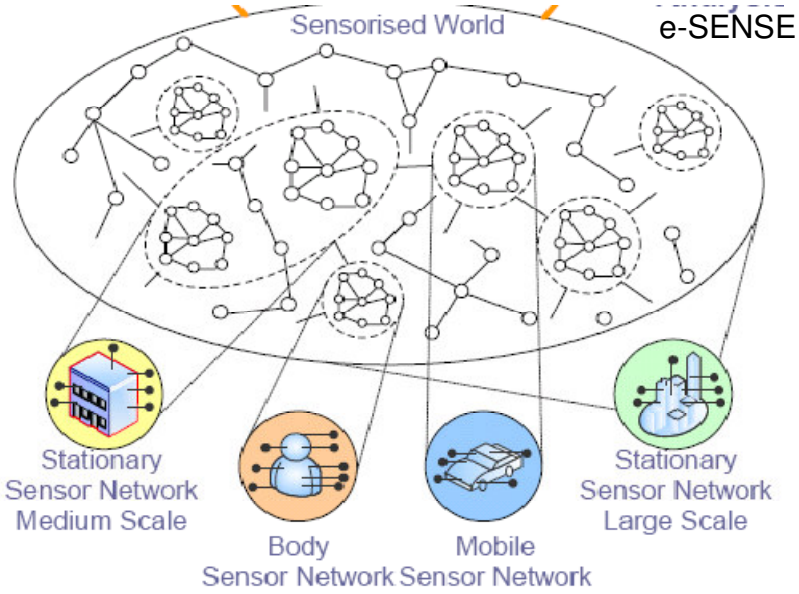
- Motivation
  - Virtual Sensor Networks (VSNs)
- Cluster & cluster tree formation algorithm
  - Simple Hierarchical Clustering (SHC)
  - Hop-ahead Hierarchical Clustering (HHC)
- Routing
  - Hierarchical addressing scheme
  - Cross-links based routing
  - Circular path based routing
- Forming Virtual Sensor Networks
- Secure backbone design

# Wireless Sensor Networks (WSNs)

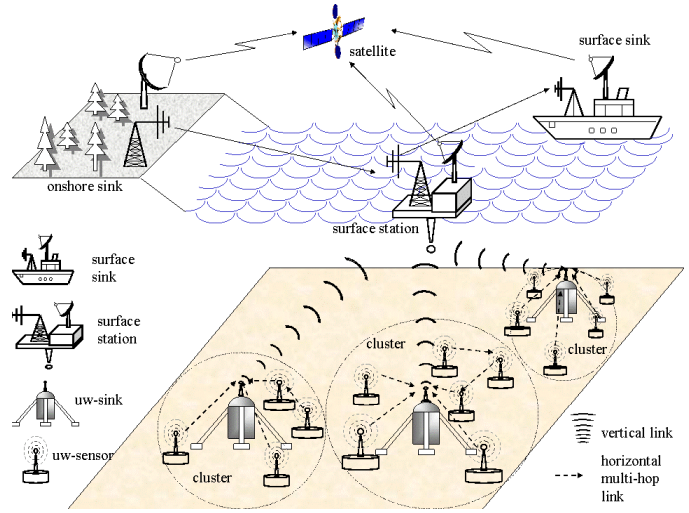
- Sensing of physical world at a far greater temporal & spatial granularity
- Novel applications
  - Habitat monitoring, earthquake monitoring, disaster response, eldercare, battlefield intelligence, etc.
- Sensor nodes are resource constrained
  - Battery powered, low processing, memory, & transmission power
- In most cases
  - Randomly deployed, location unaware, no time synchronization, unreliable, & dense networks



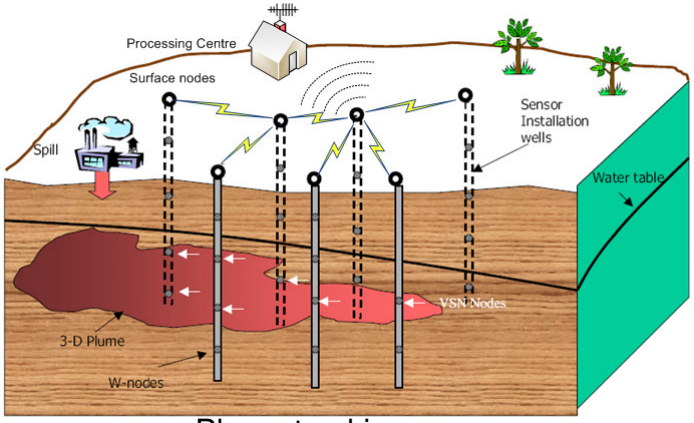
# Motivation – Collaborative WSNs



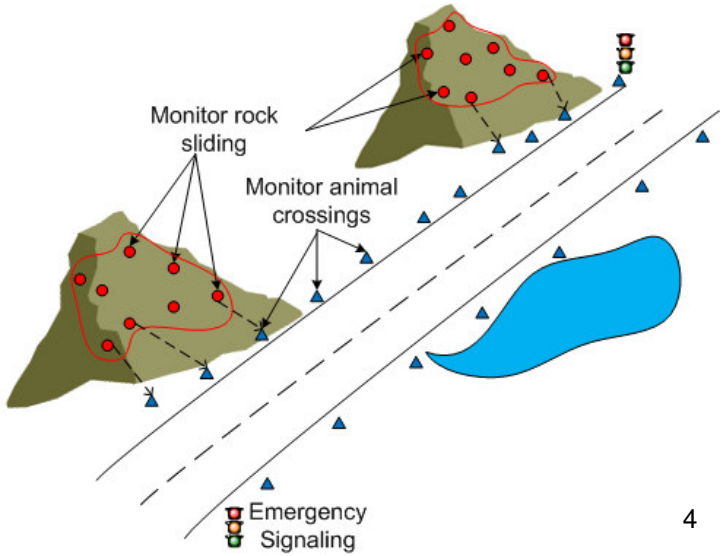

e-SENSE project [1]




Underwater Acoustic Sensor Networks project [2]




Plume tracking




[1] www.ist-esense.org
[2] http://www.ece.gatech.edu/research/labs/bwn/UWASN/work.html

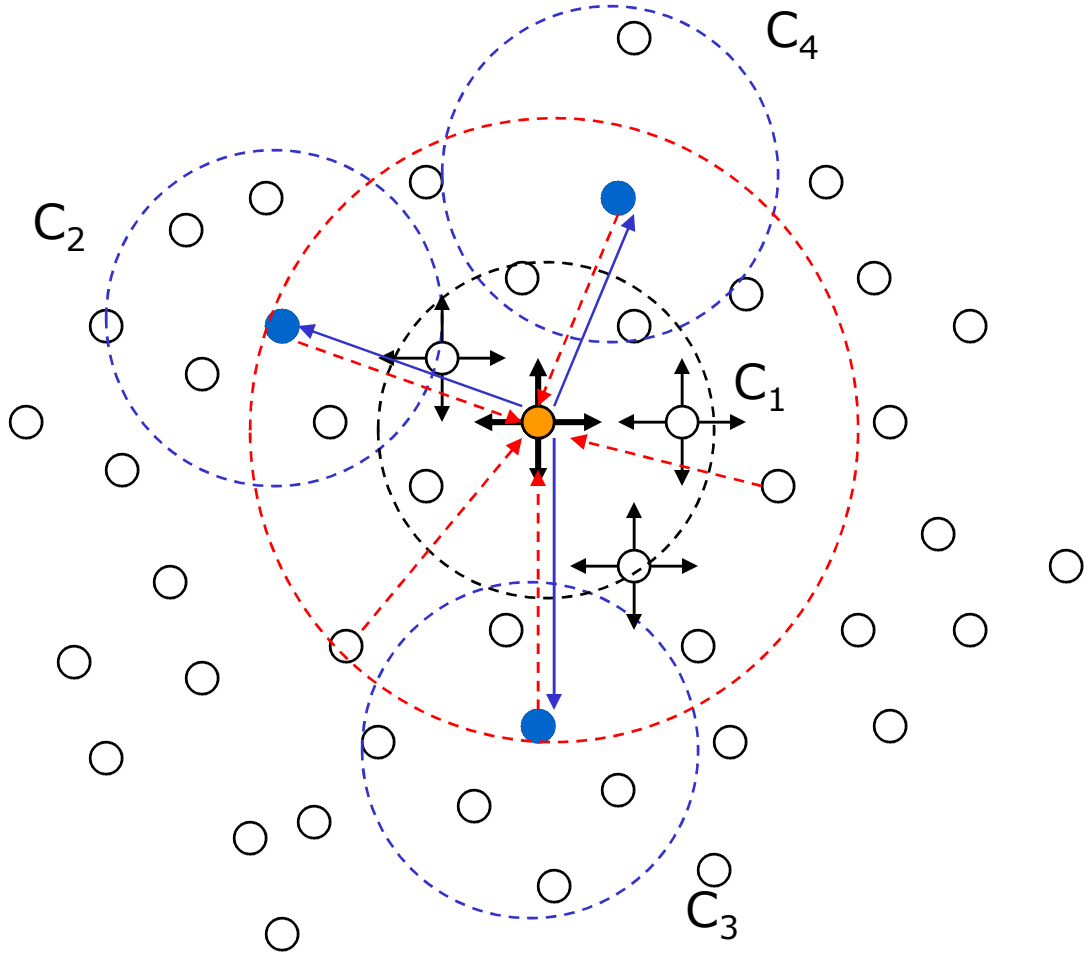
# Virtual Sensor Networks (VSNs)

- An emerging concept that
  - supports collaborative, resource efficient, & multipurpose WSNs
  - involve dynamically varying subset of sensor & users
- Provide protocol support for
  - formation, usage, adaptation, & maintenance
- Realization of VSNs require
  - some structure within the network
  - many-to-many communication
  - VSN management functions
- The solutions should be independent of
  - neighbourhood information, location awareness, network topology, time synchronization, etc.

# Contributions

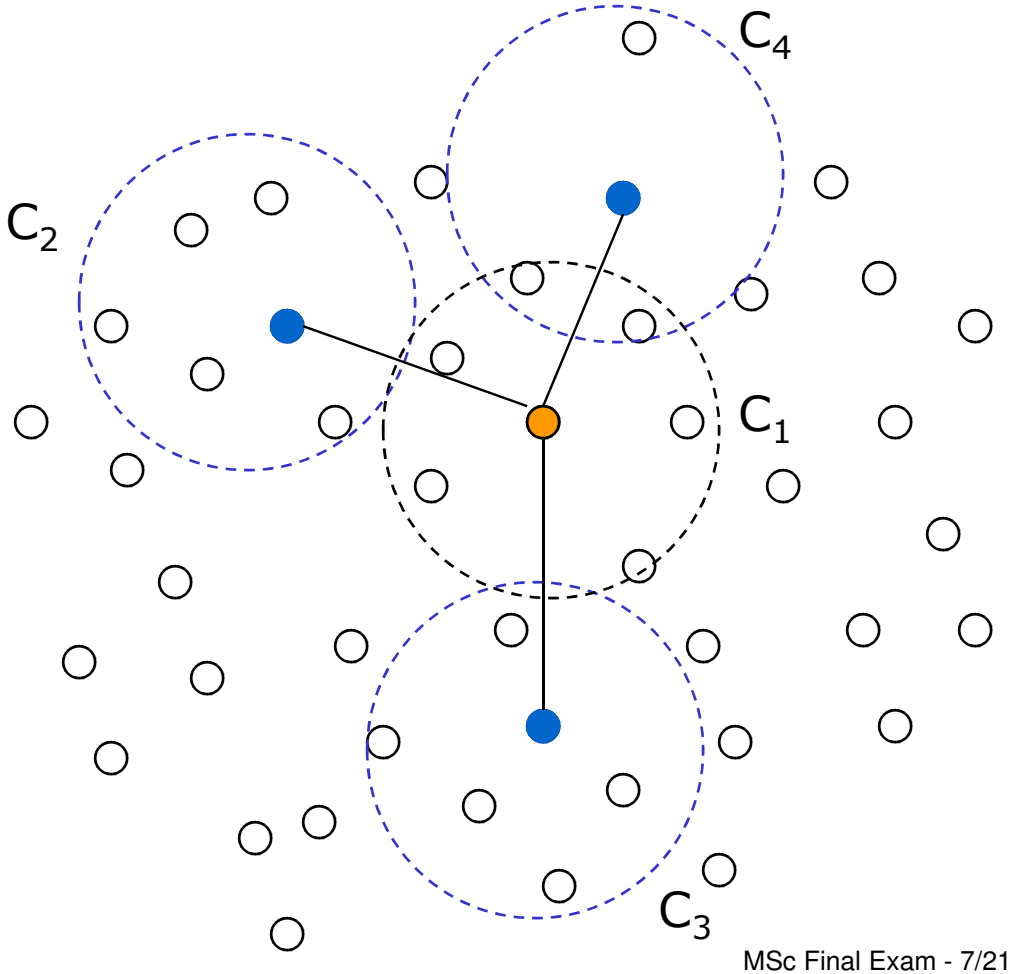
- Clustering algorithm
  - 2 clustering schemes
  - Cluster tree formation
  - Performance analysis
- Routing
  - Hierarchical addressing scheme
  - 3 routing mechanisms
  - Performance analysis
- Virtual Sensor Networks
  - Formation
  - Communication
- Secure backbone design

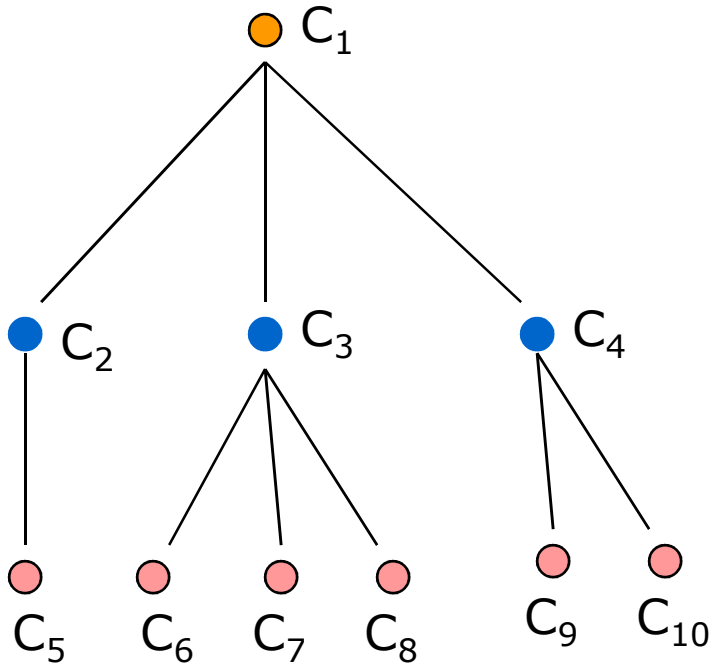
# Generic Top-Down Cluster & cluster tree formation (GTC) algorithm



# GTC - Cluster tree formation

- Cluster tree is formed by keeping track of parent & child relationships



# GTC algorithm

***Form_Cluster(NID$_{CH}$, CID$_{CH}$, delay, n$_{CCHs}$, hops$_{max}$, TTL$_{max}$, depth)***

*Wait(delay)*

*TTL ← TTL$_{max}$*

*Broadcast_Cluster(NID$_{CH}$, CID$_{CH}$, hops$_{max}$, TTL$_{max}$, TTL, depth)*

*ack_list ← Receive_ACK(NID$_{child}$, hops, p$_1$, p$_2$, timeout$_{ACK}$)*

***IF**(ack_list = NULL)*

*Join_Cluster()*

***FOR** i = 1 **TO** n$_{CCHs}$*

*CCH$_i$ ← Select_Candidate_CHs(ack_list)*

*CID$_i$ ← Select_next_CID(i)*

*delay$_i$ ← Select_delay(i)*

*depth$_i$ ← depth + 1*

*Request_Form_Cluster(CCH$_i$, CID$_i$, delay$_i$, n$_{CCHs}$, hops$_{max}$, TTL$_{max}$, depth$_i$)*

# GTC algorithm (cont.)

***Join_Cluster()***

*Listen_Broadcast_Cluster($NID_{CH}$, $CID_{CH}$, $hops_{max}$, $TTL_{max}$, TTL, depth)*

*TTL ← TTL – 1, hops ← $TTL_{max}$ – TTL*

***IF*** *(hops ≤ $hops_{max}$* ***AND*** *my_CID = 0)*

*my_CID ← $CID_{CH}$, my_CH ← $NID_{CH}$, my_depth ← depth + 1*

*Send_ACK(my_NID, hops, $p_1$, $p_2$)*

***IF****(TTL > 0)*

*Wait(Random(backoff_time))*

*Forward_Broadcast_Cluster($NID_{CH}$, $CID_{CH}$, $hops_{max}$,, $TTL_{max}$, TTL, depth)*

***IF****(hops ≤ hopsmax)*

*Exit()*

***ELSE***

*IF(Wait_Listen_Neighbors(Random(backoff_time) = FALSE)*

*Send_ACK(my_NID, hops, $p_1$, $p_2$)*

***IF****(Listen_Form_Cluster(CCH, CID, delay, $n_{CCHs}$, $hops_{max}$, $TTL_{max}$, depth, timeout) = TRUE)*

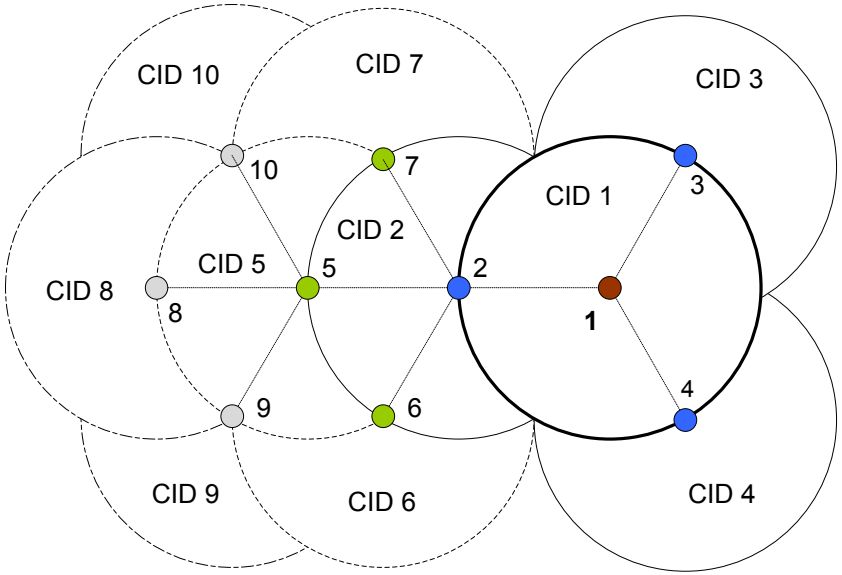
*Form_Cluster(my_NID, CID, delay, $n_{CCHs}$, $hops_{max}$, $TTL_{max}$, depth)*

*Exit()*

*Join_Cluster()*

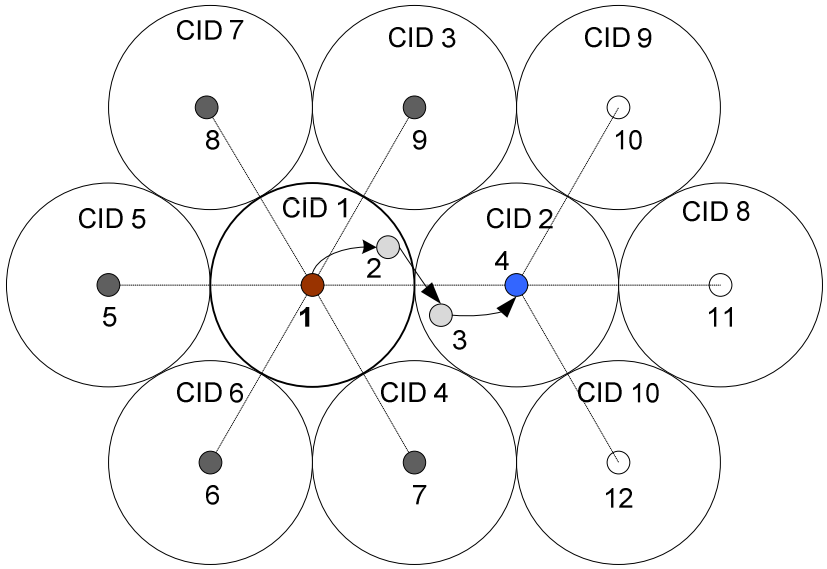
# GTC algorithm (cont.)

- SHC – Simple Hierarchical Clustering
- HHC – Hop-ahead Hierarchical Clustering




SHC clusters

$hops_{max} = TTL_{max} = 1$

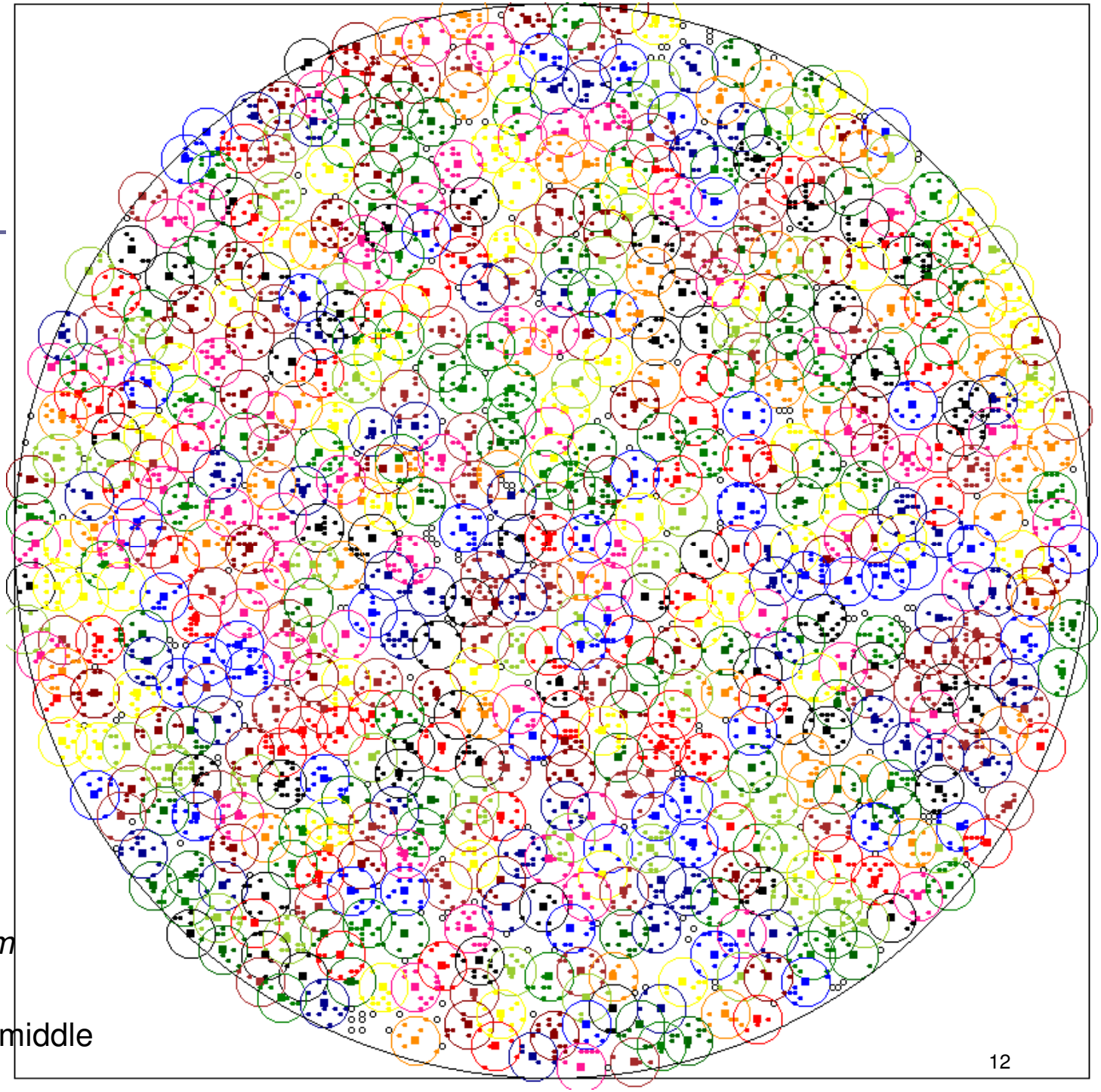



HHC clusters

$TTL_{max} = 2 \times hops_{max} + 1$

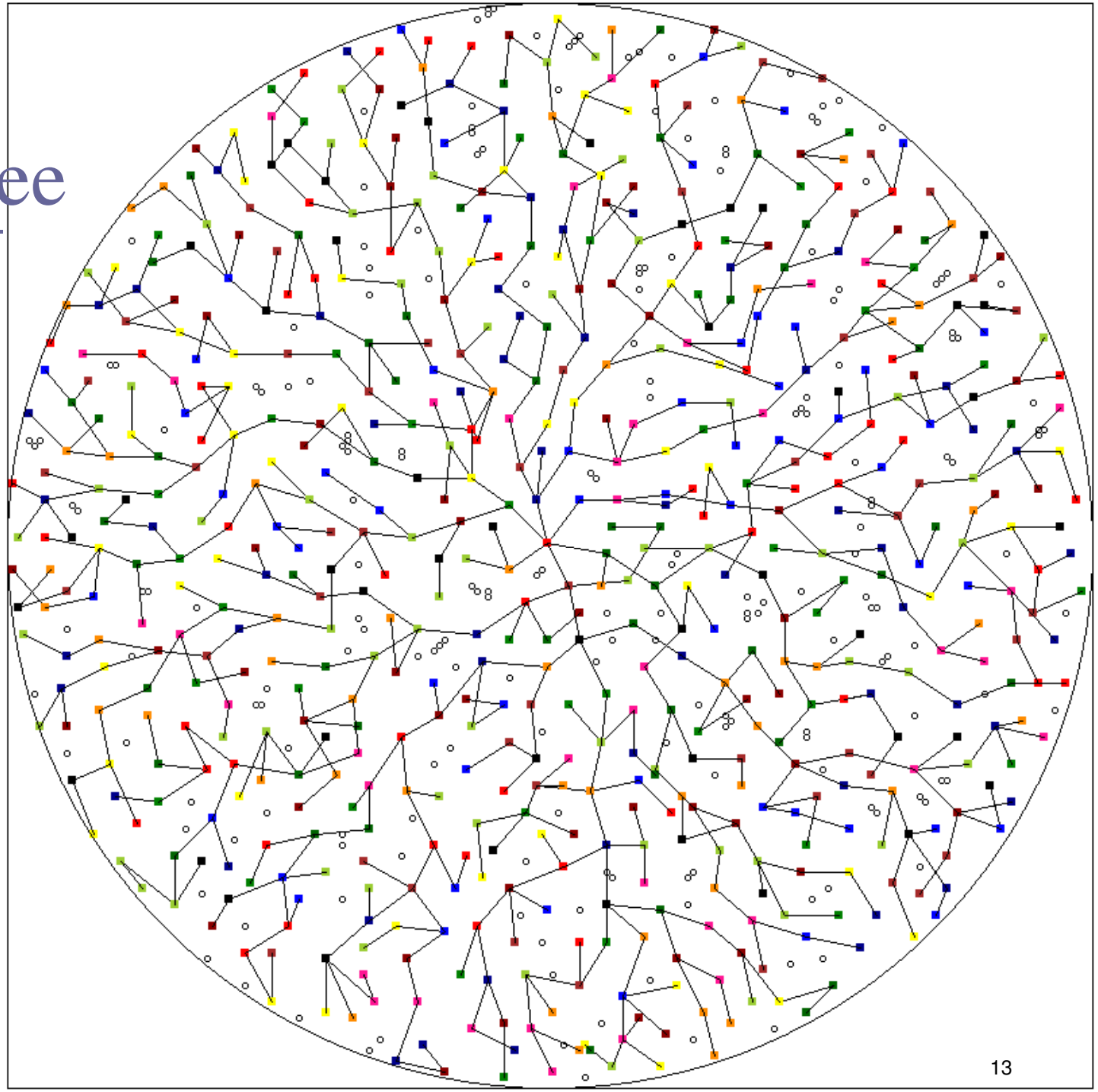
*Similar to IEEE 802.15.4 cluster tree*

# Clusters

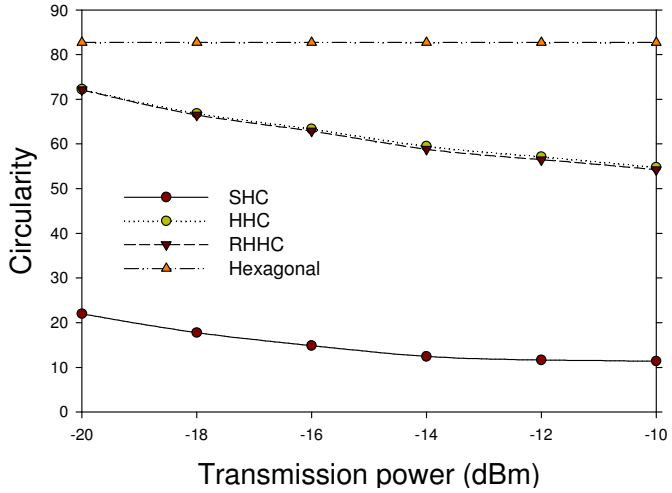


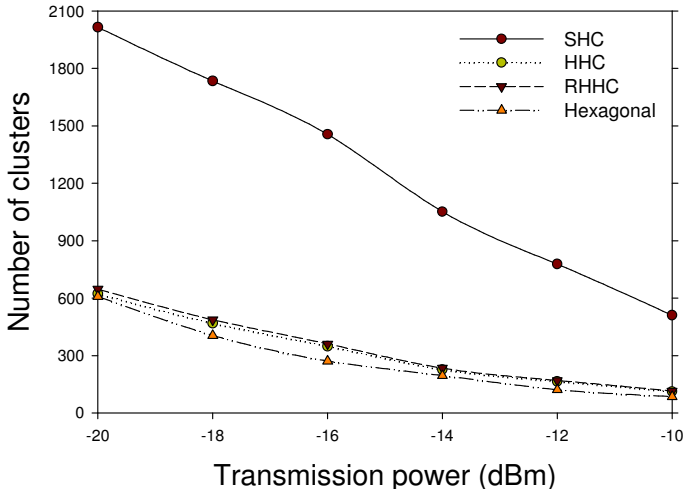
- HHC
- 5000 nodes
- Grid - *201×201*
- Grid spacing – *5m*
- *R = -20dBm*
- Root node in the middle

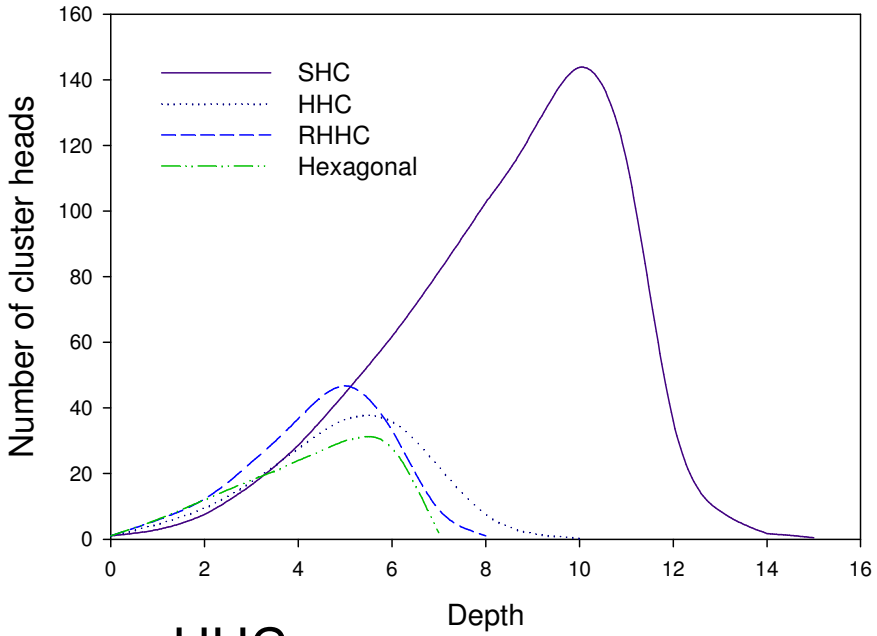
# Cluster tree



# Performance analysis

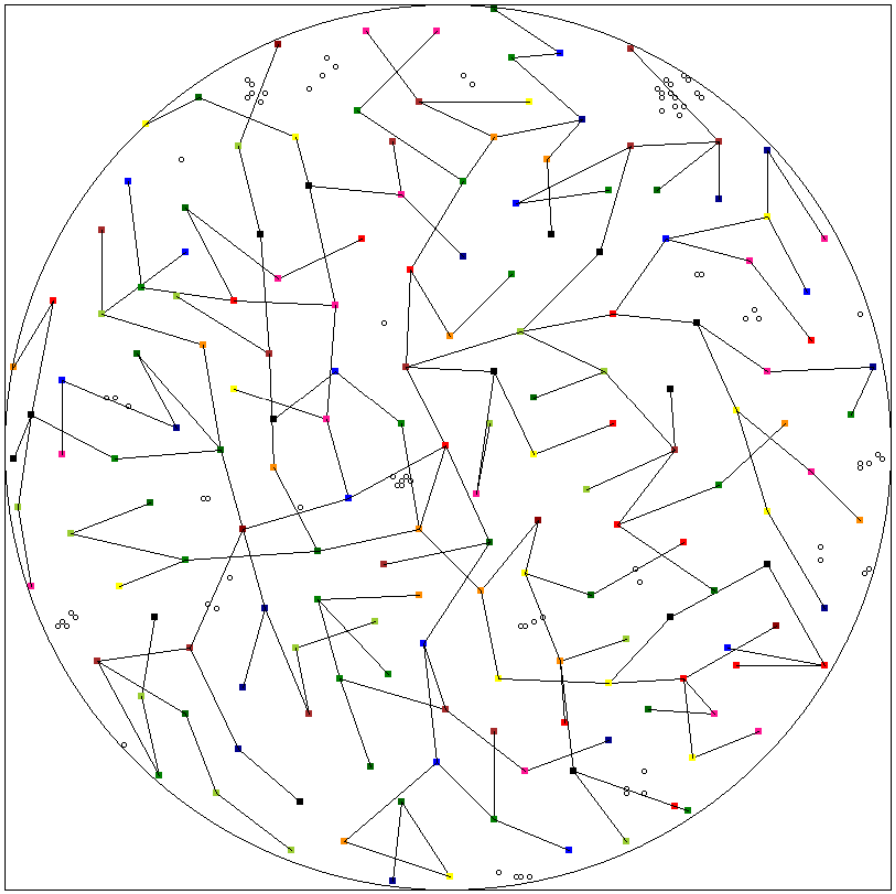


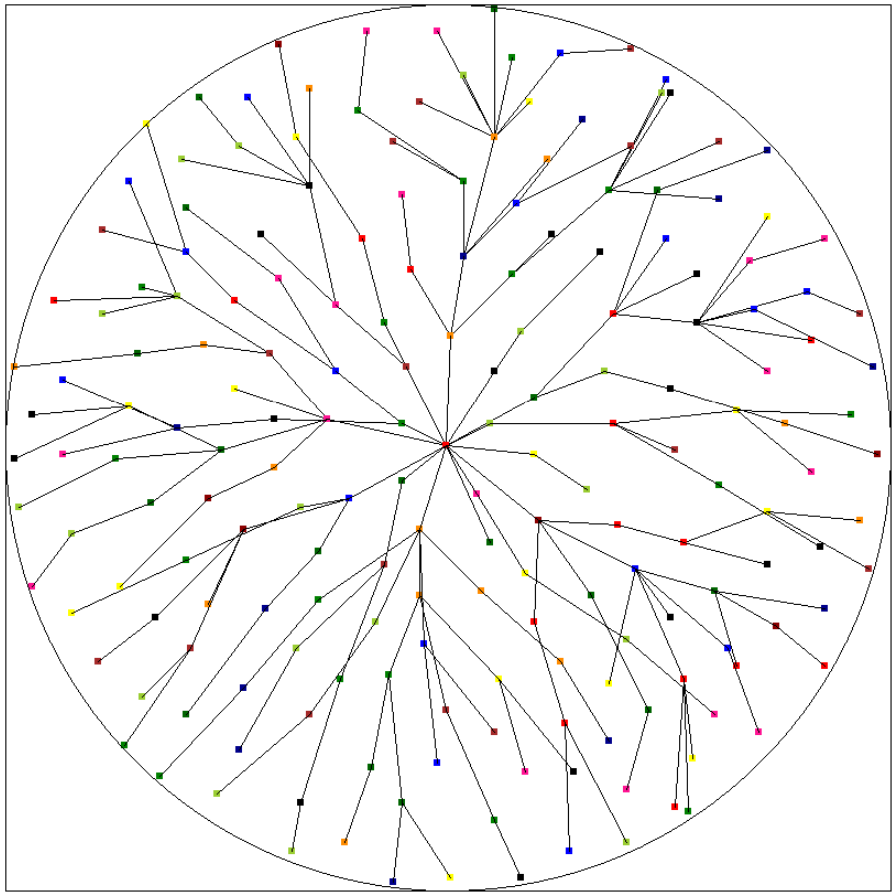




- HHC
  - Uniform clusters
  - Better circularity
  - Lower number of clusters
  - Lower depth
  - Message complexity *O(n)*

# Optimization phase –
## Handling disconnected nodes & optimizing cluster tree





*$P_T$ = -12dBm, 5000 nodes*

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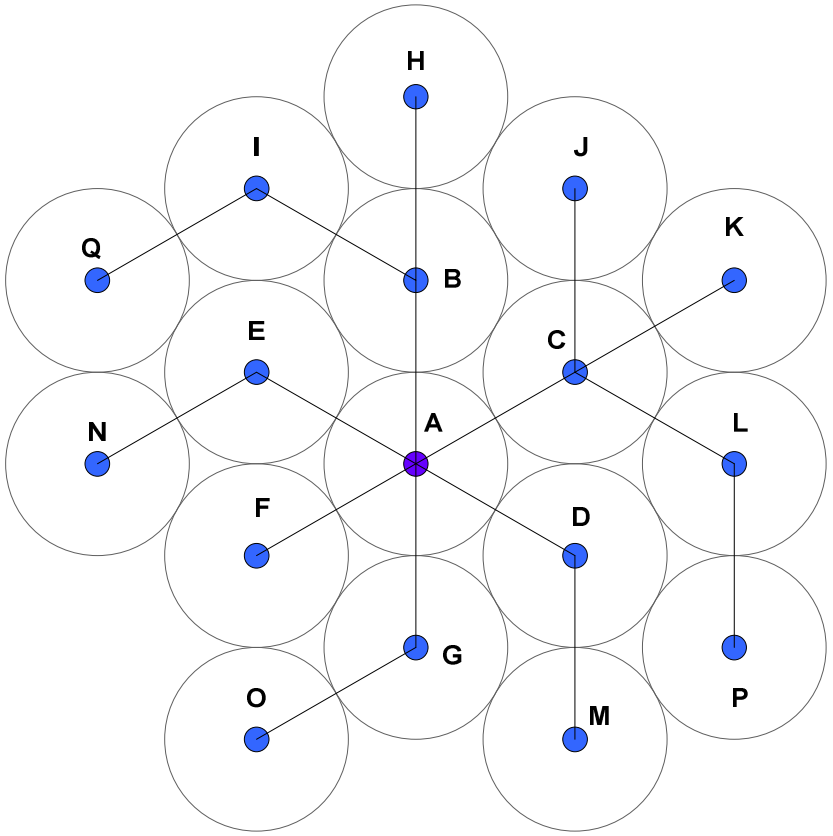
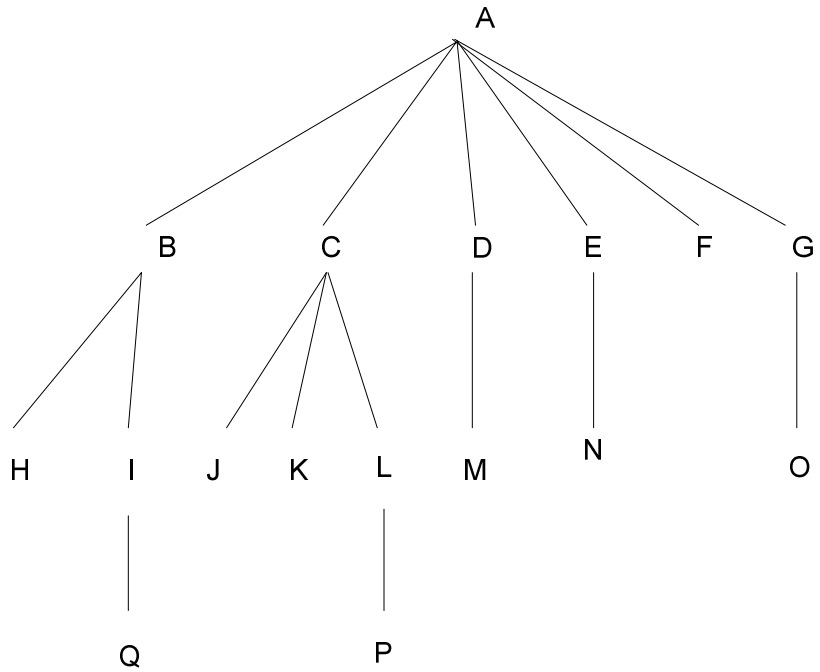
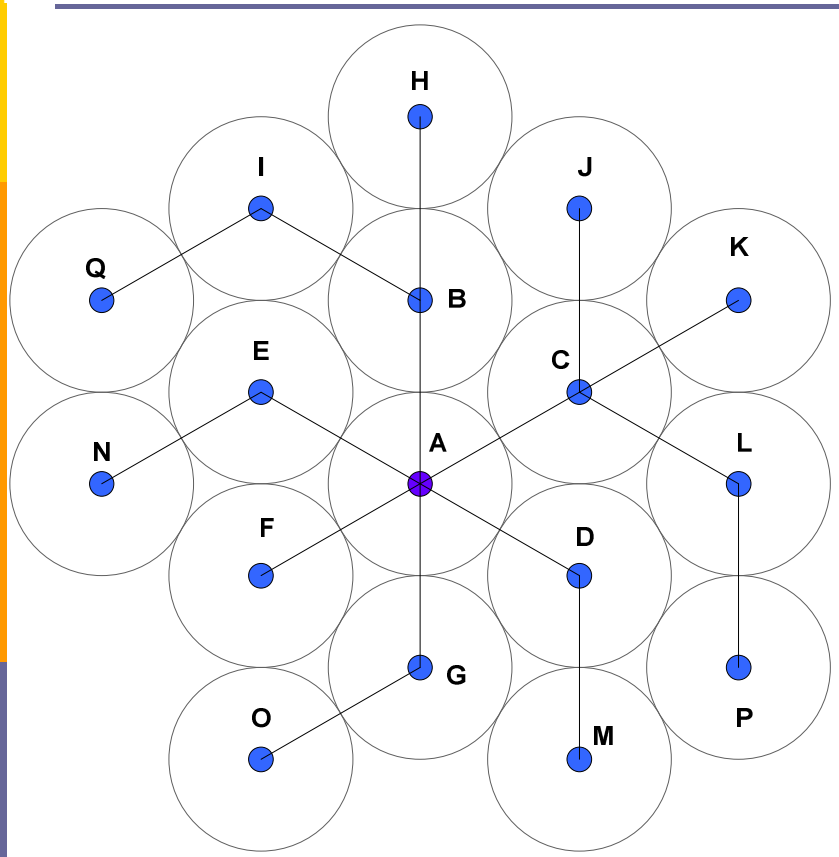
# Cluster tree based routing

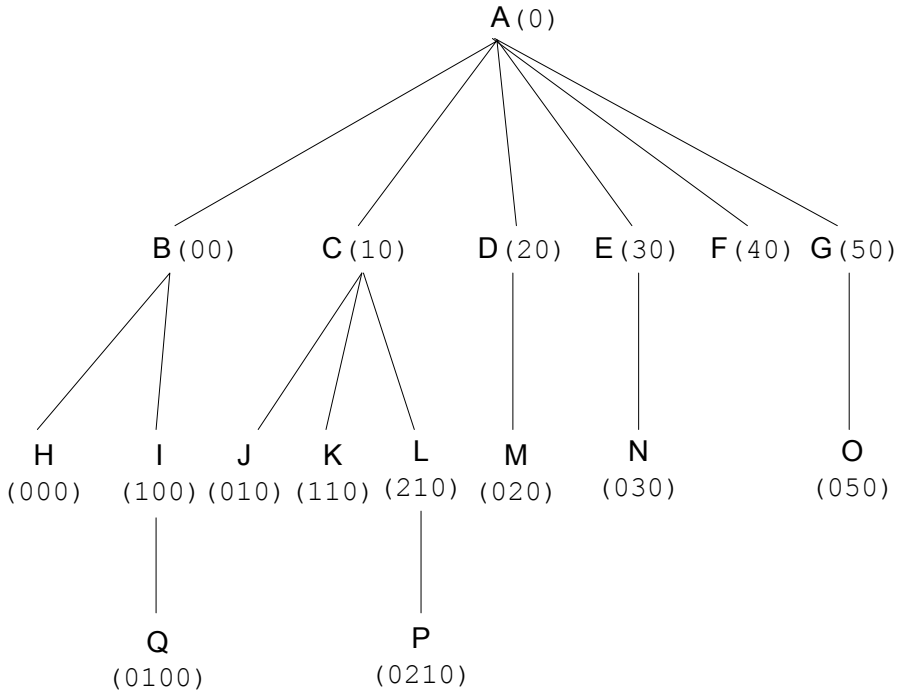



- Need some sort of an addressing scheme to route

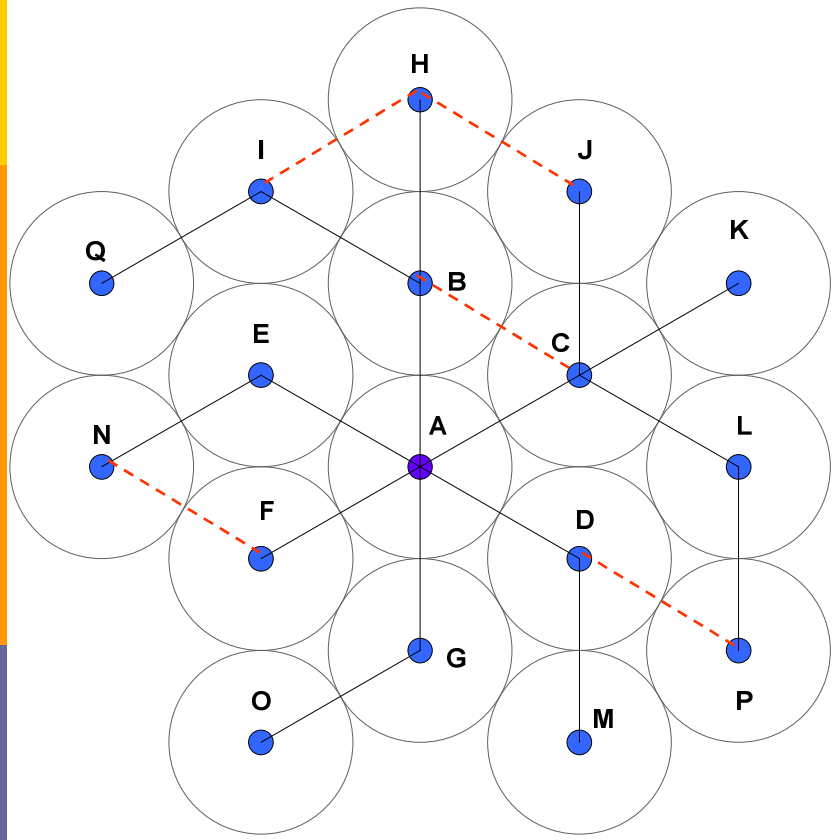
# Hierarchical addressing

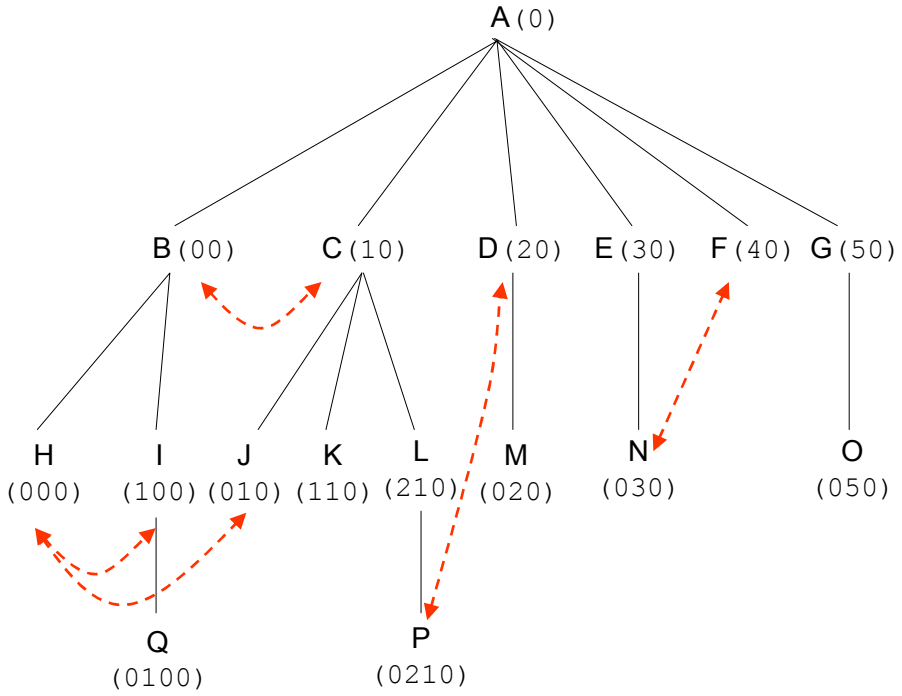



- Single point of failure at root node

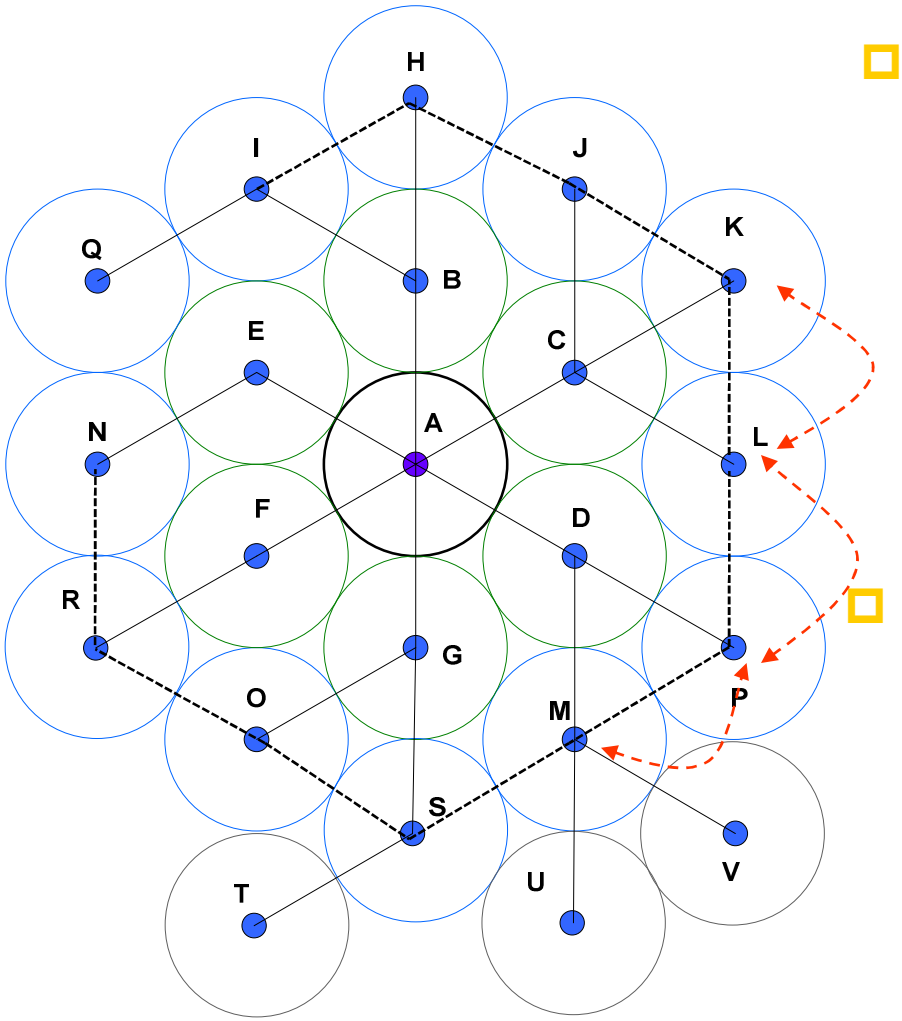
# Cross-links based routing



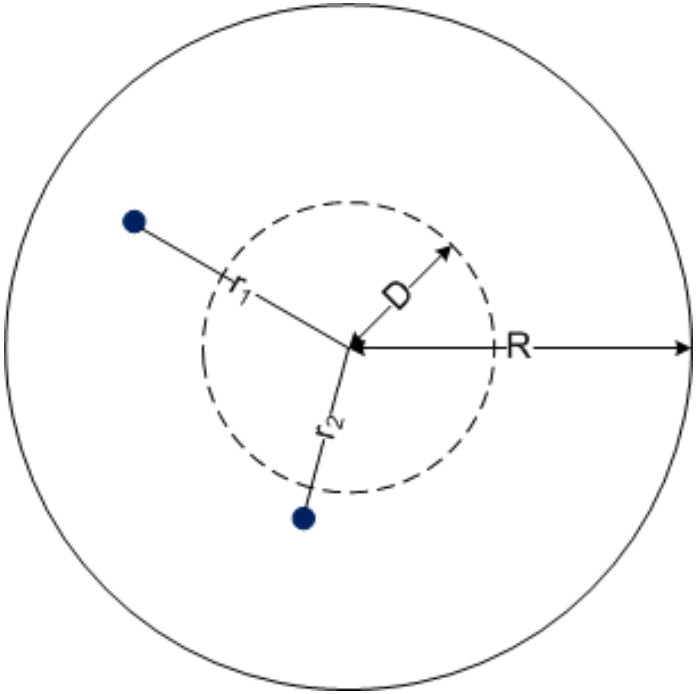

- Routing through cross links
  - Reduce burden on the root node
- Use hierarchical addresses

# Circular path based routing




- Send message from U to K
  - Hierarchical routing - 5 hops
  - Cross links - 5 hops
  - Circular path - 4 hops
- Circular path
  - Connects clusters at the same depth
  - Reduce workload on root node
  - Use hierarchical addresses

# Circular path based routing – Analytical model




$$E[cost] = E[energy\ to\ transmit]$$
$$= E[energy\ \ per\ hop \times hops]$$
$$= E\left[ energy\ \ per\ hop \times \frac{distance}{transmission\ range} \right]$$
$$= \frac{E_T}{r} \times E[d]$$

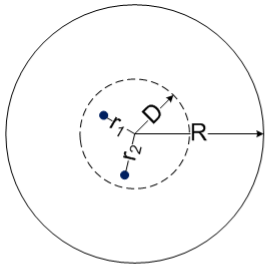
$$where \quad d = r_1 + r_2$$

$$E[d] = \iiint d(r_1, r_2, \theta)\, p(r_1, r_2, \theta)\, dr_1 dr_2 d_\theta$$

- $R$ – Radius of sensor field
- $D$ – Radius of circular link
- $r$ – Transmission range of a node
- $r_1$ – distance to source node
- $r_2$ – distance to destination node
- $E_T$ – energy to send a message

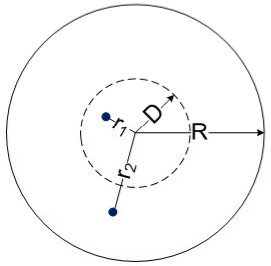
# Analytical model (cont.)

(a)



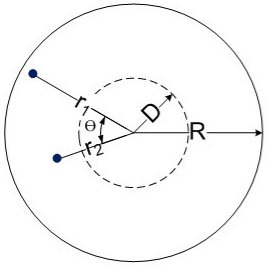

$0 \le r_1 < D$
$0 \le r_2 < D$
$0 \le \theta \le 2\pi$
$d = r_1 + r_2$

(b)



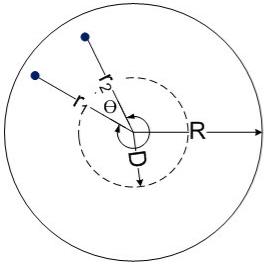

$0 \le r_1 < D$
$D \le r_2 \le R$
$0 \le \theta \le 2\pi$
$d = r_1 + r_2$

(c)



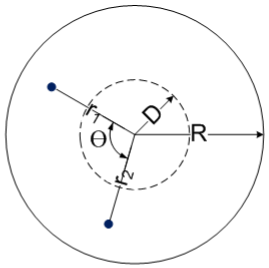

$D \le r_1 \le R$
$D \le r_2 \le R$
$0 \le \theta \le \alpha$
$d = (r_1 - D) + (r_2 - D) + D\theta$

(d)



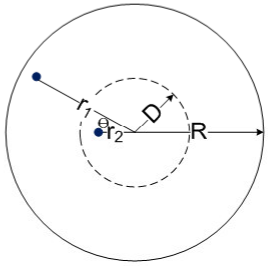

$D \le r_1 \le R$
$D \le r_2 \le R$
$2\pi - \alpha \le \Theta \le 2\pi$
$d = (r_1 - D) + (r_2 - D) + D(2\pi - \Theta)$

(e)



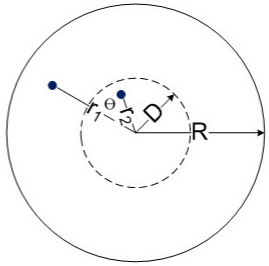

$D \le r_1 \le R$
$D \le r_2 \le R$
$\alpha < \Theta < 2\pi - \alpha$
$d = r_1 + r_2$

(f)



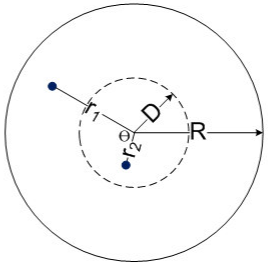

$D \le r_1 \le R$
$0 \le r_2 < D$
$0 \le \Theta \le \beta$
$d = (r_1 - D) + (D - r_2) + D\Theta$

(g)




$D \le r_1 \le R$
$0 \le r_2 < D$
$2\pi - \beta \le \Theta \le 2\pi$
$d = (r_1 - D) + (D - r_2) + D(2\pi - \Theta)$

(h)




$D \le r_1 \le R$
$0 \le r_2 < D$
$\beta < \Theta < 2\pi - \beta$
$d = r_1 + r_2$

# Analytical model (cont.)

$$E[d] = \frac{4R}{3} - \frac{2D}{\pi} + \frac{3D^3}{\pi R^2} - \frac{D^5}{\pi R^4}$$

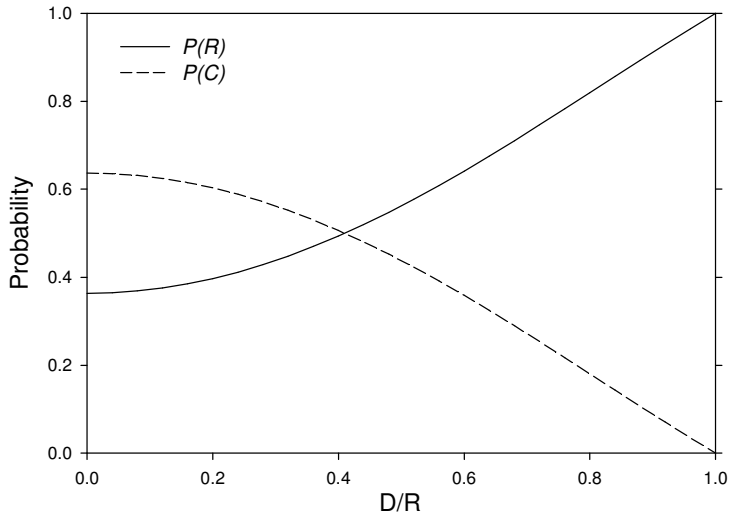
$$\frac{E[d]}{dD} = -\frac{2}{\pi} + \frac{9D^2}{\pi R^2} - \frac{5D^4}{\pi R^4}$$

$$\therefore D = 0.509R$$

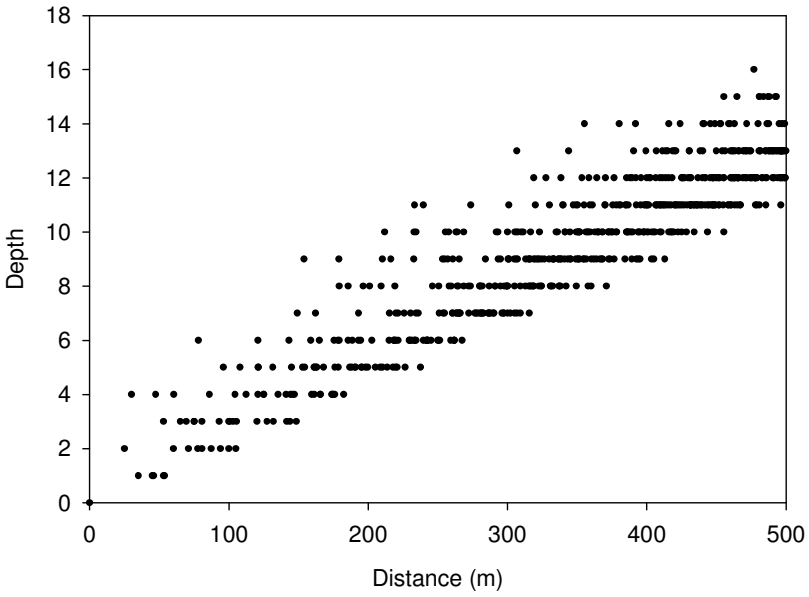
$$P(R) = \frac{\pi - 2}{\pi} + \frac{8D^2}{3\pi R^2} - \frac{2D^4}{3\pi R4}$$

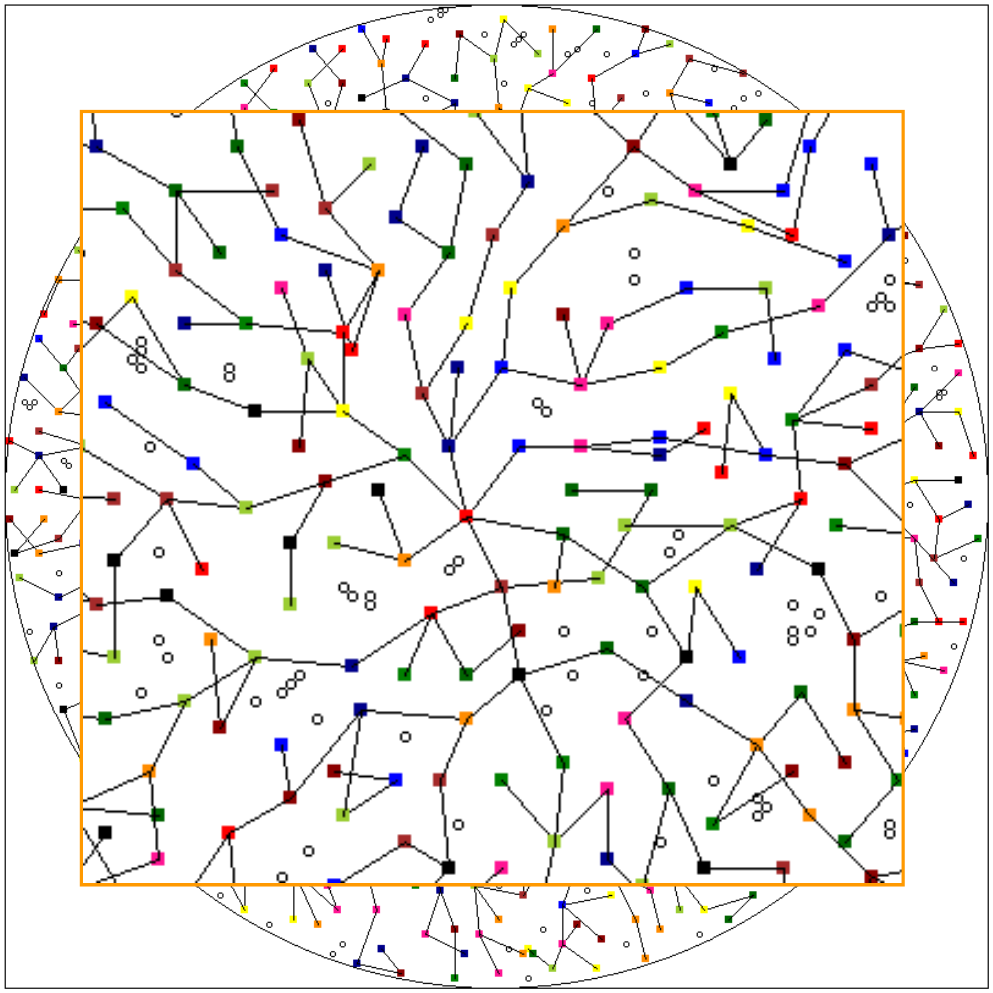
$$P(C) = \frac{2}{\pi} - \frac{8D^2}{3\pi R^2} + \frac{2D^4}{3\pi R4}$$

- *P(R)* – Probability of going through root node
- *P(C)* – Probability of going through circular path



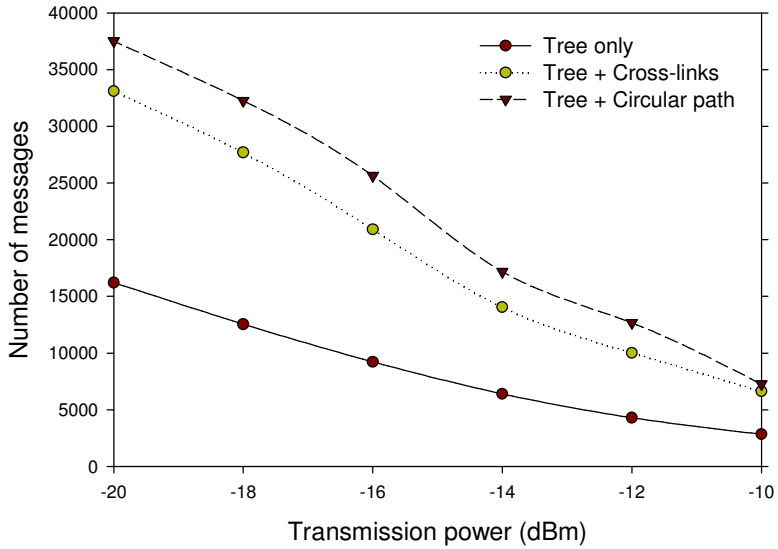
# Routing - Performance analysis



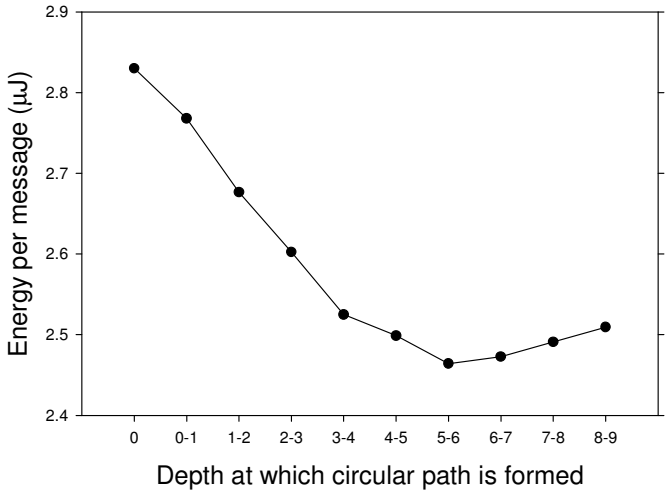
$P_T$ = -20dBm, 5000 nodes

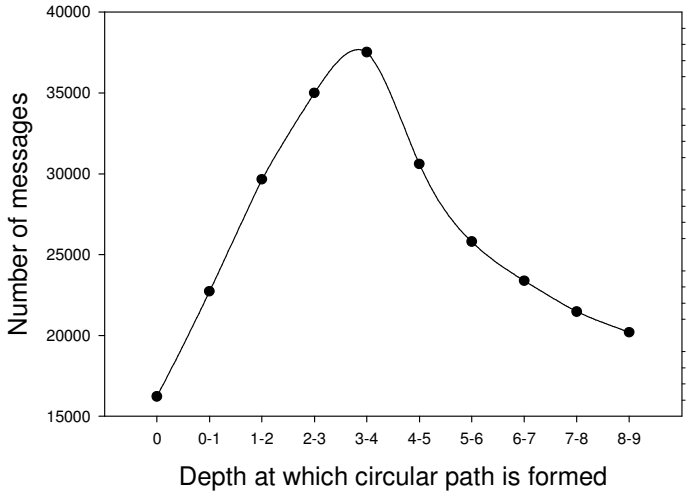
# Performance analysis (cont.)




5000 nodes, circular sensor field

- Cross links helps to deliver more messages
- Circular path delivers even more messages




$P_T$ = -20dBm

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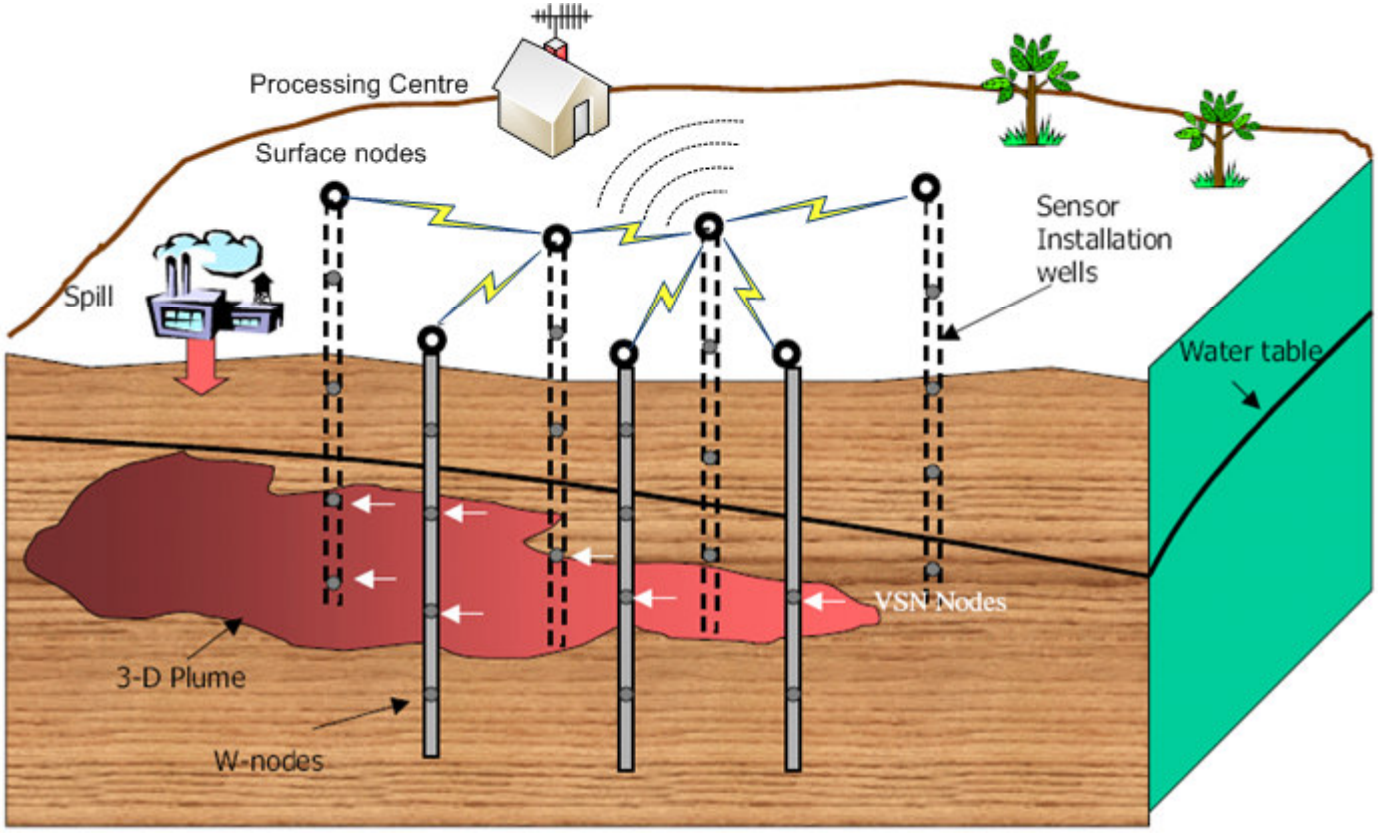
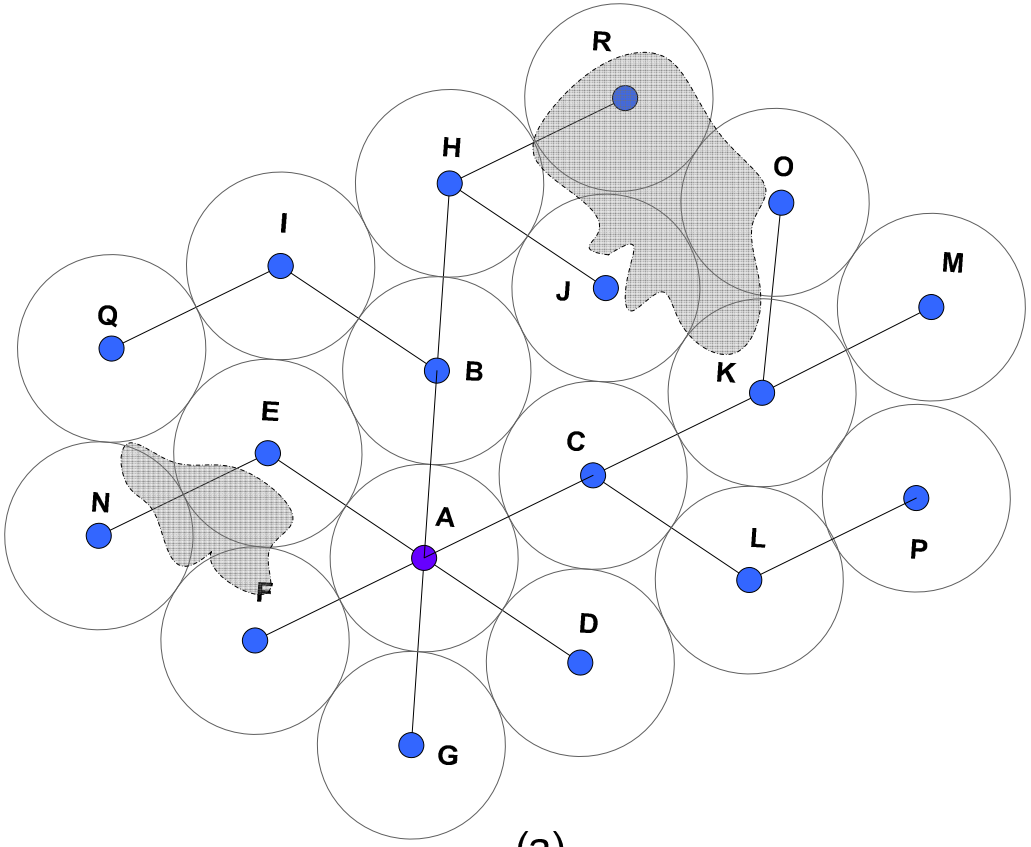
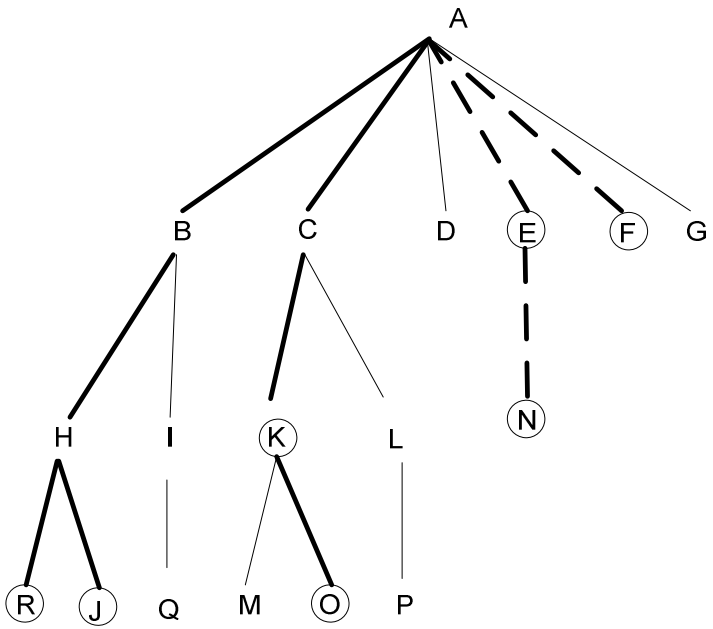


# Forming VSNs



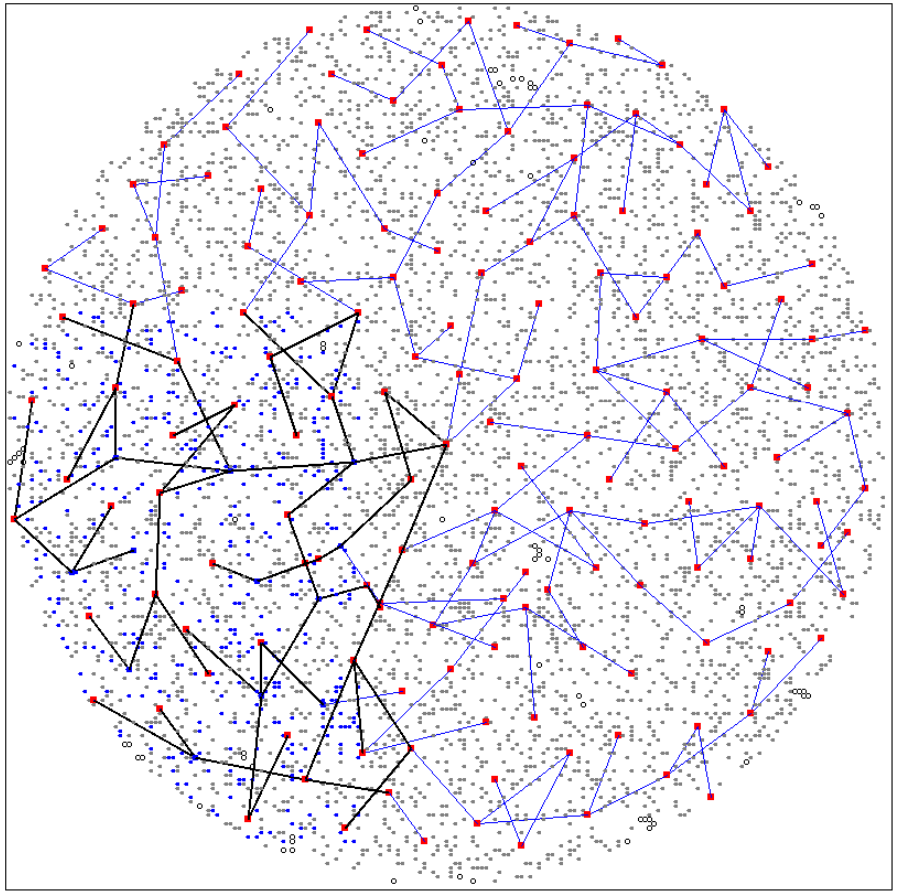

(a)



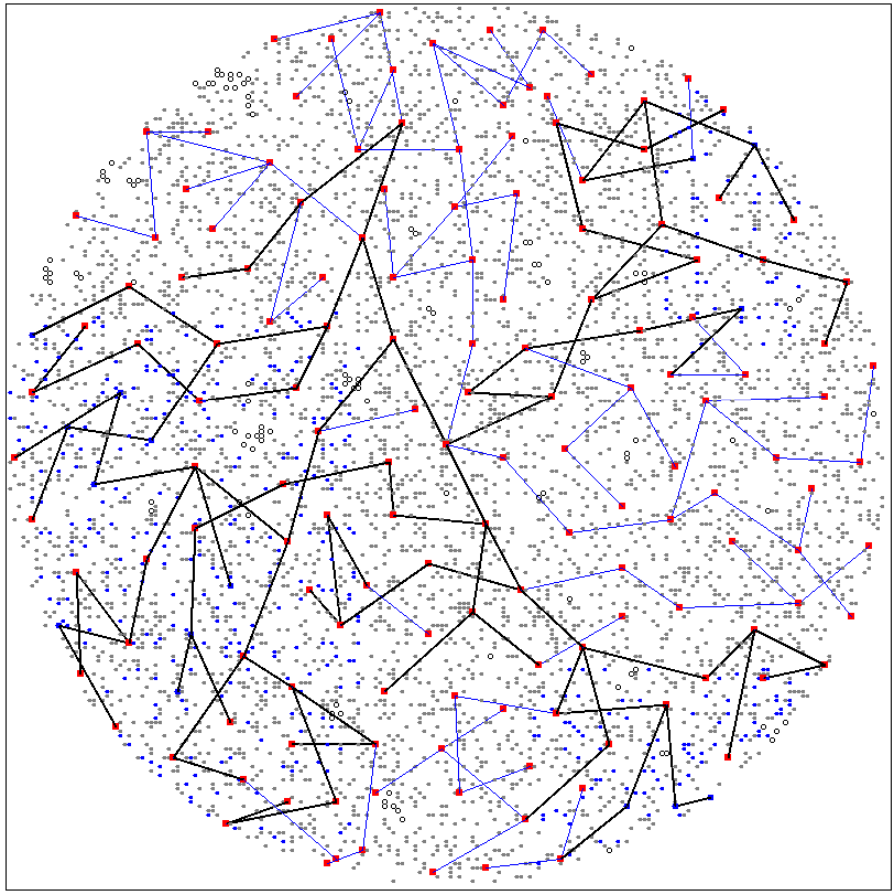

(b)

- Messages are guaranteed to meet at root node
  - Forms a virtual tree
  - More efficient & reliable than rumor & ant routing

# Forming VSN –
## Virtual tree that connects VSN members

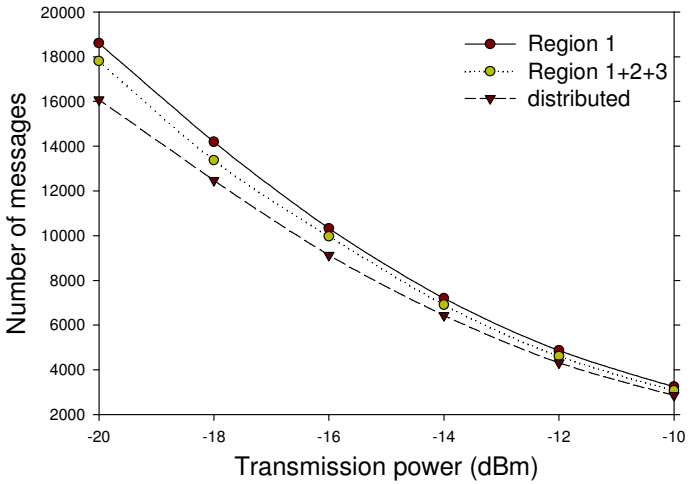


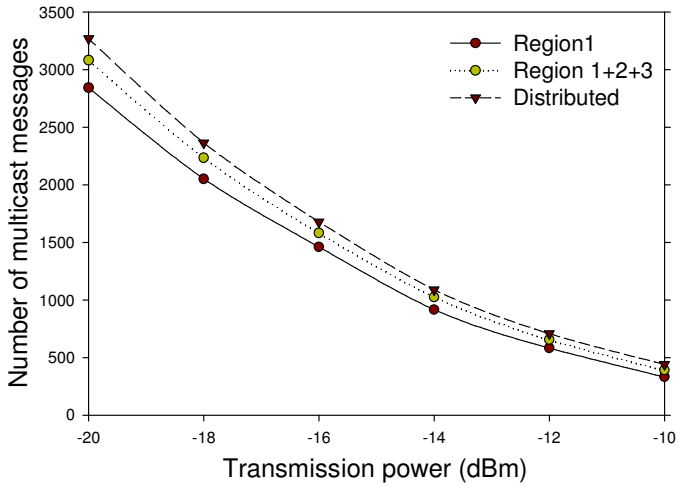
Single event region

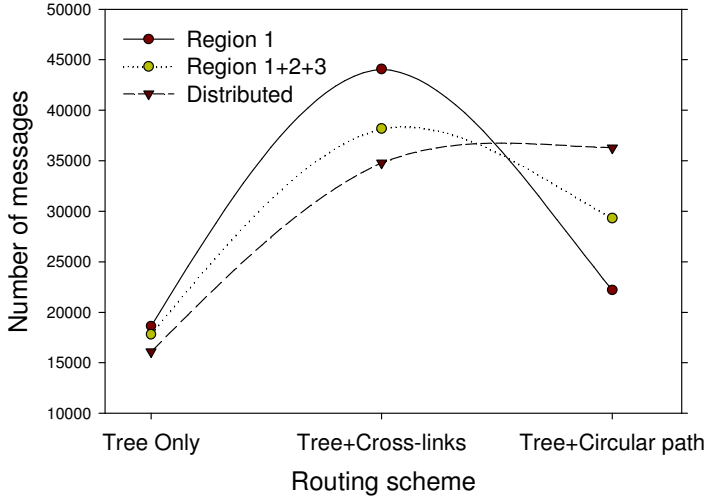


Three event regions

# VSN - Performance analysis



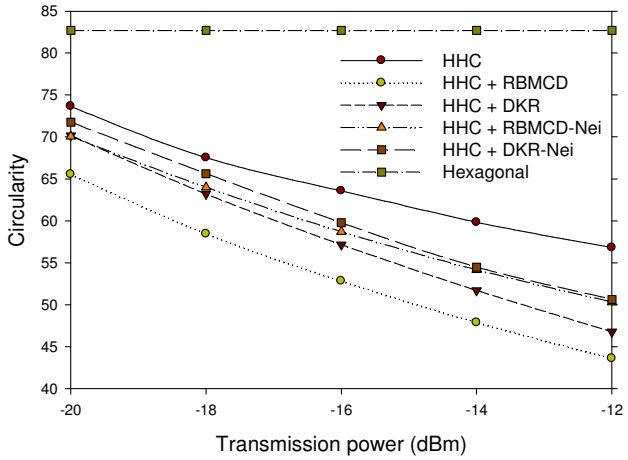



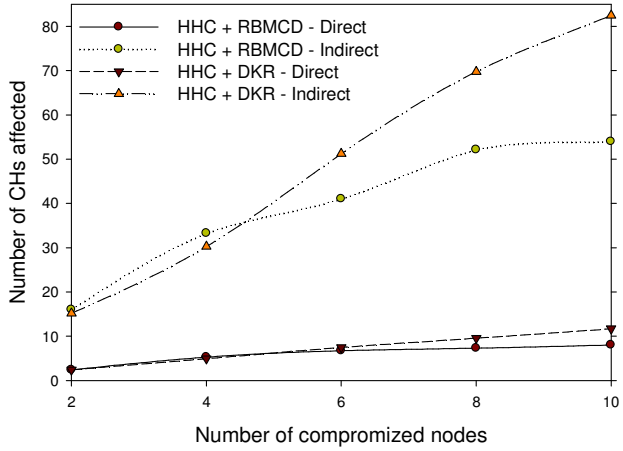




$P_T$ = -20dBm

# Secure backbone design

- Can support
  - dynamic key distribution
  - secure upper layer functions
- Secure VSNs need dynamic key assignment
- GTC algorithm can be extended to build a secure backbone
  - No significant changes are required
- Retains most of its desirable characteristics



# Future directions

- Test performance of our algorithms on a rigorous simulation platform such as TOSSIM
- Use actual data from a tank based testbed
- VSN management functions
  - VSN dynamics
    - e.g., migrating, disappearing, merging, & splitting plumes
  - Identifying multiple networks
  - Connecting them
- Routing algorithms that are not tied to the cluster tree
- Dynamic key distribution with & across VSNs

# Summary

- A mechanism to form VSNs
  - Connect nodes observing the same phenomenon
  - Inter-VSN & intra-VSN communication
- A cluster & cluster tree formation algorithm
  - Hop-ahead Hierarchical Clustering (HHC)
    - More uniform & circular clusters
    - Cluster tree with lower depth
    - Properties are comparable with hexagonal packing
- Cluster tree based routing
  - Hierarchical addressing scheme
  - Cross-links & circular path based routing schemes increase network lifetime at least by a factor of 2

# Related publications

- Conference Papers
  - H. M. N. D. Bandara and A. P. Jayasumana, “An enhanced top-down cluster and cluster tree formation algorithm for wireless sensor networks”, 2nd International Conference on Industrial and Information Systems (ICIIS 2007), Sri Lanka, Aug. 2007.
  - H. M. N. D. Bandara, A. P. Jayasumana, and I. Ray, “Key pre-distribution based secure backbone design for wireless sensor networks”, *3rd International Workshop on Practical Issues in Building Sensor Network Applications (SenseApp 08)*, Oct. 2008, *to be published*.

- Posters
  - H. M. N. D. Bandara, A. P. Jayasumana, T. H. Illangasekare, and Qi Han, “A wireless sensor network based system for underground chemical plume tracking,” *CSU Ventures*, Fort Collins, CO, Feb. 2008.
    - First place - ISTeC Student Research Poster Contest

# Questions ?

Thank You…