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Topology Control and Routing in Mobile Ad Hoc Networks

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Introduction -- Mobile Ad Hoc Networks (MANET)

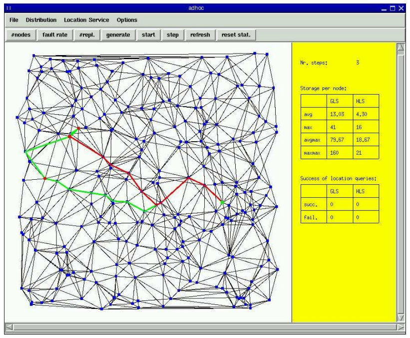
- **Formed by mobile wireless hosts**
- **Each node may act as a router**
- **Routes between nodes may contain multiple hops**
- **Pre-existing infrastructure is not required**

Introduction – Challenges

- **Self-construction, self-maintenance**
- **Scalability**
- **Reliability**
- **Resource efficiency**
  - **Energy**
  - **Storage**
- **Fault- / disaster-tolerance**
  - **Tolerates simultaneous (node/link) faults**
  - **Fast reconfiguration on detection of faults**

Applications

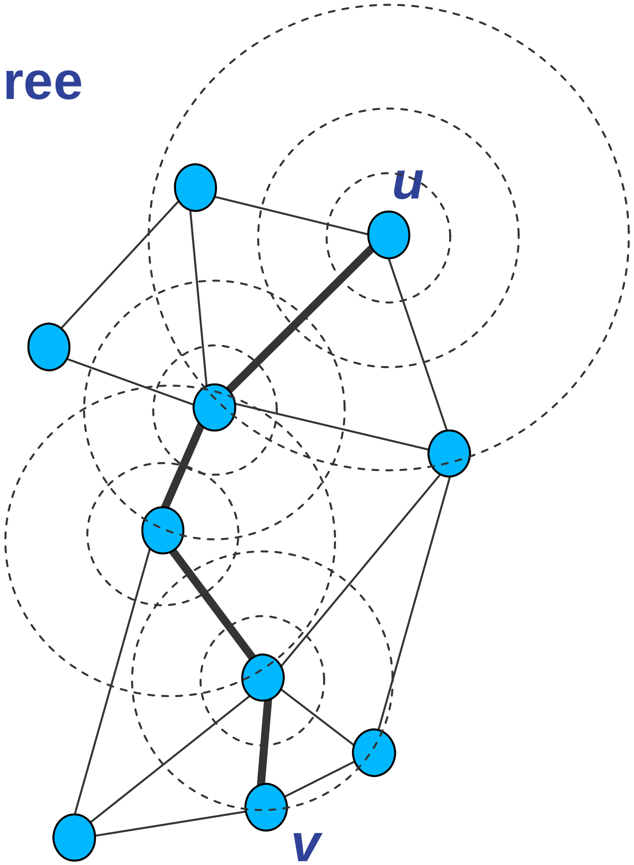
- **Extension for existing cellular networks**
- **Rooftop networks, hybrid networks**
- **Network level support for position based services**
- **Sensor networks**
- **Inter-vehicle networks**



Demonstrator

Focus I – Topology Control

- **Sparse topologies, low node degree**
  - **Storage efficiency**
- **Short and low energy paths**
  - **Energy: battery lifetime**
  - **health aspects**
- **Low congestion path system**
  - **Reliability**
- **Efficient distributed construction and maintenance**
  - **Scalability**
  - **Fault tolerance**



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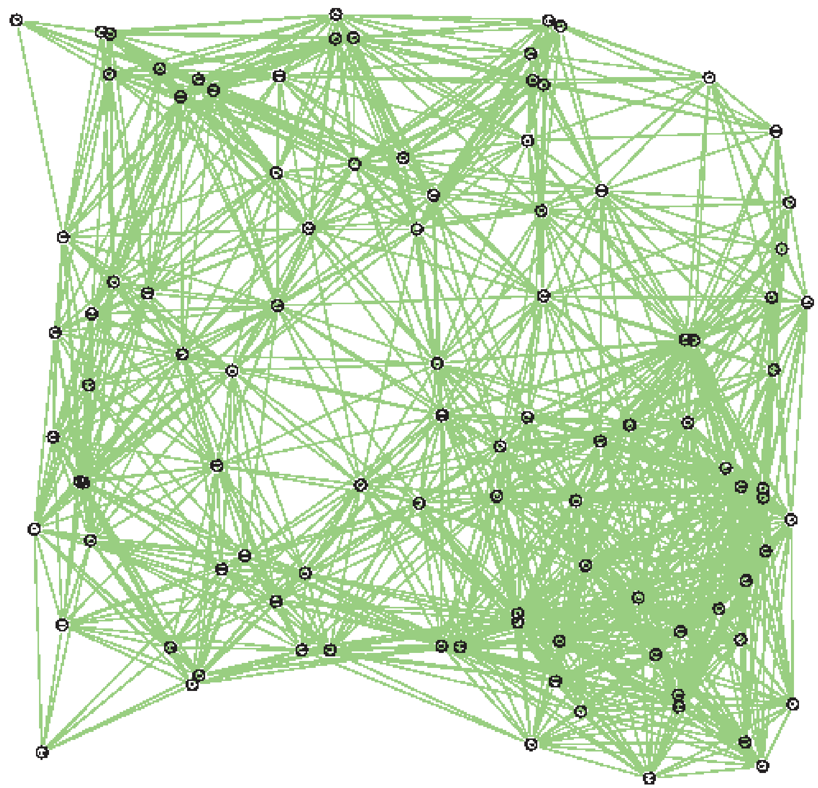
Focus I – Topology Control

Example of No Topology Control

with maximum transmission radius *R* (maximum connected node set)



- **High energy consumption**
- **High interference**
- **Low throughput**

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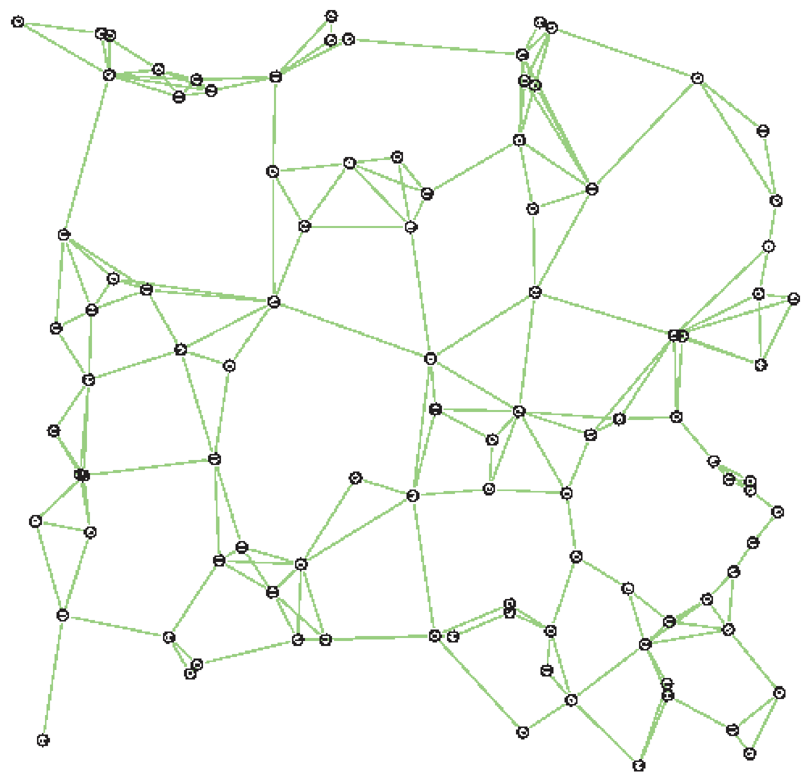
Focus I – Topology Control

Example of Topology Control



- Global connectivity
- Low energy consumption
- Low interference
- High throughput

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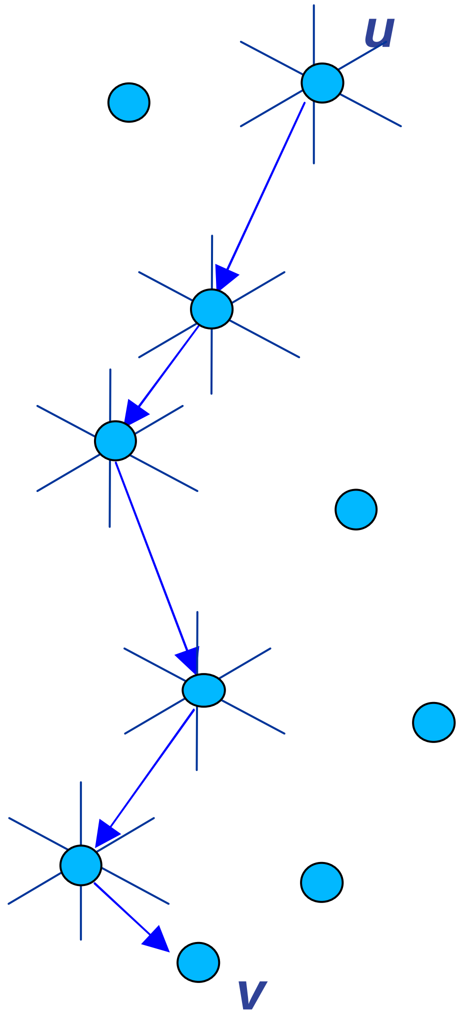
Focus II - Position Based Routing

- **Packets are forwarded “on-the-fly” based on the geographic position of the**
  - **current node,**
  - **neighbors of the current node,**
  - **destination node**
- **Routing table is not required**
  - **Storage efficiency, low update costs**
- **Suited for networks with**
  - **high node velocity**
  - **frequent topology changes**
- **Immediate support of routing to a**
  - **geographic area**
  - **(near to) a position**
- **How can the source discover the position of the destination?**



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Focus III – Distributed Location Services

Centralized solution - Problems

- Each node has to know the position of the node, which provides the location service (chicken-egg-problem)
- Very high traffic at the location servers

Distributed location service - Desirable properties

- Load is distributed evenly over all nodes
- Low storage and communication costs at the nodes
- Short location discovery paths
- Fault- / disaster-tolerance

Own Contributions*

Topology Control

- **Fundamental results (upper&lower bounds, tradeoffs)**
  - **degree, energy, congestion, maintenance overhead**
  - **dealing with mobility**

Location Services

- **HLS – new disaster tolerant, storage efficient distributed location service**

Model

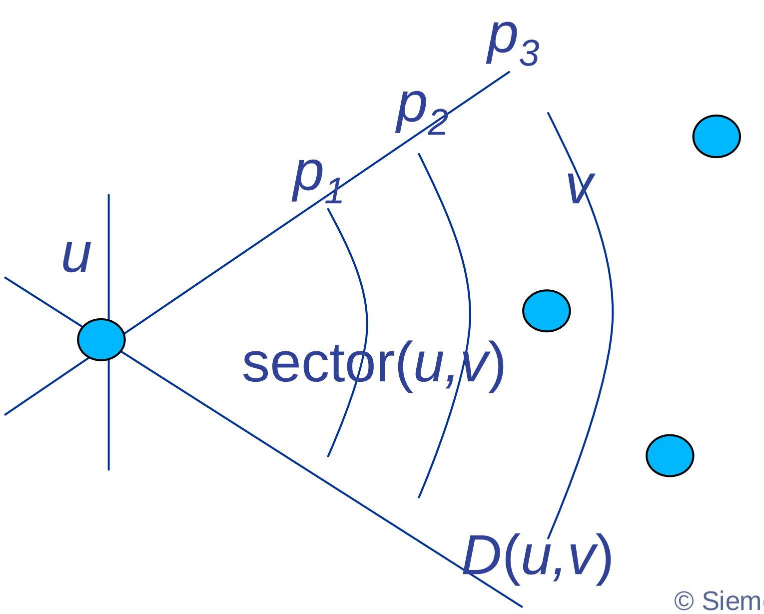
Communication Model

- **Nodes enter or leave**
- **Types of incoming signals:**
  - no signal,
  - interference,
  - clear signal (one frequency)
- **Two types of interferences**
  - uni-directional and bi-directional

Model

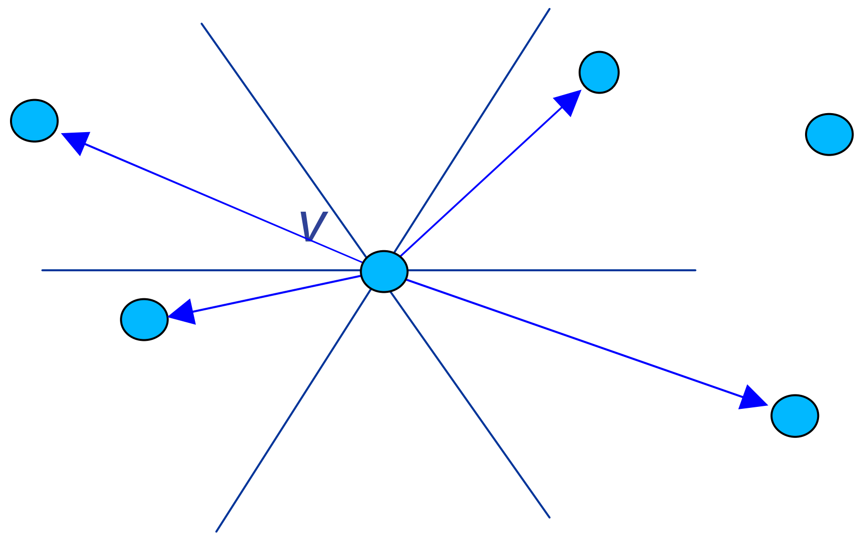
Hardware Model

- **Adjustable transmitting power, discrete choices: $p_1,\ldots, p_s$**
- ***k* sending and receiving devices (antenna) per node**
  - are able to work independently in parallel
  - define sectors
- **Orientation and location of the nodes is unknown**



Network Topologies

Yao graph [Yao 82]: Around each node $v \in V$, the plane is divided in sectors of an angle $\theta \leq \pi/3$



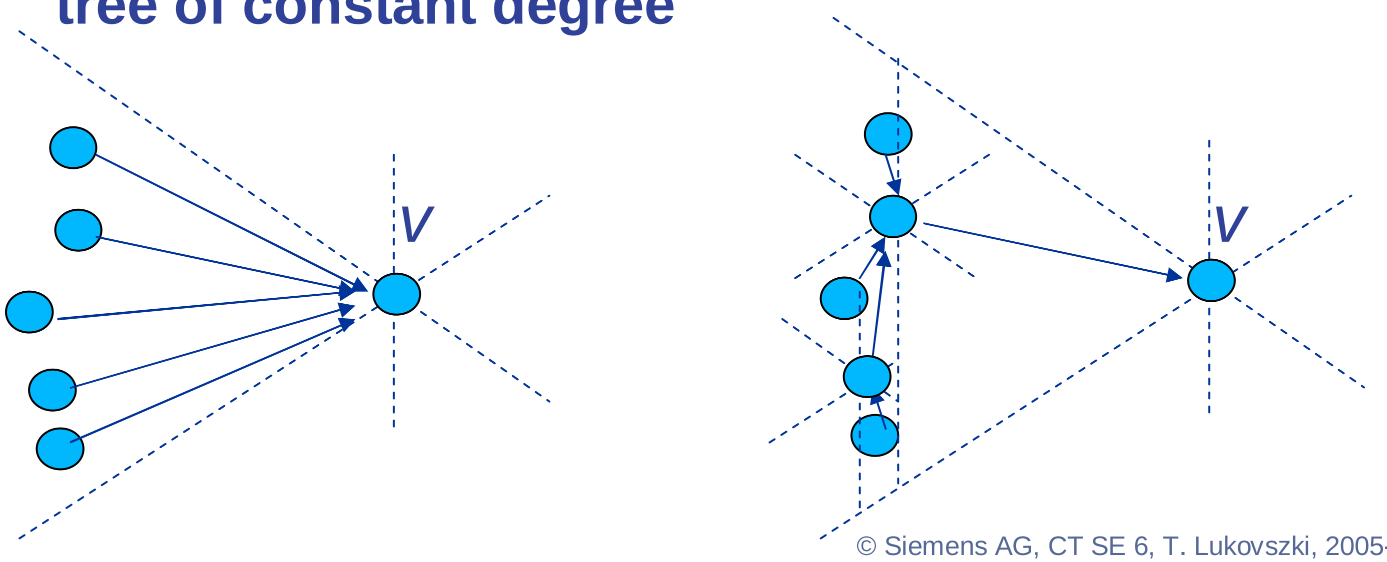
Each node is connected to its nearest neighbor in each sector by a link:

$$E := \{(u,v) \mid \forall\, w \neq v : \text{sector}(u,v) = \text{sector}(u,w) \Rightarrow D(u,v) < D(u,w)\}$$

Network Topologies

Let G_Y be the Yao graph.
The Bounded Degree Yao graph (BoundY) [Arya et al. 95] is defined by the following procedure:

- **<u>For each</u> *v* in *V* and <u>for each</u> sector around *v* <u>do</u>**
  - **$N(v) := \{ w \mid (w,v) \in E(G_Y) \text{ and } w \in \text{sector}(v) \}$**
  - **Replace the star $\{ (w,v) \mid w \in N(v) \}$ by a certain tree of constant degree**



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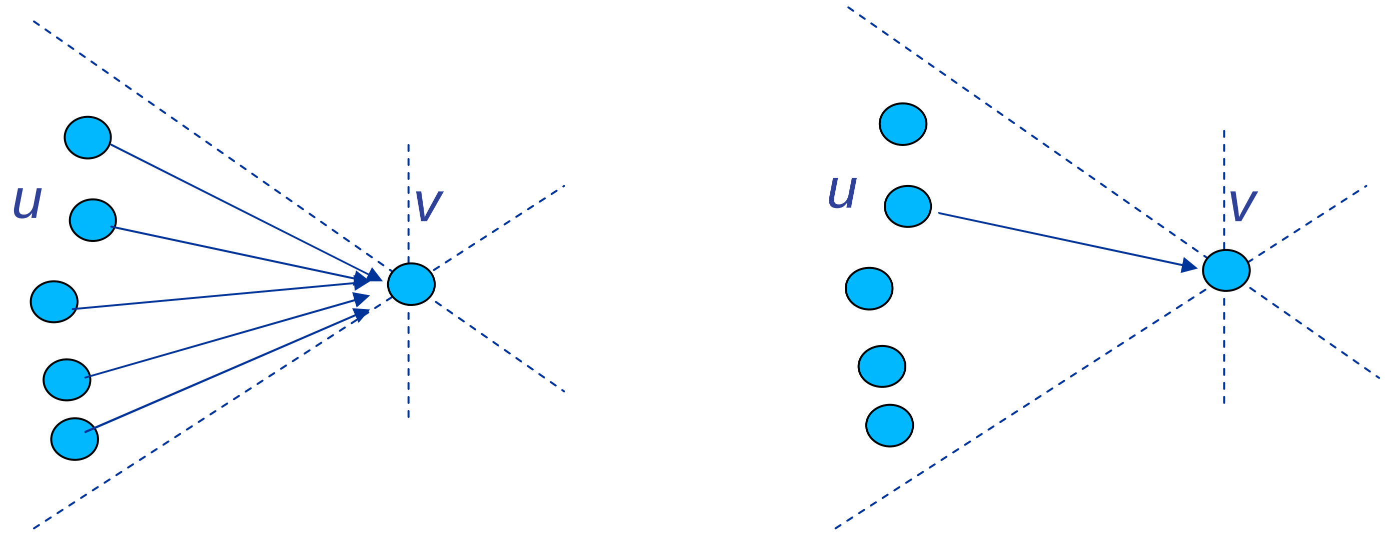
Network Topologies

Let G_Y be the Yao graph.
The Sparsified Yao graph (SparsY) [Li et al. 01] is defined by the following set of directed edges:

$$E := \{ (u,v) \in E(G_Y) \mid \forall\, w : (w,v) \in E(G_Y) \text{ and } \text{sector}(v,w) = \text{sector}(v,u) \Rightarrow D(v,u) < D(v,w) \}$$



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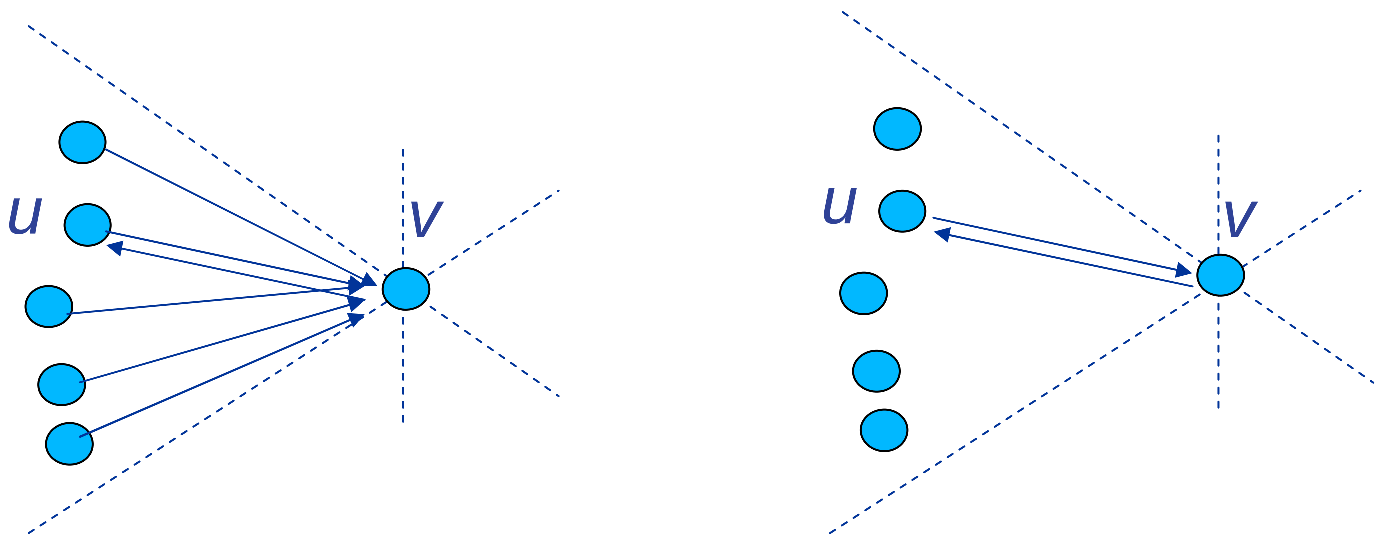
Network Topologies

Let G_Y be the Yao graph.
The Symmetric Yao graph (SymmY) [Li et al. 01] is defined by the following set of directed edges:

$$E := \{ (u,v) \in E(G_Y) \mid (v,u) \in E(G_Y) \}$$



Network Topologies

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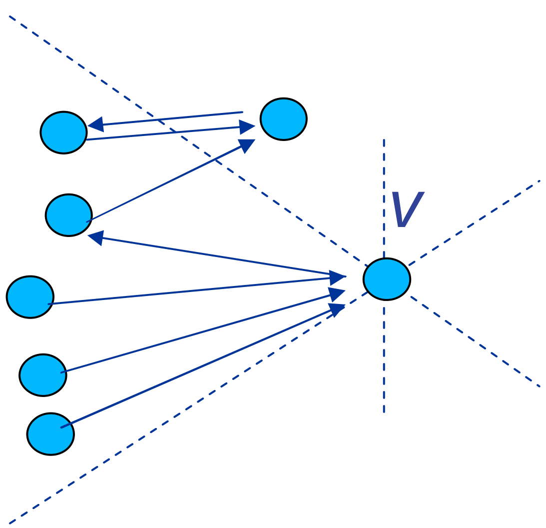

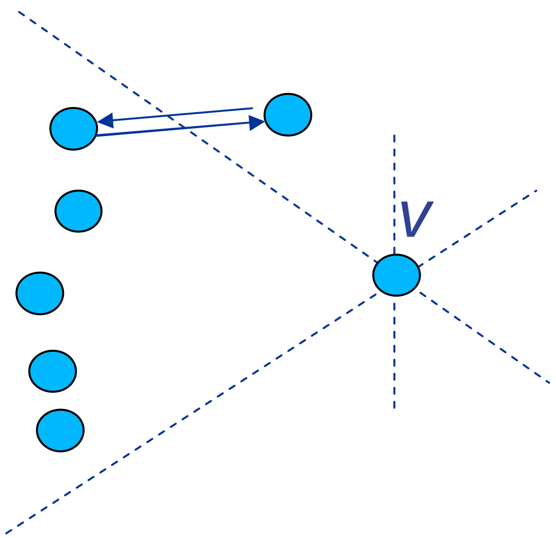

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Network Topologies

The Hierarchical Layer graph* (LH) is defined by the union of w graphs (layers) $L_0,\dots,L_w$.

$$V = V(L_0) \supseteq V(L_1) \supseteq \dots \supseteq V(L_w) = \{v_0\}$$

Properties of $V(L_i)$:

Let $\alpha \geq \beta > 1$, $r_0 \leq \min_{u,v \in V} ||u,v||_2$, $r_i := \beta^i r_0$

- **Minimum distance:**

$$\forall L_i \ \forall u,v \in V(L_i) : ||u,v||_2 \geq r_i$$

- **Covering:**

$$\forall u \in V(L_i) \ \exists v \in V(L_{i+1}) : ||u,v||_2 \leq r_{i+1}$$

Edge set:

$$E(L_i) := \{ (u,v) \mid u,v \in V(L_i) \text{ and } ||u,v||_2 \leq \alpha r_i \}$$

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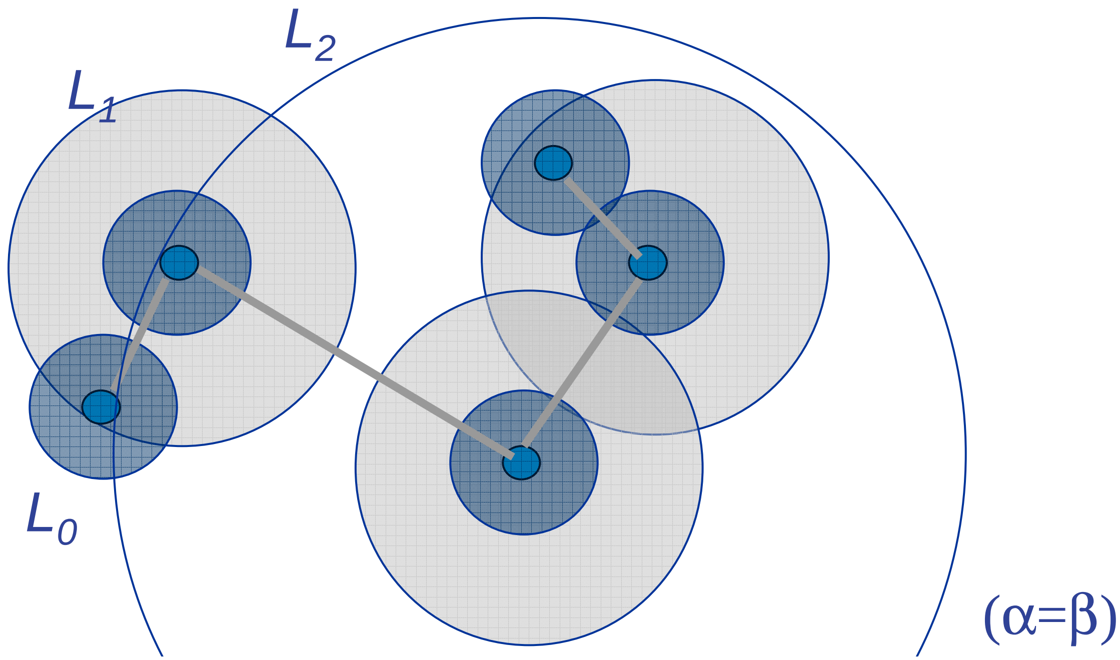
Network Topologies

 # layers in the HL graph for normal a vertex set is
$w = O(\log n)$



Graph Properties

$$\text{SymmY}(V) \subseteq \text{SparsY}(V) \subseteq \text{Yao}(V)$$
$$\text{SparsY}(V) \subseteq \text{BoundY}(V).$$

Let V be a nice vertex set. Then

Topology	Yao	BoundY	SparsY	SymmY	HL
in-degree	n-1	$(k+1)^2$	k	k	$O(\log n)$
out-degree	k	k	k	k	$O(\log n)$
degree	n-1+k	$(k+1)^2+k$	$2k$	k	$O(\log n)$

Graph Properties

Definitions: Let $G=(V,E)$ be a graph

- **G is a c-spanner, if $\forall\, u,v \in V$ $\exists$ path P from u to v with**
  $$\|P\|_2 := \sum_{e \in P} \|e\|_2 \leq c\, \|u,v\|_2$$
- **G is a weak c-spanner, if $\forall\, u,v \in V$ $\exists$ path P from u to v which is covered by a disk of radius $c\, \|u,v\|_2$ centered at u**
- **G is a (c,d)-power spanner, if $\forall\, u,v \in V$ $\exists$ path**
  $P = (u=u_1, \ldots, u_m=v)$ from u to v such that

$$\sum_{i=1}^{m-1} (\| u_i, u_{i+1} \|_2)^d \leq c \cdot \min_{(u=v_1,\ldots,v_m=v)} \sum_{i=1}^{m-1} (\| u_i, u_{i+1} \|_2)^d$$

- **G is a power spanner, if for all $d > 1$ there exists a constant c such that G is a (c,d)-power spanner.**

Graph Properties

Let *V* be a set of *n* points in R^2. Then Yao(*V*) is

- **a *c*-spanner for *k* > 6 with [Ruppert & Seidel 91]**

$$c = \frac{1}{1 - 2\sin(\Theta/2)}$$

- **a weak *c*-spanner for k ≥ 6 with [Fischer et al. 97]**

$$c = \max\left\{\sqrt{1 + 48\sin^4(\Theta/2)}, \sqrt{5 - \cos\Theta}\right\}$$

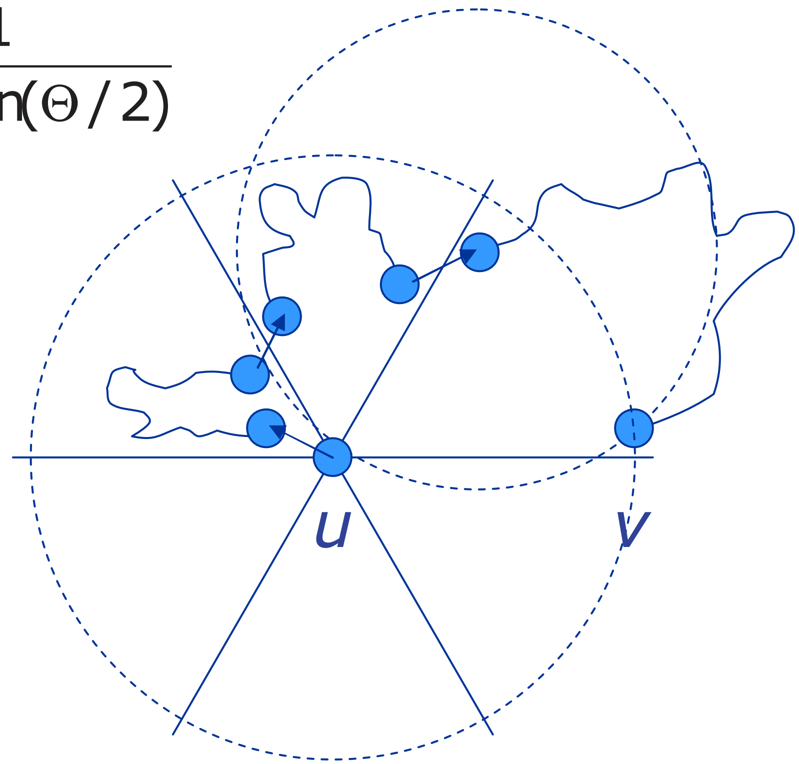
- **a weak *c*-spanner for k = 4 with [Fischer et al. 98] ***

$$c = \sqrt{3 + \sqrt{5}}$$

Graph Properties

Theorem*: Let *V* is a set of n points in R^2. Then, SparsY(*V*) is a weak *c*-spanner for k > 6 with

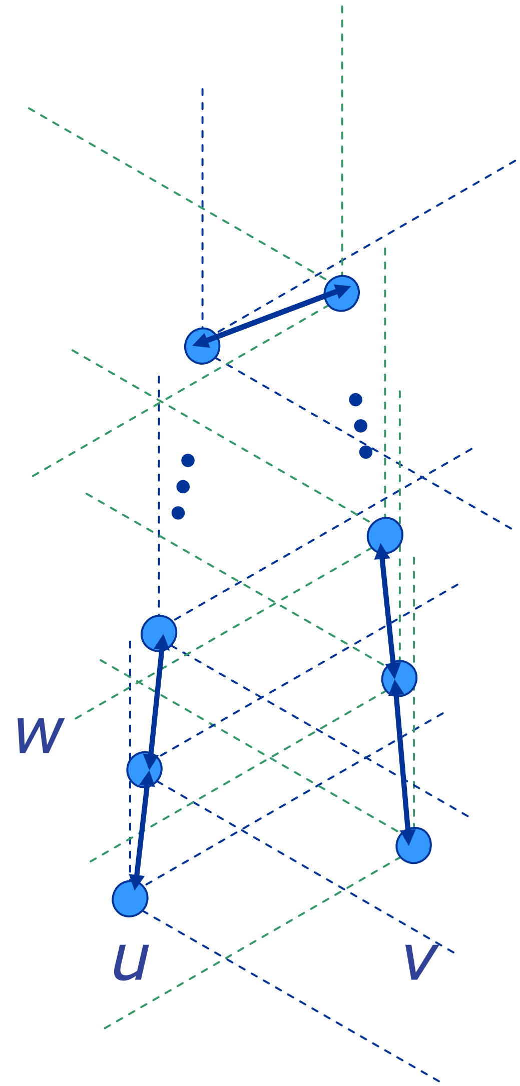
$$c = \frac{1}{1 - 2\sin(\Theta/2)}$$



Graph Properties

Theorem*: Let *V* be a set of *n* points in R^2. Then SymmY(*V*) is

- **connected for k ≥ 6**
- **neither a weak *c*-spanner for any const. *c* in R, nor a (*c*,*d*)-power spanner**



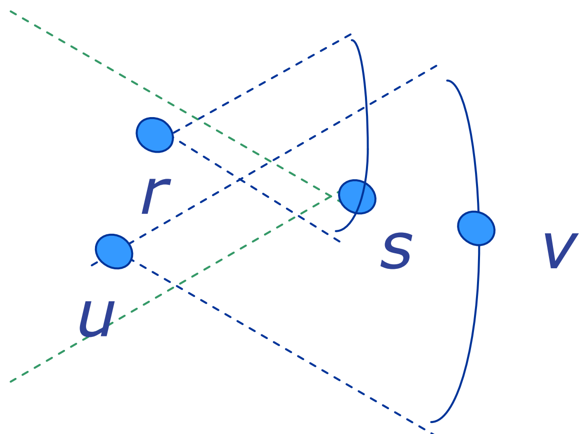
Graph Properties

Theorem*: Let V be a set of n points in R^2 and let $\alpha > 2\beta / (\beta-1)$. Then HL($V$) is a c-spanner with

$$c = \max\left\{\beta\frac{\alpha(\beta-1)+2\beta}{\alpha(\beta-1)-2\beta}, \frac{\alpha}{\beta}\right\}$$

Communication Features

- **An edge (*r*,*s*) has an uni-directional interference caused by (*u*,*v*), if sector(*s*,*r*) = sector(*s*,*u*) and sector(*u*,*s*) = sector(*u*,*v*) and *D*(*u*,*v*) ≥ *D*(*u*,*s*).**



- **An edge (*r*,*s*) has a bi-directional interference caused by (*u*,*v*), if (*r*,*s*) has an uni-directional interference caused by (*u*,*v*) or if (*u*,*v*) has an uni-directional interference caused by (*r*,*s*).**

Communication Features

Let P be a path system for V, E(P) the set of edges in P, and $\ell(e)$ the load on an edge e.

Congestion $C_P(V)$ and energy $E_P(V)$:

$$C_P(V) := \max_{e \in E(P)} \left\{ \ell(e) + \sum_{e' \in Int(e)} \ell(e') \right\}$$

$$E_P(V) := \sum_{e \in E(P)} \ell(e) \cdot \| e \|_2^{\,2}$$

Communication Features

Theorem*: Let *G* be a *c*-spanner. Then *G* is a (c^d,*d*)-power spanner.

Theorem: [Meyer a.d.H. et al. 02]: If for a *normal* vertex set a graph *G* is a weak *c*-spanner with uni-directional interference number *q*, then there is a path system in *G* which approximates the congestion optimal path system by a factor of $O(q \log n)$

- **A vertex set is *normal*, if for a fixed polynomial *p*(*n*):**

$$\frac{\max_{u,v \in V} ||u,v||_2}{\min_{u,v \in V} ||u,v||_2} \leq p(n)$$

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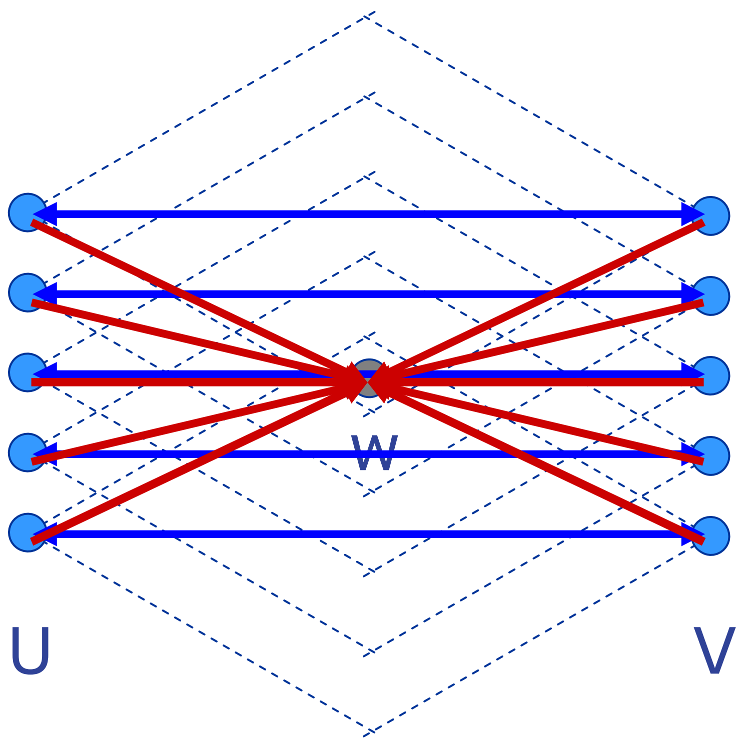
Communication Features

Theorem*: For a normal vertex set *V* the following table describes the worst case behavior, whether it hosts optimal path systems approximating energy or congestion.

Topology	uni-directional interference number	spanner	Energy approx. factor	Congestion approx. factor
Yao	n-1	yes	$O(1)$	--
BoundY	$\Theta(n)$	yes	$O(1)$	--
SparsY	1	weak and power	$O(1)$	$O(\log n)$
SymmY	1 (also bi-dir.!)	no, but connected	--	--
HL	$O(\log n)$	yes	$O(1)$	$O(\log^2 n)$

Maintaining the Network

Theorem*: Let *V* be a normal and nicely located vertex set. Then Θ(|*V*|) edges need to be changed, if an enter **or** leave **operation takes place in Yao(*V*), BoundY(*V*), SparsY(*V*) or SymmY(*V*). For HL(*V*) this number is *O*(log|*V*|).**



Maintaining the Network

Theorem*: Let *V* be a normal and nicely located vertex set and *m* the number of involved edges. Then the network structure of Yao(*V*), BoundY(*V*), SparsY(*V*) and SymmY(*V*) can be rebuilt in *O*(*m* log *s*) time. For HL(*V*) we need *O*(log|*V*| + log *s*) time.
For Yao(*V*):

enter

- Inform the nodes that *u* has entered
- Search for next neighbor of *u* in each sector
- The informed nodes check empty sectors, whether *u* can be its nearest neighbor
- The informed nodes check not-empty sectors, whether *u* is closer

leave

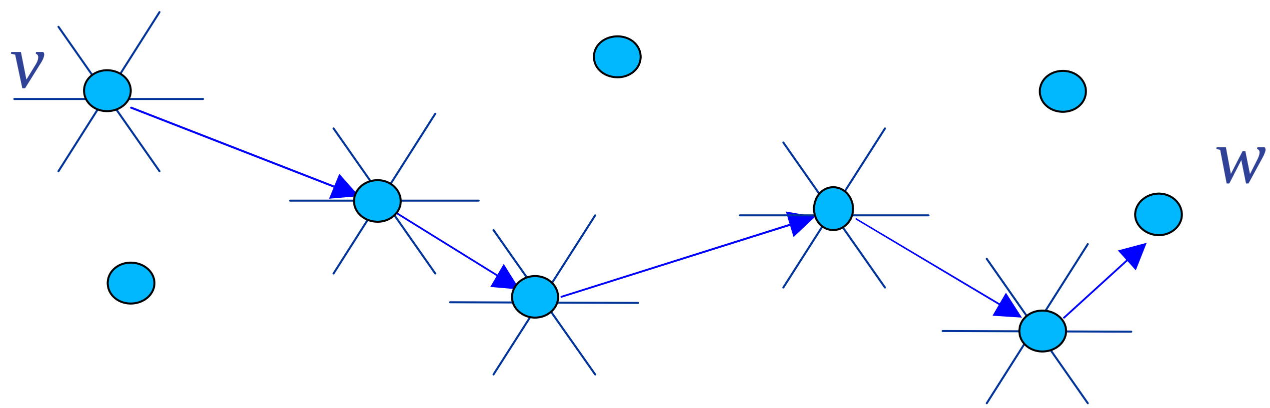
- At some time the node *v* notices that *u* has left the network
- *v* informs other nodes that *u* has left
- All nodes adjacent to *u* have to determine new neighbors (this is done by a reduced version of the enter-algorithm)

Summary – Topology Control

Topology	Congestion approx. factor	Energy approx. factor	enter/leave involved nodes	Time for enter/leave
Yao	--	$O(1)$	$\Theta(n)$	$O(n \log s)$
BoundY	--	$O(1)$	$\Theta(n)$	$O(n \log s)$
SparsY	$O(\log n)$	$O(1)$	$\Theta(n)$	$O(n \log s)$
SymmY	--	--	$\Theta(n)$	$O(n \log s)$
HL	$O(\log^2 n)$	$O(1)$	$O(\log n)$	$O(\log n + \log s)$

Position Based Ad-Hoc Routing

- **Each node knows its position (GPS)**
- **Example: The Yao-graph**
- **It allows a memoryless position based routing**
- **Forward the package to the neighbor in the sector which contains the destination node**
- **But how can the source discover the position of the destination?**



Hypercubic Location Service (HLS)*

Theorem*: HLS has the properties:

- **Storage requirement per node: $\Theta(\log n)$ with high probability (w.h.p.), i.e. Prob ≥ 1- $n^{-\alpha}$.**
  - **independent from the geographic distribution of the nodes**
- **Fault tolerance: Even if a constant fraction of the nodes fails simultanously, a packet will be delivered w.h.p.**
- **Update costs, when a node enters or leaves:**
  - **# affected nodes: $O(\log n)$, w.h.p.**
  - **time at an affected node: $O(\log n)$, w.h.p.**

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Summary

- **Focus:** **I Topology Control**
  II Position Based Routing
  III Distributed Location Services
- **Immediate network level support for position based services**
- **Cost efficient and highly reliable self-organizing (and hybrid) multihop networks for future networking scenarios**

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