Self-Organization of Wireless Ad Hoc Networks as Small Worlds Using Long Range Directional Beams

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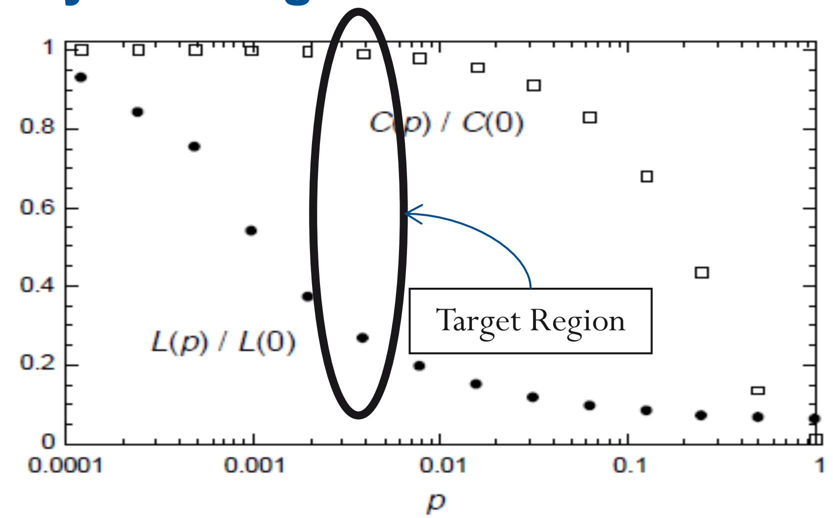
Small World Networks

Properties

- Logarithmic growth of average path length in the network size
- High clustering coefficient resulting in high connectivity

Can be achieved by randomly rewiring a small fraction of links in the network [1]



[1] D.J. Watts, S.H. Strogatz, Collective dynamics of 'small-world' networks, Nature 393 (6684) (1998) 440–442.

Small Worlds in Wireless Networks

Desirable Model for Wireless Networks as

- Bounded path length ensures guaranteed performance
- High connectivity implies reliability

Challenges

- Spatial network implies that link rewiring cannot be totally random
- Links are range limited
- Long range links require additional transmission power

Outline of work

- **Analyze effect of directional antennas on small world behavior in wireless networks**
  - Simulation based study
  - Random link creation
  - Identify effect on path length reduction and connectivity
- **Deterministic creation of long range links**
  - Define a new centrality measure
  - Identify optimal set of nodes to beamform

Using Directional Beams to realize small world behavior

- **Advantages**
  - Longer transmission range can be achieved using same transmission power of omnidirectional antennas
  - Small world behavior may be realized for a generic setup in which nodes have the same capabilities

- **Challenges**
  - Using directional beams with a single beamforming antenna results in link rewiring rather than addition – adversely affects connectivity
  - Directed links can result in unidirectional paths

Simulation Based Analysis

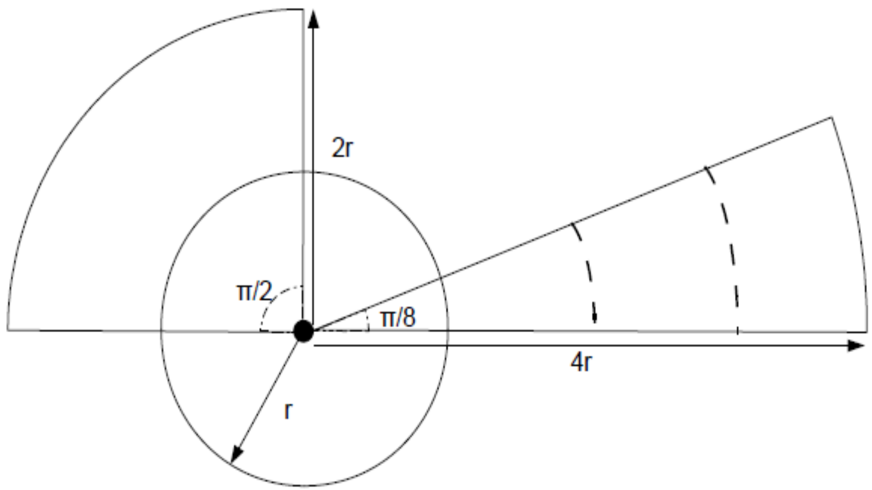
Use randomized beamforming

- Fraction p of nodes use randomly oriented directional beams
- Analogous to traditional models of rewiring links

Directional Antenna Settings

- Use sector model as it is easier for analysis
- Compare results with realistic Uniform Linear Array (ULA) antenna model
- Operate in Directional Transmission while Omnidirectional Reception (DTOR) mode

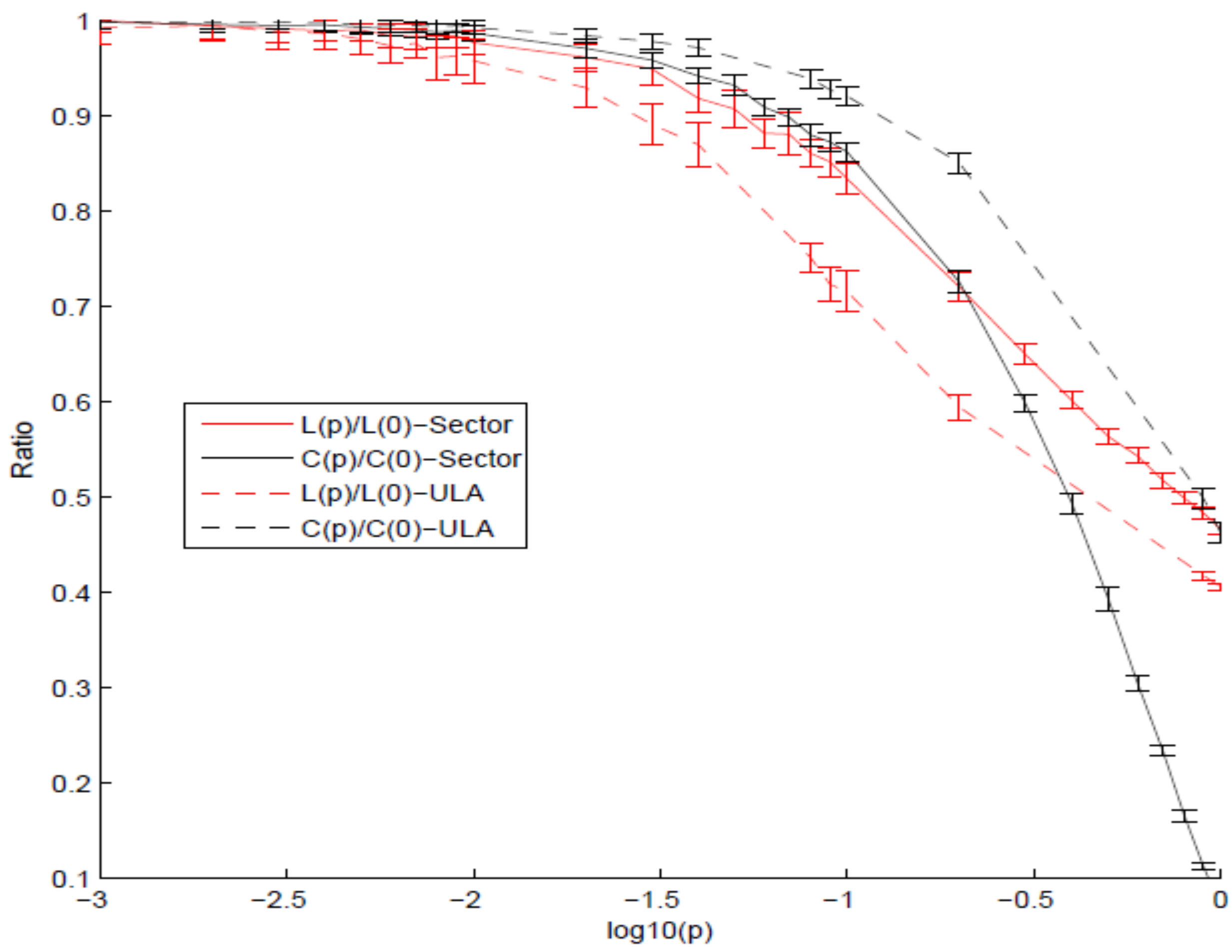
Antenna Configuration



- **Beam-width chosen so as to maximize beam-length while maintaining connectivity**

$$\theta^* = \arg\max_{\theta} \left[r\sqrt{\frac{2\pi}{\theta}} \right] p_{nf} p_{nl}$$

Results



L(p)/L(0)−Sector
C(p)/C(0)−Sector
L(p)/L(0)−ULA
C(p)/C(0)−ULA
Ratio
log10(p)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
−3
−2.5
−2
−1.5
−1
−0.5
0

Self-Organization using Traffic Aware Centrality

Objective

- Identify optimum set of nodes to beam form such that the average path length is minimized while maintaining connectivity

Outline

- Define a measure of centrality based on traffic flow
  - Does not incur explicit overheads
- Outline algorithm to determine
  - Set of nodes to beam form
  - Beam direction

Motivation for a Traffic Aware Centrality Measure

- **Individual decision making of beam forming at nodes**
  - Distributed computation of centralities
  - Distributed estimation of centrality rank in the network
- **Minimize explicit overheads involved in self-organization**
  - Can we exploit wireless broadcast advantage (WBA)?
- **Allow self-organization to take place with regular network operations**
  - Information about routes can be estimated from traffic flow in the network

Wireless Flow Betweenness (WFB)

- **If node *v* forwards a packet in time slot t, it updates its WFB value as**

$$w^t(v) = \frac{g^t(v)}{w^{t-1}(v) \sum_{u \in \{\mathcal{N}(v) \cup v\}} \frac{g^{t-1}(u)}{w^{t-1}(u)}}$$

  - Appends the value to the transmitted packet

- **Each neighbor *u* of *v* updates its own value as**

$$w^t(u) = \frac{g^t(u)}{w^{t-1}(u) \left[\frac{g^t(v)}{w^t(v)} + \sum_{u' \in \{\{\mathcal{N}(u) \setminus v\} \cup u\}} \frac{g^{t-1}(u')}{w^{t-1}(u')} \right]}$$

- **Recursive computation results in propagation of network information over multiple hops**

Algorithm

- **After *t* time slots, node *v* decides to use a beam if its own WFB is close to that of the neighborhood by a factor β**

$$|w^t_{avg}(\mathcal{N}(v)) - w^t(v)| < \beta w^t(v)$$

  - $\mathcal{N}(v)$ – set of neighbors of *v*
  - Beam direction chosen as one in which *v* records maximum path length
  - Beam width chosen as earlier
- **Node *v* broadcasts its decision to its directional and omnidirectional neighborhoods**
- **Any node overhearing this decides against beam forming even if the first condition is satisfied**

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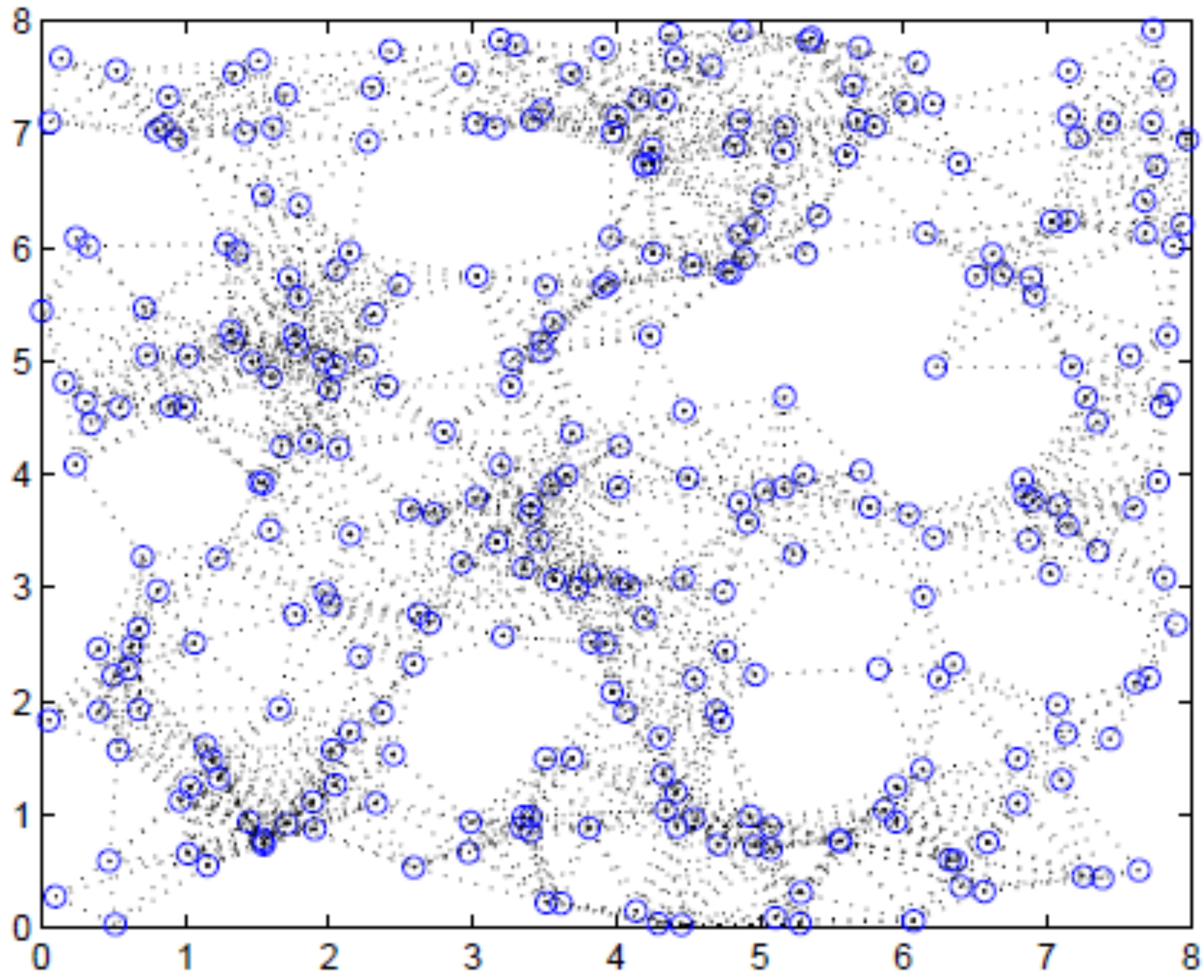
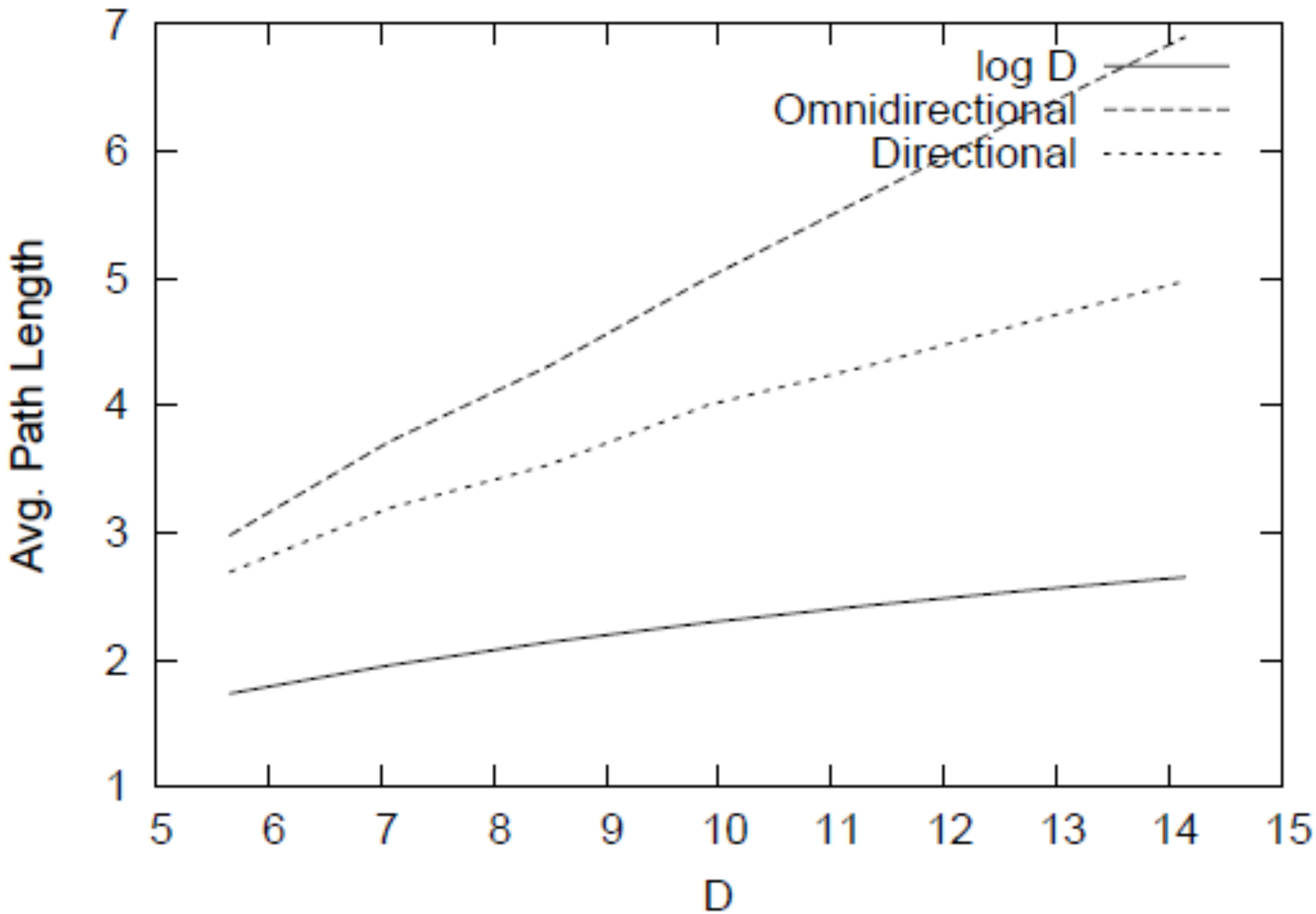
Illustration



Simulation Results



Conclusion

- **Beamforming used to achieve Small World Properties in wireless networks**
  - Tradeoff exists between path length reduction & connectivity
- **Distributed algorithm design**
  - Identify beamforming nodes depending on structural importance in network
  - Nodes decide using purely local information
  - Maintains connectivity while achieving low path length
- **New definition of centrality**
  - Exploits Wireless Broadcast Advantage (WBA)

Future Work

- **Enhance definition of WFB to obtain a better approximation of Flow Betweenness**
- **Study navigability of small world wireless networks**
- **Investigate the use of WFB for network protocol design**