Topology-Related Modeling and Characterization of Wireless Sensor Networks

PE-WASUN'2011

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Motivation

- Node deployment, and the consequent induced topology, plays an important role in the design of wireless sensor networks
- Homogeneous ad hoc networks suffer from fundamental limitations and, hence, exhibit poor network performance
- Another class of WSN models assume that there are different sets of nodes, each one with different capabilities
- For instance, suppose we have two sets of nodes: H-sensors and L-sensors
- A homogeneous WSN becomes a particular case of a HSN
- Energy hole happens in the neighborhood of each H-sensor

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Stochastic Point Process

- A stochastic point process is a probability law that describes the location of a number of points in a region of the space
- The most common model used in WSN simulation is the binomial, i.e., a fixed number of n points obeys a binomial distribution on $W = [0, \ell]^2 \subset \mathbb{R}^2$
- $2n$ independent identically distributed random variables $X_1, \dots, X_n, Y_1, \dots, Y_n$, obeying the uniform law on $[0, \ell]$, say $x_1, \dots, x_n, y_1, \dots, y_n$, and then placing the n points on coordinates $(x_i, y_i)_{1 \le i \le n}$

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Poisson Point Process

Definition

1. Number of points in every compact set $A \subset W$, denoted by $C(A)$ for "counts", follows a Poisson distribution with mean $\lambda\mu(A)$
2. If $A_1, A_2, \dots, A_m$ are disjoint subsets of W, then $C(A_1), C(A_2), \dots, C(A_m)$ are collectively independent random variables

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M^{2}P^2

M^{2}P^2$(m, n, a, r_c, r_{ch}, r_i)$ on $W \subset \mathbb{R}^2$

It is a compounded process consisting of:

- m samples of: $H(m, 2r_i)$ (H-sensors).
- $n - m$ samples of $\Lambda(n - m, a, \boldsymbol{h})$ (L-sensors)

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H-sensors Deployment Model

$H(m, 2r_i)$

It places the maximum number of m H-sensors on a window W repulsed by an inhibition distance $2r_i$. This process follows the SSI (Simple Sequential Inhibition) stochastic point process

L-sensors Deployment Model

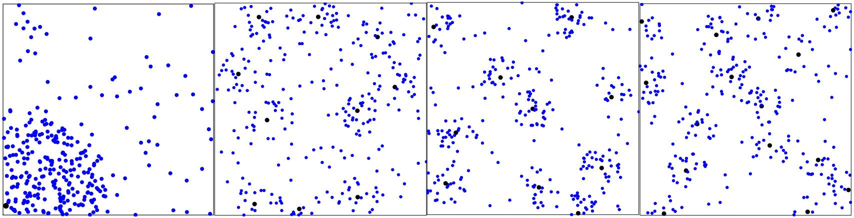
$\Lambda(n-m, a, \boldsymbol{h})$

An inhomogeneous Poisson process with intensity function defined as:

$$\lambda(x,y) = \begin{cases} a, \text{ if } d((x,y),(hx_i,hy_i)) \leq r_c, 1 \leq i \leq m, \\ 1, \text{ otherwise} \end{cases}$$

where $a \geq 1$ (the attractiveness parameter), d is any distance measure, and r_c is the communication radius of the L-sensors

Examples of $\mathrm{M}^2\mathrm{P}^2$



Outcomes of $\mathrm{M}^2\mathrm{P}^2$ for 300 nodes with 1, 10, 10 and 15 H-sensors (in black) and attractiveness 15, 5, 15 and 15

Evaluation of M^{2}P^2

- Small-world characterization and energy hole behavior
- H-sensors and L-sensors present same sensing capabilities (r_s) and two levels of transmission range (r_c and r_{ch}).
- H-sensors have a two-channel radio
- Each sensor sends 1 packet$/$min
- Each sensor reports its collected data by using a minimum cost path to the sink (not a fixed tree)
- An error- and a collision-free MAC protocol was used to isolate its influence

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Simulation Scenarios

Parameter	**Value**
sink node	1 (center-most node)
network size	$n \in \{1000, 1500, 2000\}$ nodes
communication radius (L-sensors)	50 m
communication radius (H-sensors)	$r_{ch} \in \{100, 300, 500\}$ m
number of H-sensors	$m \in \{1, 10, 30, 50\}$ nodes
deployment model parameter	$a \in \{0, 1, 5, 15, 30\}$
event duration	1000 s
data rate	1 packet/min
sensing radius	30 m
sensor field	$1000 \times 1000\,\text{m}^2$

Assessed Topologies

1. **independent | independent ($a = 0$):** binomial deployment for both L-sensors and H-sensors, also called totally independent deployment
2. **independent | repulsive ($a = 1$):** binomial deployment for L-sensors and repulsive deployment for H-sensors
3. **slightly attractive | repulsive ($a = 5$):** slightly attractive deployment for L-sensors and repulsive deployment for H-sensors
4. **fairly attractive | repulsive ($a = 15$):** fairly attractive deployment for L-sensors and repulsive deployment for H-sensors
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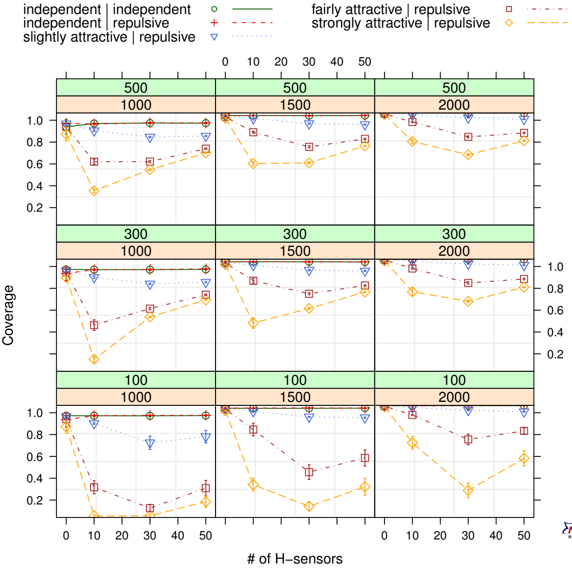

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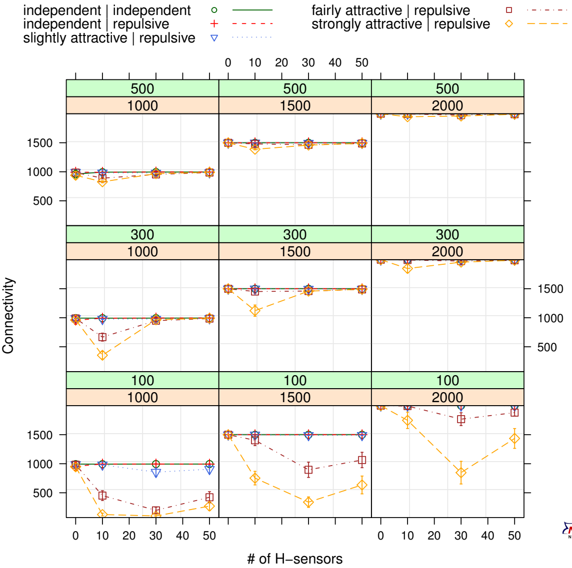

Small World Effect

- A small world network is characterized by short path lengths as random graphs and relatively large clustering coefficient as regular lattice
- Good characteristics for:
  - information dissemination
  - fault tolerance

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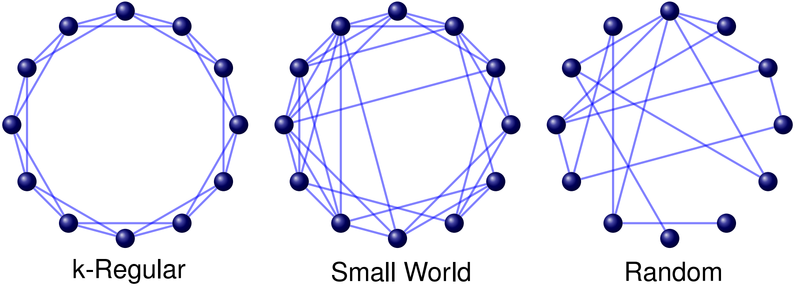

Small world characterization

Topology	$\overline{CC}$	$\widehat{\sigma}_{CC}$	$\overline{L}$	$\widehat{\sigma}_L$
slightly attractive | repulsive	0.658	0.009	6.313	0.553
independent | independent	0.584	0.005	8.205	0.901
homogeneous network	0.595	0.007	13.878	0.194
Erdös-Rényi random graph	0.011	0.001	2.848	0.006

1500 nodes. In the first two topologies, there are 30 H-sensors and $r_{ch} = 300$

Network Centrality

- In general, the more central the node is the more packets it will transmit (sink in the center)
- We study some centrality metrics that appear in the theory of complex networks and describe the centrality in different ways.
- (i) Betweenness, (ii) eigenvector centrality, (iii) closeness, (iv) degree centrality, (v) Google page rank, (vi) constraints centrality, (vii) hubscore centrality, and (viii) authority centrality
- Betweenness appears as the metric that best describes the relay task

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Betweenness Centrality

Definitions

Betweenness

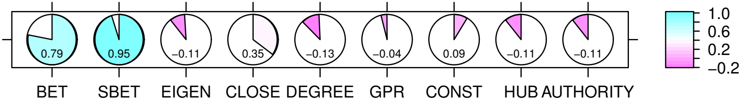
$$B_v = \sum_{s=1}^{n} \sum_{t=1}^{n} \frac{\sigma_{st}(v)}{\sigma_{st}},$$

Sink-Betweenness

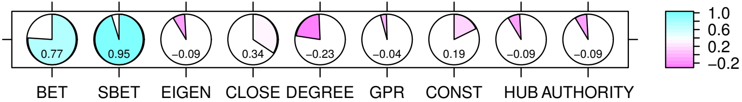
$$SB_v = \sum_{t=1}^{n} \frac{\sigma_{s_k t}(v)}{\sigma_{s_k t}}.$$

Network Centrality and Transmitted Messages

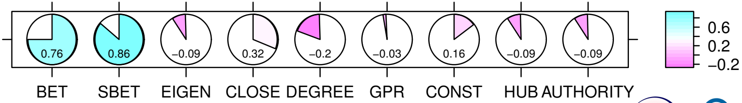
Sink in the center:



Sink in a corner:



Sink randomly placed:



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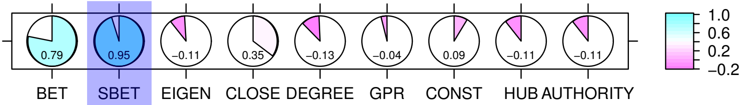

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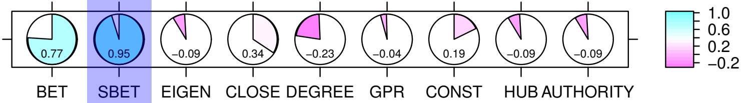

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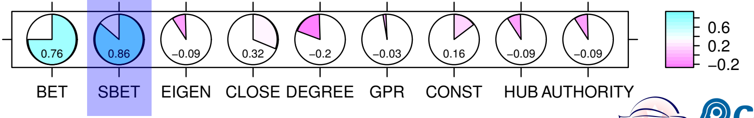

A Guide to Stochastic Planned Deployment

Parameters of M^{2}P$^2(m, n, a, r_c, r_{ch}, r_i)$ model:

- Window W where the process takes place
- Communication radii should be carefully specified as a function of the communication channel. This distance specifies r_c and r_{ch}
- Number (n) and type of sensors required for precise, lasting and economic data acquisition and delivery
- Inhibition parameter r_i, $r_i \geq r_c$ (areas of influence of H-sensors do not overlap) and $r_i < \ell/m^{1/2}$ (allows the placement of all the m H-sensors on the window $W = [0, \ell]^2$)
- Intensity parameter $a > 1$
- L-Sensors around each H-Sensor: $E(Z) = \frac{n-m}{m\left(\frac{1}{a}\left(\frac{\mu(W)}{\mu(W')}-1\right)+1\right)}$

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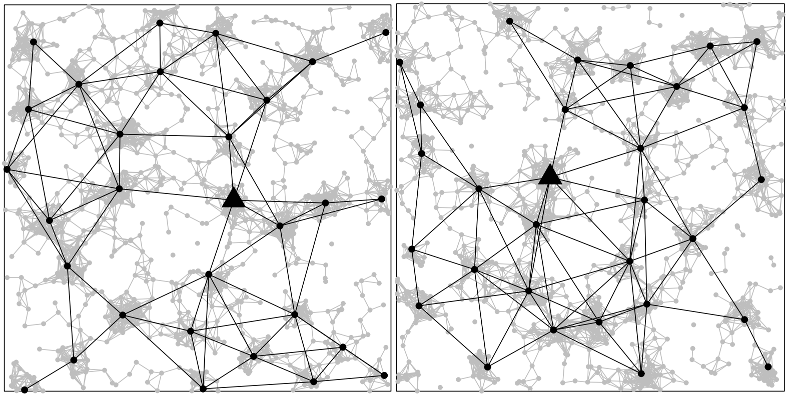
Two outcomes of network graphs generated by the M^{2}P^2 model



1000 nodes, 30 H-sensors, 1000×1000 sensor field, $r_c = 50$, $r_{ch} = 300$ and $a = 5$. $E(Z) = 19.6$ L-sensors.

Final Remarks

- We showed a novel modeling solution able to represent a wide variety of WSNs scenarios
- The common random deployment is a particular case of our model
- This model represents WSNs and HSNs showing characteristics of small world networks and can help to address the energy hole problem
- We only need about 3% of H-sensors (50 out of 1500) to obtain important features such as low average path length, and high cluster coefficient
- We propose the Sink Betweenness, a metric suitable to characterize the relay task of a node
- This work suggests other possibilities, such as the use of the Sink Betweenness in the design of HSNs and WSNs

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- We only need about 3% of H-sensors (50 out of 1500) to obtain important features such as low average path length, and high cluster coefficient
- We propose the Sink Betweenness, a metric suitable to characterize the relay task of a node
- This work suggests other possibilities, such as the use of the Sink Betweenness in the design of HSNs and WSNs

Final Remarks

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Thank you!