NETWORK PROBLEMS IN MULTI-HOP WIRELESS NETWORKS

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• Network systems
  – Computer networks, Internet, …
  – Telephone networks, Mobile networks, …
  – Road networks, Power transmission systems, …
  – Social networks, web networks, …
  – etc.

• Development of strategies for network control using topological properties of the systems

• Network design principles based on topological properties of the systems

• Tools
  – Graph theory
  – Network theory
  – Queueing theory
  – Stochastic geometry and so on.
Fundamental network problems in mobile multi-hop wireless networks

- Characterization of connectivity of multi-hop cellular networks
- Location of relay facilities to improve connectivity
- Basic properties of a charging and rewarding scheme
PART 1

Characterization of connectivity of multi-hop cellular networks

Multi-hop Cellular
• Multi-hop networking can extend a cell
  – Next generation mobile systems
    • Higher bit rates ---> higher frequency bands ---> micro cellular ---> many BSs ---> cost reduction
  – Dead Spot Problem
Multi-hop cellular with fixed relay facilities

- **Advantage:**
  - Stable route, easy route set up
- **Disadvantage**
  - Preplanning, actual location of relay nodes,
  - Rearrangement is required if the environment has changed

**Mobile multi-hop cellular**

- **Advantage:**
  - Multi-hop paths will be provided automatically and adaptively to the environment around the mobiles
- **Disadvantage**
  - Route set up, frequent route update
  - Mobiles have to be relay nodes for the provider’s benefit

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**Multi-hop path between a mobile and BS**

Suppose that a mobile leaves a cell and moves away from the base station. This mobile has at least a path to BS in the ON intervals and does not in the OFF intervals.

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Time scale for multi-hop paths by fixed relay facilities:

- ON
- OFF

Time scale for multi-hop paths by mobiles:

- ON
- OFF
- ON
- OFF
- ON
- OFF
Problem statement

- Mobile multi-hop networking provides multi-hop paths with frequent ON-OFF transitions
- For cell design, we have to well understand behaviors of the multi-hop paths
  - Length of the ON period
  - Length of the OFF period
- What limits ON period and what causes OFF period?
  - Mobility of nodes.
  - Randomness of distribution of nodes
  - Capacity of relay nodes (relaying capability)
- Estimation by Stochastic Geometry

Mobility

- One dimensional movement along a street (Street micro cellular is assumed)
  - Case 1: Relay terminals are fixed
  - Case 2: All relay terminals move right
  - Case 3: Some relay terminals are fixed and other terminals move right
  - Case 4: Relay terminals move right or left
- Velocity: constant or random variable
- Intersections
Fixed relay facilities

• If distance between two nodes is not greater than $d$, there exist a link between them.
• If we have $n$ facilities, the degree of cell extension is $nd$.

Fixed but random

• The distribution of nodes obeys a Poisson distribution of intensity $\lambda$.
• If distance between two nodes is not greater than $d$, there exist a link between them.
• Mean length of extended area is $\frac{e^{\lambda d} - 1}{\lambda} - d$.
• Fixed relay nodes.
• Only a node $mn_0$ move right at velocity $v_1$.
• Life time of the connection: $\mathbb{T}_1' - \mathbb{T}_1$
• Mean life time
  \[
  \frac{1}{v_1} \left( \frac{e^{vd} - 1}{\lambda - d} \right)
  \]
<table>
<thead>
<tr>
<th>Case</th>
<th>( E(T_1) ): Mean length of the first ON period</th>
<th>( E(T_2) ): Second ON period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1: Fixed relay nodes. Only ( mn_0 ) moves right at ( v_1 )</td>
<td>( \frac{1}{v_1} \left( \frac{e^{\lambda d} - 1}{\lambda} - d \right) )</td>
<td>0</td>
</tr>
<tr>
<td>Case 2: All nodes move right at ( v_1 )</td>
<td>( \frac{1}{v_1} \left( \frac{e^{\lambda d} - 1}{\lambda} - d \right) )</td>
<td>0</td>
</tr>
<tr>
<td>Case 3: Mobile nodes move right at ( v_1 ), and other nodes are fixed</td>
<td>( \frac{2}{v_1} \left( \frac{e^{\lambda d/2} - 1}{\lambda/2} - d \right) )</td>
<td>( \frac{1}{v_1} \left( \frac{e^{\lambda d/2} - 1}{\lambda} \right) )</td>
</tr>
<tr>
<td>Case 4: Mobile nodes move right at ( v_1 ) or move left at ( v_2 )</td>
<td>( \frac{2v_1 + v_2}{v_1(v_1 + v_2)} \left( \frac{e^{\lambda d/2} - 1}{\lambda/2} - d \right) )</td>
<td>( \frac{1}{v_1 + v_2} \left( \frac{e^{\lambda d/2} - 1}{\lambda} \right) )</td>
</tr>
</tbody>
</table>

\( \lambda \): Mean number of nodes per unit length

<table>
<thead>
<tr>
<th>Case</th>
<th>Lower bound of the mean length of an OFF period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1: Fixed relay nodes. Only ( mn_0 ) moves right at ( v_1 )</td>
<td>( \infty )</td>
</tr>
<tr>
<td>Case 2: All nodes move right at ( v_1 )</td>
<td>( \infty )</td>
</tr>
<tr>
<td>Case 3: Mobile nodes move right at ( v_1 ), and other nodes are fixed</td>
<td>( \frac{1}{v_1} \left( \frac{4}{\lambda} \right) )</td>
</tr>
<tr>
<td>Case 4: Mobile nodes move right at ( v_1 ) or move left at ( v_2 )</td>
<td>( \frac{1}{v_1 + v_2} \left( \frac{4}{\lambda} \right) )</td>
</tr>
</tbody>
</table>

\( \lambda \): Mean number of nodes per unit length
\[ \theta = 0.5, \, v_1 = v_2 = 1 \text{ m/s}, \, d = 10 \text{ m} \]

\[ \theta = 0.7, \, v_1 = v_2 = 1 \text{ m/s}, \, d = 10 \text{ m} \]
\[ \square = 0.3, \ v_1 = v_2 = 1 \text{ (m/s)}, \ d = 10 \text{ (m)} \]

### Length of ON period

### Length of OFF period

### Effects of intersection

Without intersection

With intersection
Effects of the relaying capacity of a node on cell extension by multi-hop networking
Waiting Time for Patterns

- Choose a character from \{1, 2, \ldots, m\} until one of \(n\) given patterns \(S_1, S_2, \ldots, S_n\) appears.
- The digits occur with probabilities \(p_1, p_2, \ldots, p_m\).
- Mean waiting time \(E[N]\) is obtained from the following simultaneous equations:

\[
\begin{align*}
\sum_{j=1}^{n} e_{ij} \pi_j &= E[N], i = 1, 2, \ldots, n \\
\sum_{j=1}^{n} \pi_j &= 1,
\end{align*}
\]

\[
e_{ij} = \sum_{r=1}^{L} \varepsilon_r(i, j) \frac{e_{ij}}{p_{c_1} p_{c_2} \ldots p_{c_r}}
\]

\(L = \min(L_i, L_j)\), where \(L_i\) is Length of \(S_i\)

\(\varepsilon_r(i, j) = 1\) if \(S_i\) ends with \(c_1c_2\ldots c_r\) and \(S_j\) begins with \(c_1c_2\ldots c_r\) and \(\varepsilon_r(i, j) = 0\) otherwise.

\(\pi_j\) is the probability that the sequence ends in pattern \(S_j\)

Effects on capacity on cell extension

- A node can carry only one communication
- Multiple communication requirements
Assumptions on distribution of nodes

Two nodes communicate with BS simultaneously ($k=2$).

- Probability $p$
- Probability $1-p$

$\Delta x \rightarrow 0$  Exponential distribution

- Capacity is 1 --> A node can be a relay node for only one node.
- Communication range: $d = m \Delta x$

$m=4, k=2$

All nodes move right
Problem
What is the mean length of interval between the time at which $mn_0$ leaves the cell and the time at which $mn_0$ or $mn_1$ loses connection to BS?

$m=4, k=2$

Communicating nodes

No path for $mn_1$
Answer is
\[
\left\{E(N) - (m-k+1)\right\} \frac{\Delta x}{v}
\]

- \(E(N)\) is the waiting time until one of the patterns \(000, 0010, 0100\) appears in a random sequence of 0 and 1.
- \(m=4\)
  - Communication range \(d = m \cdot x\)

\[
E(N) = \frac{1}{1-p} + \frac{1}{(1-p)^2} + \frac{1}{(1-p)^3} \left(1 + p + p^2\right)^2
\]

No limit for relay
\[
E(N) = \frac{1}{1-p} + \frac{1}{(1-p)^2} + \frac{1}{(1-p)^3} + \frac{1}{(1-p)^4}
\]

Communication range \(d=1\)

\[\square \ x=1/256 \ (Theory)\]
\[\square \ x=1/128 \ (Theory)\]
\[\square \ x->\square \ (Simulation)\]
\[\square \ (Intensity \ of \ nodes)\]

Two paths

No limit
Current status

• $E\{T_1\}$ for fixed relay nodes has been obtained.
• $E\{T_1\}$ for relay nodes moving toward one direction has been obtained.
• Upper and lower bounds of $E\{T_1\}$ for relay nodes moving right or left have been obtained.
• An approximate method for $E\{T_1\}$ for relay nodes moving right or left have been proposed.