

Topology Control in Multi-Hop Wireless Ad Hoc Networks

Presenter: Ellen (Xiaolan) Zhang
Red Team: Wei Wei, Huan Li

Papers: Distributed Topology Control for Power Efficient Operation in Multihop Wireless Ad Hoc Networks, INFOCOM 2001,
Analysis of a Cone-Based Distributed Topology Control Algorithm for Wireless Multihop Networks, ACM PODC 2001

Slides adapted from those of :

Li (Erran) Li, erranli@dnrc.bell-labs.com

Outline

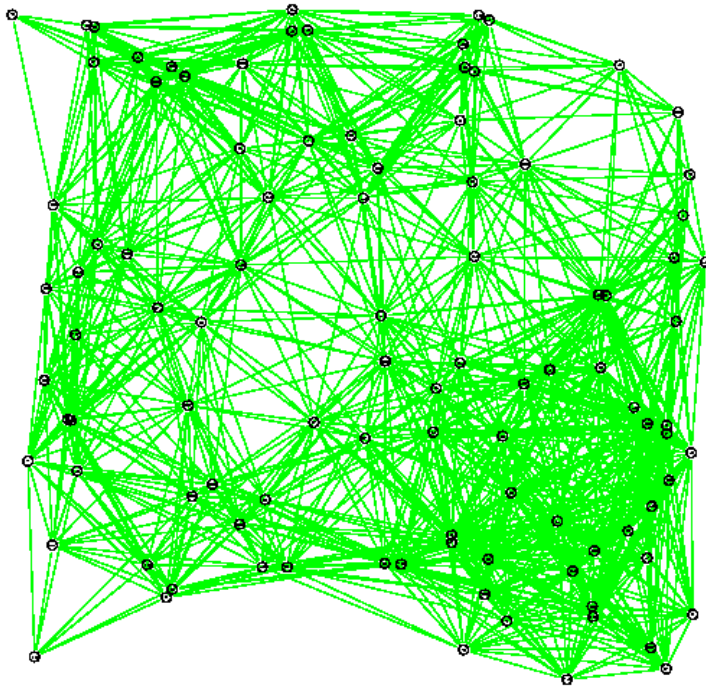
- Introduction
- Design goals
- Cone-based algorithm
 - Connectivity, power efficiency
 - Optimizations
- Performance results
- Conclusions

Introduction

- Problem definition
 - Multi-hop wireless ad-hoc network
 - Nodes discover neighboring nodes
 - Routing protocol built on-top the discovered network topology
 - Topology control determines the network topology by controlling the transmission power of sending a physical layer broadcast.

Motivation

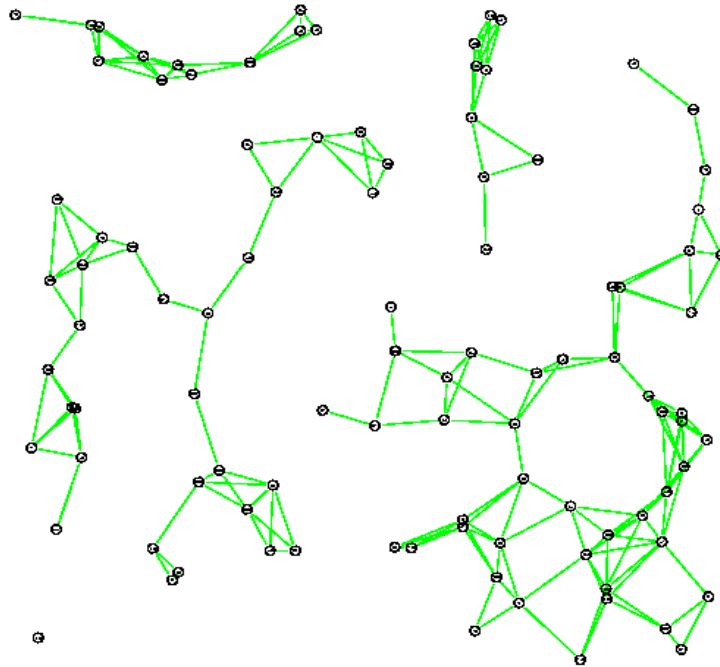
- No topology control: large transmission radius



- high interference
- High energy consumption
 - Power grows at least quadratically with distance, reply path is often more power efficient
- Low throughput

Motivation (cont'd)

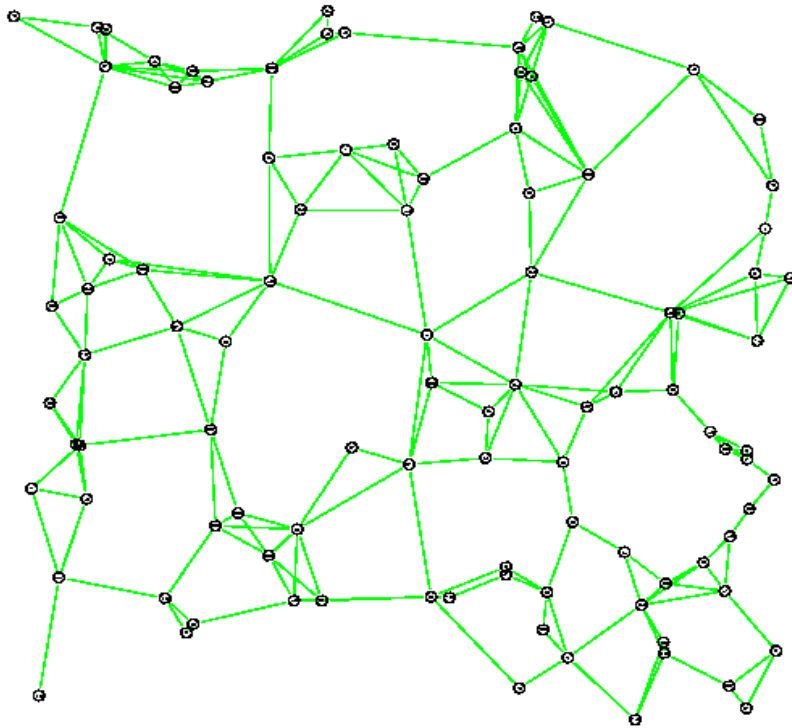
- No topology control: small transmission radius



- Network may partition

Motivation (cont'd)

- With topology control



- Global network connectivity
- Little interference
- Low energy consumption
- High throughput (less contention)

Design Goals

- Low energy consumption
- Maintain global connectivity
- Distributed protocol using local information
- Heuristic guidelines:
 - Minimize the transmission radius of each node
 - Bound node degree
- Other metrics (studied in simulation)
 - High throughput
 - Low delay

Basic Cone-based Algorithm

■ *Assumption*

- receiver can determine the direction of the sender :
 - Directional antenna community: Angle of Arrival problem
- Nodes send broadcast message with arbitrary power p , $0 \leq p \leq P$, P : maximum power, same for all nodes
- Power is a uniform and non-decreasing (unknown) function of distance d .

Model and Notations

- Graph $G'=\{V,E'\}$
 - the connection graph when all nodes always beacon with max. power P)
- Graph G :
 - The connection graph when each node u transmit with power $p(u)$ ($\leq P$) which is determined by topology control
- $p(u,v)$: denotes the power required to reach v from u
- $p(d)$: the power required to reach distance of d
- $C(r)$: the total power consumption for a route (sum of the power to traverse each edges)

Basic Cone-Based Algorithm

- A simple protocol with two phases
 - Phase 1: Each node A discovers neighboring nodes until it finds a node in every cone of degree α or it reaches the maximum power.
 - Symmetric: if u wants node v to be its neighbor, then node v also needs to put u as its neighbor
 - Denote by $N(u)$ the set of neighbors of u discovered.

Basic Cone-Based Algorithm (phase 1)



Can I stop? **No! There's an α -gap!**

Need a neighbor in every α -cone.

Basic Cone-Based Algorithm (phase 2)

- Phase 2: remove inefficient edges while keeping all the best routes (least power)

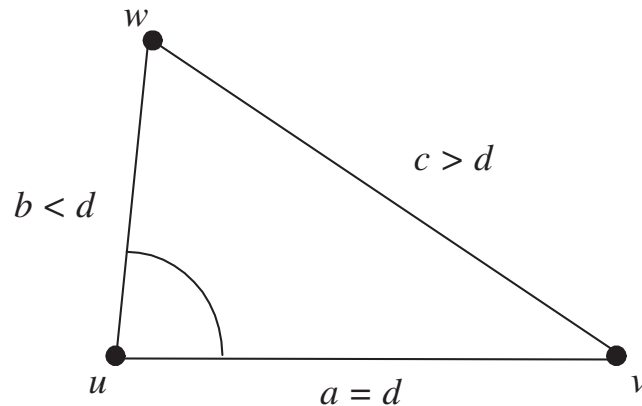
If node u has two neighbor nodes:

$$v, w \in N(u)$$

- and $p(u,v)+p(v,w) \leq q \cdot p(u,w)$, $q \geq 1$
- Then remove w from $N(u)$ (and u from $N(w)$).
- When $q=1$, keeping all the best routes, i.e. minimum power routes
- When $q>1$, bound the number of neighbors of a node

Connectivity

- Theorem: if $\alpha \leq 2\pi/3$, if $G' = \{V, E'\}$ is connected, then G (constructed by the algorithm) is also connected



Let u, v be a pair of nodes with no path, and with minimum power among all such pairs, $p(u, v) \leq P$

w is any neighbor of u , then $b < d$. If $c < d$, then w, v must have path, and therefore u, v have path. So $c > d$, which implies $\angle wuv > \pi/3$. There is no nodes in a $2\pi/3$ cone, algorithm shouldn't have stopped.

Power Efficiency

- Assumption: power $p(d)$ consumed to transmit to a distance of d satisfies:

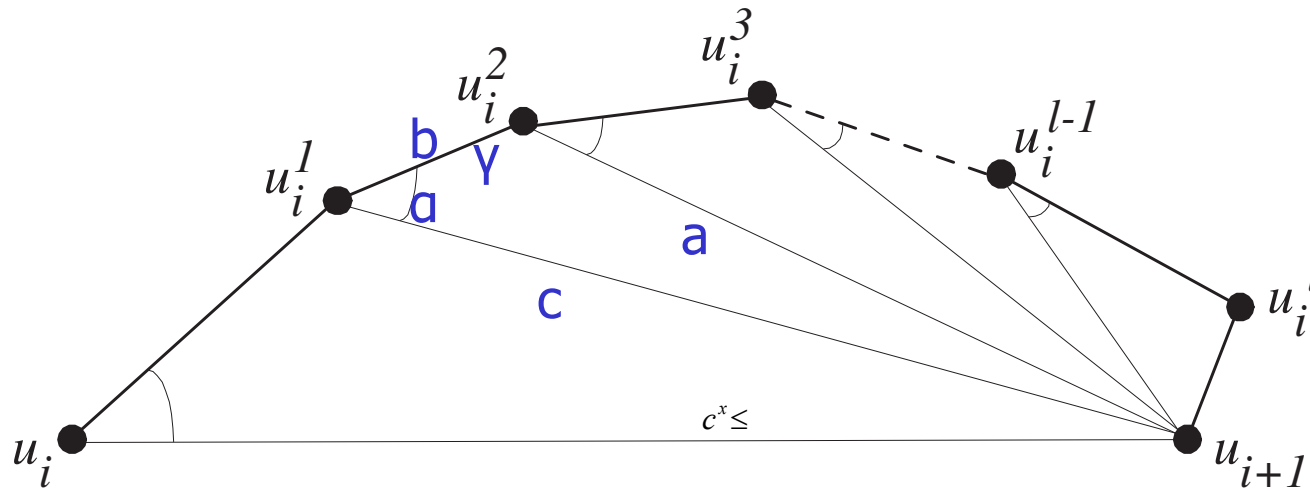
$$cd^x \leq p(d) \leq czd^x, z \geq 1, x \geq 2$$

- Routing algorithm : find minimum power route in a graph G
- Theorem: if $\alpha \leq \pi/2$, s, t be the source, sink node, then

$$C(r) \leq C(r')zq(1 + 2 \sin(\alpha / 2))$$

Where r, r' is the minimum power routes in G and G' respectively

Constructive Proof



For $r^*=(s=u_1, u_2, \dots, u_k=t)$ in G' , construct a path r in G by finding a path from u_i to u_{i+1} .

By algorithm construction, exists an next node such that $\alpha \leq 4/\pi$,

Case 1: if $a > b$, then $\gamma > \pi/2$, and $a < c$, and therefore $a^x + b^x \leq c^x$

Case 2: if $a < b$, done, and $a^x + b^x \leq c^x (1 + 2 \sin(\alpha / 2))$

Combined with power model to prove the power spanner property.

Other results

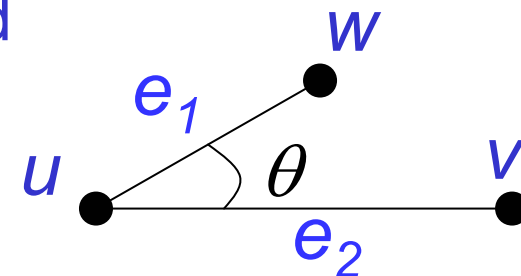
- Let $z=q=1$, to guarantee paths that use at most $1+\varepsilon$ of the power of optimal path, we need $\alpha \leq 1 \arcsin(\varepsilon/2)$.
- Let q (of phase 2) ≥ 2 , then degree of node is at most 6

Tight bound on α to preserve connectivity

- The algorithm constructs $G_\alpha = (V, E_\alpha)$, where $E_\alpha = \{ (u,v) \in V \times V: v \text{ is a discovered neighbor by node } u \text{ or vice versa} \}$
- Connectivity Theorem:
 - if $\alpha \leq 5\pi/6$, then G_α is connected if and only if G' is connected
 - the $5\pi/6$ degree bound is tight.

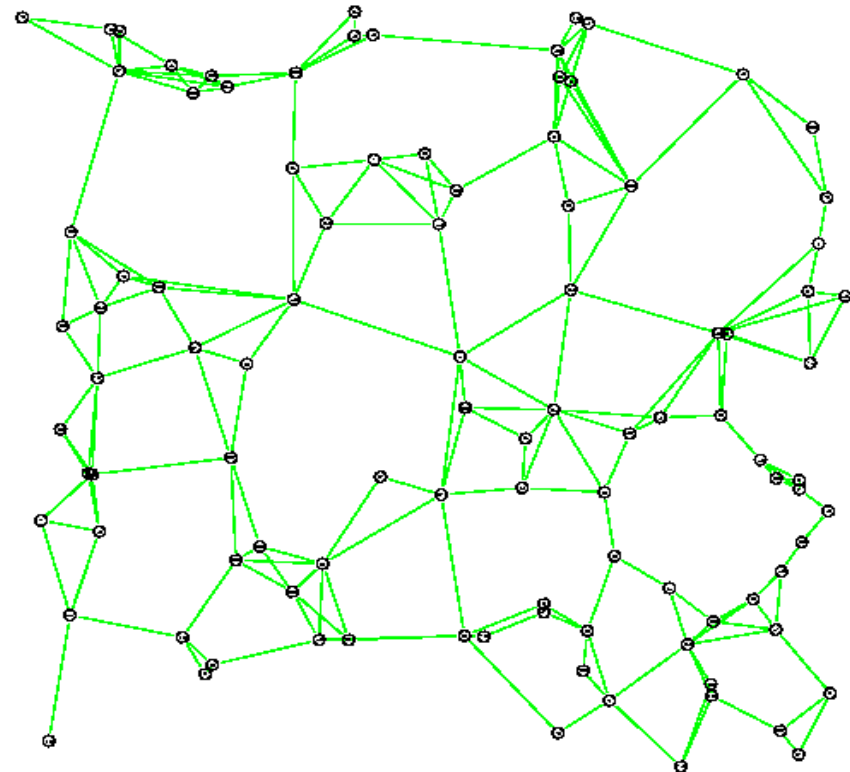
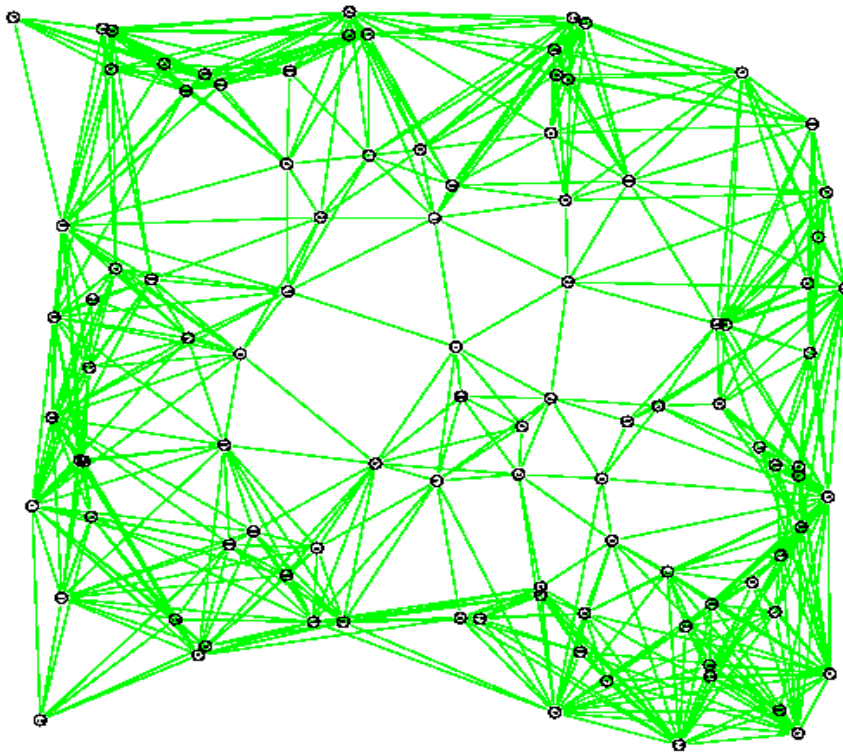
Optimizations on the Basic Algorithm

- Shrink-back operation
 - “Boundary nodes” can shrink radius as long as not reducing cone coverage.
- Asymmetric edge removal
 - If $\alpha \leq 2\pi/3$, remove all asymmetric edges
 - An edge (u,v) is *asymmetric* if u needs v for cone coverage but v does not need u .
- Pairwise edge removal
 - An edge (u,v) is *redundant* if there exists an edge (u,w) such that $d(u,v) > d(u,w)$ and $\angle vuw < \pi/3$.



Optimizations on the Basic Algorithm (Cont'd)

- Effect of optimizations: reduce node degree by 3-5 times, reduce average radius 3 times



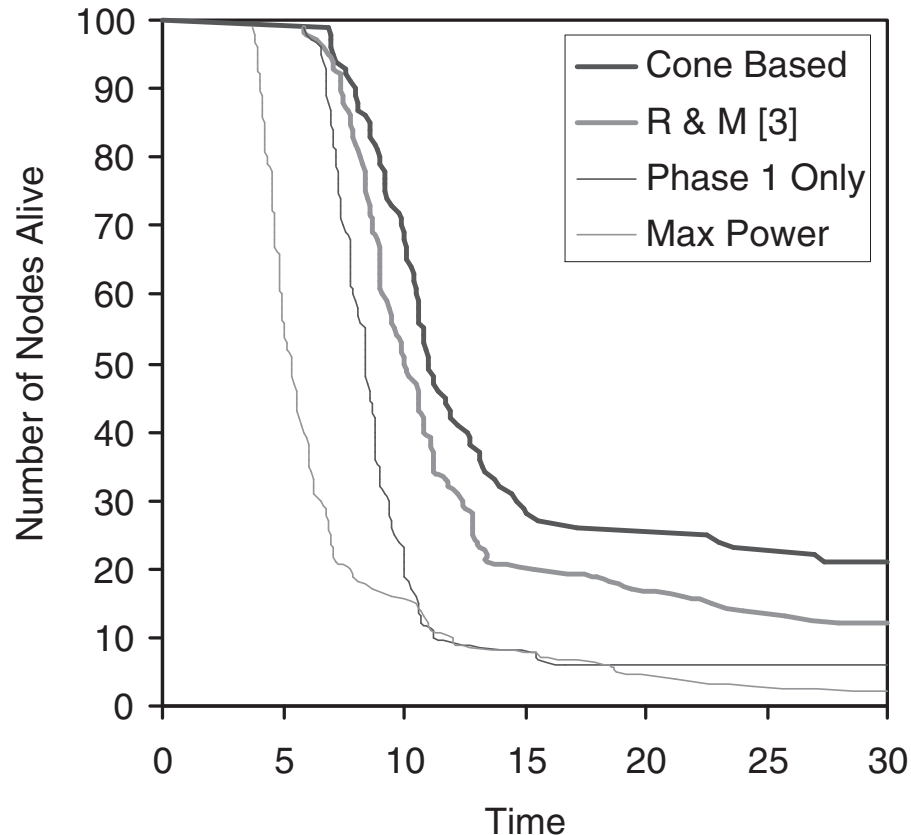
Evaluation through Simulation

- Simulation Environment
 - 100 nodes with WaveLan-I radios, placed uniformly at random at 1500*1500 meter region
 - Propagation model, wireless channel assumptions, CSMA/CA MAC
 - Routing: AODV using minimum energy metric
 - Application: all nodes periodically send UDP traffic to the master node at the boundary
- Topology control
 - Phase1Only, R&M (previous work use location info), ConeBased, MAXPower(no topology control)

Comparison : Resulting topology

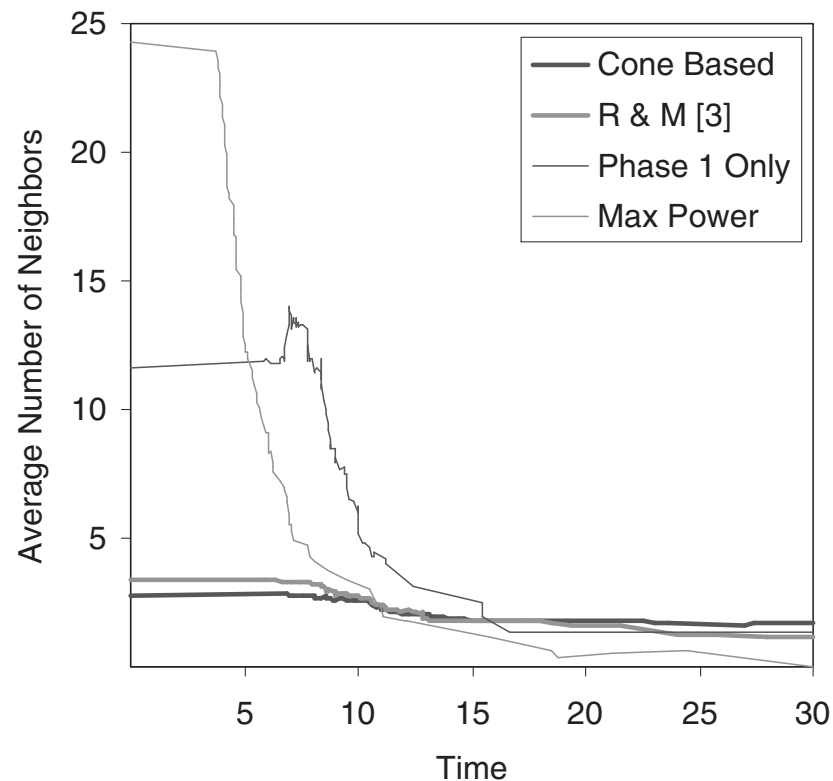
- Average degree
 - Phase1Only: $\alpha=2\pi/3$: 11.6, $\alpha=\pi/2$: 15.6
 - Cone-based: $\alpha=2\pi/3$: 2.8, $\alpha=\pi/2$: 2.8
 - R&M: 3.4
 - Max Power: 24.3
- Throughput
 - ConeBased, R&M achieve 4 times the thrput of MaxPower
 - Phase1Only achieves 3 times the thrput of MaxPower

Network Lifetime



- ConeBased and R&M have 90% nodes alive when with MaxPower 80% nodes dies
- Phase1Only still have more than 60% nodes alive when 80% of the MaxPower nodes are dead
- Why a sudden drop in # of alive nodes ? No dynamic load balancing mechanism.

Average Node Degree Over time



- Topology control maintain same avg. node degree as nodes die over time until $\leq 40\%$ nodes alive
- MaxPower node degree decrease quickly

Conclusions

- Contribution: distributed topology control algorithm
 - using only directional information
 - Condition for Preserve connectivity ($\alpha \leq 5/6\pi$)
 - Achieve power spanner property under certain power model and $\alpha \leq 1/2\pi$
 - Maintain low (bounded) node degree
 - Optimizations

Comments and Discussions

- What I like about the paper
 - simple algorithm with weak assumption about physical radio propagation model
 - only required directional information
 - The proof of the properties
- Limitation
 - Consider only homogeneous network (each node has the same maximum transmission power)
 - Other properties ? Bi-connectivity, Planar etc
 - Simplified power consumption model : for example the power consumption of receiving in relay nodes are ignored
 - Small node degree doesn't imply low interference
 - Power efficiency of running the protocol is not studied; important for network with high mobility. E.g. tradeoff of choosing α

Thanks ! 😊