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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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 $X_1, \ldots, X_n, Y_1, \ldots, Y_n$, obeying the uniform law on $[0, \ell]$, say $x_1, \ldots, x_n, y_1, \ldots, y_n$, and then placing the $n$ points on coordinates $(x_i, y_i)_{1 \leq i \leq n}$. 
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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 $A_1, A_2, \ldots, A_m$ are disjoint subsets of $W$, then $C(A_1), C(A_2), \ldots, C(A_m)$ 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 \( \Lambda(n - m, a, h) \) (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

$\Lambda(n - m, a, h)$

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 $M^2P^2$

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

- 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

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

**Legend:**
- **independent | independent**
- **repulsive**
- **slightly attractive | repulsive**
- **fairly attractive | repulsive**
- **strongly attractive | repulsive**

**Graph:**
- **# of H−sensors**
- **Coverage**
- **# of H−sensors vs. Coverage**

**Annotations:**
- 500, 1000, 1500, 2000
- 0.2, 0.4, 0.6, 0.8, 1.0
- 0, 10, 20, 30, 40, 50
- 1000, 100
- 1500, 300
- 2000, 500

**Key Points:**
- Coverage varies with the number of H−sensors.
- Connectivity is affected by the interaction between sensors.
- Different interaction types yield distinct coverage patterns.

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**A Guide to Stochastic Planned Deployment**
Coverage and Connectivity

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<tr>
<th># of H-sensors</th>
<th>Connectivity</th>
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<tbody>
<tr>
<td>500</td>
<td></td>
</tr>
<tr>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>1500</td>
<td></td>
</tr>
<tr>
<td>2000</td>
<td></td>
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Legend:
- | independent |
- | repulsive |
- | fairly attractive |
- | repulsive |
- | strongly attractive |
- | repulsive |
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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k-Regular

Small World

Random
## Small world characterization

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<th>$\overline{CC}$</th>
<th>$\hat{\sigma}_{CC}$</th>
<th>$\overline{L}$</th>
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<tbody>
<tr>
<td>slightly attractive</td>
<td>repulsive</td>
<td>0.658</td>
<td>0.009</td>
<td>6.313</td>
</tr>
<tr>
<td>independent</td>
<td>independent</td>
<td>0.584</td>
<td>0.005</td>
<td>8.205</td>
</tr>
<tr>
<td>homogeneous network</td>
<td>0.595</td>
<td>0.007</td>
<td>13.878</td>
<td>0.194</td>
</tr>
<tr>
<td>Erdös-Rényi random graph</td>
<td>0.011</td>
<td>0.001</td>
<td>2.848</td>
<td>0.006</td>
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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

\[ SB_v = \sum_{t=1}^{n} \frac{\sigma_{skt}(v)}{\sigma_{skt}}. \]
Network Centrality and Transmitted Messages

Sink in the center:

Sink in a corner:

Sink randomly placed:
Network Centrality and Transmitted Messages

Sink in the center:

Sink in a corner:

Sink randomly placed:
A Guide to Stochastic Planned Deployment

Parameters of $M^2P^2(m, n, a, r_c, r_{ch}, r_i)$ 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 $M^2P^2$ 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
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- 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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Thank you!