Network Design for QoS under IEEE 802.15.4 ("Zigbee") CSMA/CA for Internet of Things Applications

EECS Symposium

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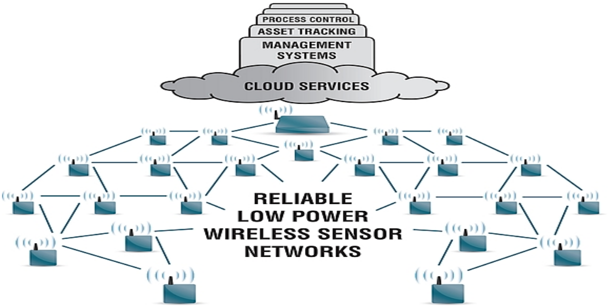
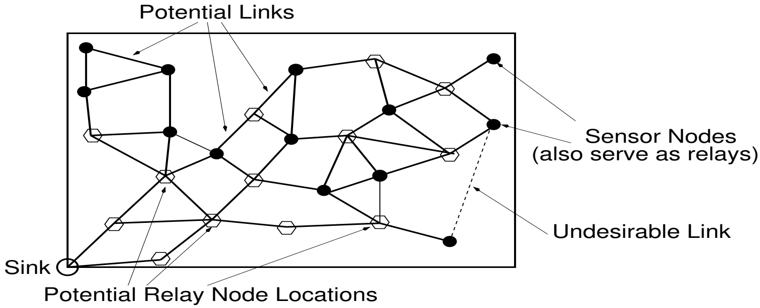
Wireless Sensor Networks and IoT



- Wireless sensor networks essential component of the emerging Internet of Things
- Sensor data → WSN → Gateway/sink → Internet → Cloud

How do we design wireless networks for interconnecting sensors in the field to the Internet with some guranteed QoS?

The Subgraph Design Problem



- Given: sensor locations, sink location, potential relay locations, *fixed* transmit power of the nodes
- Assume: the link qualities between the various locations known
    - Thus, there is a graph of "good" links
- Problem: select a set of potential relay locations to place relays
    - Obtain a multihop wireless network with some desired properties, e.g.,

$$\min \quad \text{number of relays} \quad s.t. \quad P[\text{end-to-end delay} \leq d_{\max}] \geq p_{\text{del}}$$

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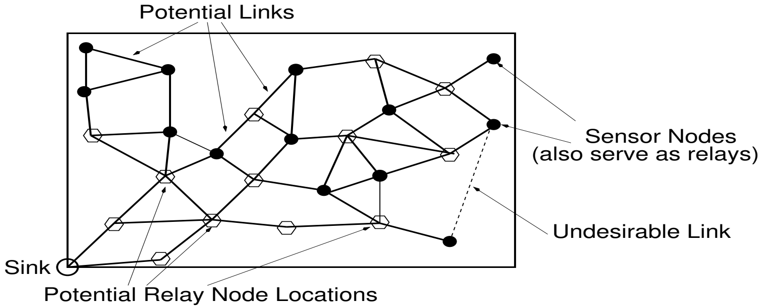

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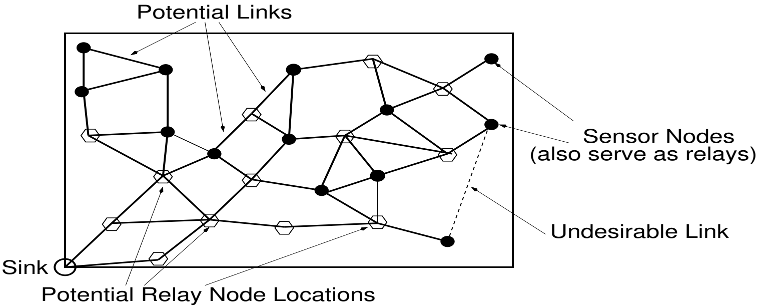

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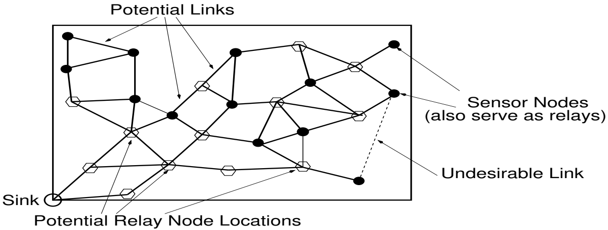
Traffic Rate Regimes: Application Dependent

- **Very light traffic regime**
  - Environment/resource monitoring applications
  - Measurements required at multiple seconds or minutes
  - Essentially no inter-node contention
  - In this regime, Target $p_{\mathrm{del}} \Rightarrow$ Hop Constraint
- **Light to moderate traffic regime**
  - Sub-second measurement rates
  - E.g., health monitoring
  - Contention due to CSMA/CA

Theorem

To meet QoS target for light to moderate traffic regime, necessary to satisfy the same under very light traffic regime.

Very Light Traffic: Problem Formulation



- Given a graph over the sources, potential relay locations, and the sink
- *Problem:* Extract a subgraph spanning the sources, rooted at the sink
    - using a minimum number of relays s.t.
    - Each source is connected to the sink with hop count at most $h_{\max}$
- **Set Cover-Hard** $\Rightarrow$ We propose **approximation algorithms**

- Bhattacharya-Kumar, *Elsevier Computer Networks*, 2014

Network Design Algorithms: Outline

- Sequence of shortest path computations from the sources to the sink
  - Prune a relay in each iteration
  - Each time, compute a new SPT over only the remaining nodes
  - Until hop constraint is violated
- Trick is to choose which relay to prune next
- Empirical average case approx. ratio close to 1 from over 1000 randomly generated scenarios

Theorem

Worst case approx. ratio: $\min\{m(h_{\max}-1), (|R|-1)\}$, *where* $m = \#$ *sources,* $h_{\max} =$ *hop constraint, and* $|R| = \#$ *potential relay locations*

  - Too conservative

Average Case Analysis in a Random Geometric Graph Setting

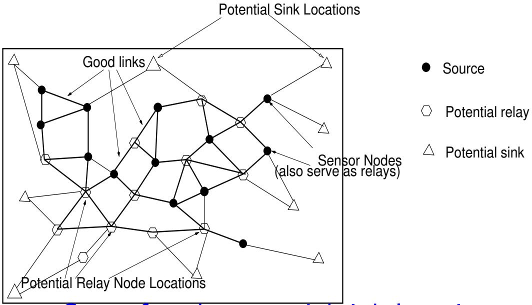
Theorem

Average case approx. ratio, $\alpha \leq \frac{\overline{N}}{\underline{R}_{Opt}}$ *where,*

$$\overline{N} \triangleq m\left[h_{\max} - \frac{1}{(1-\epsilon)^2 h_{\max}^2} - \sum_{j=2}^{h_{\max}-1} \frac{j^2}{h_{\max}^2}\right] - m + m\delta(h_{\max}-1)$$

$$\underline{R}_{Opt} \triangleq \left[1 - \left(\frac{h_{\max}-1}{(1-\epsilon)h_{\max}}\right)^{2m}\right](1-\delta)\sum_{i=1}^{h_{\max}-1}\left(1 - \frac{\frac{n_i^2}{3}}{(1-\epsilon)^2 h_{\max}^2}\right)^{m-1}$$

Multi-sink Network Deployment: An Example



- Cost of each *potential* sink location, c_s
- Cost of each *potential* relay location, c_r

The Problem

- Extract a subgraph spanning the sources
  - using a minimum cost selection of relays and sinks s.t.
  - each source has a path to at least one sink with hop count at most h_{max}
- *Set Cover Hard*; we employ a greedy heuristic
- Fast run-time; close to optimal solutions in practice
  - Bhattacharya et al., *SPCOM '14*

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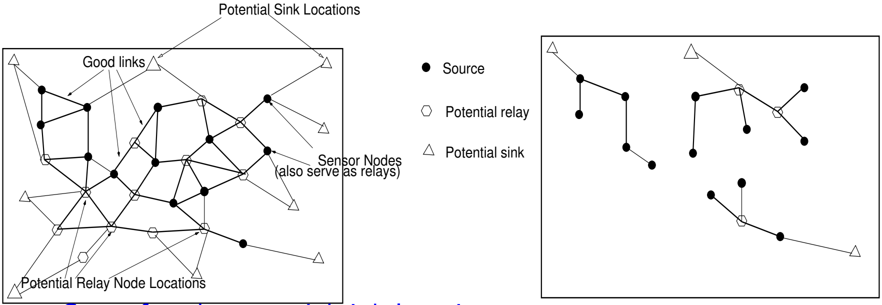

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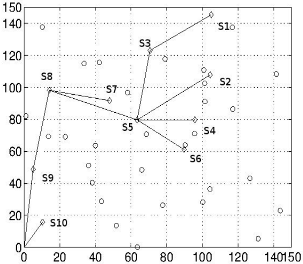
Beyond Very Light Traffic: Overview of our Approach



- Consider a **very light traffic** design
- Hop counts $h_i, 1 \leq i \leq m$, being bounded by $h_{\max}$ ($= 5$ in the example)
- Measurement generation rate at sensors is λ pkts/s
- How large can λ be until the packet drop probability at a link exceeds a target $\overline{\delta}$?

Our Approach

- Develop an analytical model for IEEE 802.15.4 CSMA/CA multihop networks
  - A decoupling approximation to analyze individual node processes
  - Yields a set of fixed point equations involving time-averaged node statistics
  - Srivastava et al., *Elsevier Ad Hoc Networks*, 2016
- Use the model to obtain constraints on arrival rates and topology to meet QoS
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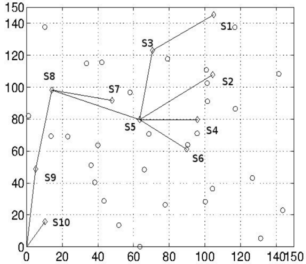

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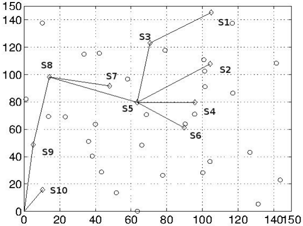
Light Traffic Design: No Hidden Nodes



- $h_i \leq h_{\max}, 1 \leq i \leq m$
- Arrival rate at each sensor λ pkts/s
- Find maximum λ s.t. drop probability at a link at most $\overline{\delta}$

- For the light traffic regime, we obtain a design constraint

$$\lambda \sum_{i=1}^{m} h_i \leq B(\overline{\delta}, T)$$

  - $T =$ packet duration on the medium; $B(\cdot,\cdot)$ has an explicit formula
  - Obtained by Taylor expansion around the detailed f.p., and analyzing the resulting simpler f.p. using several concepts from Real Analysis
- Notice that $\lambda \sum_{i=1}^{m} h_i$ is the total *offered* packet rate on the medium
- Example: $T = 262$ symbols, $\overline{\delta} = 2\% \Rightarrow B(\overline{\delta}, T) = 95.2$ pkts/s
- Consequence: A Shortest Path Tree is **approx. throughput optimal**

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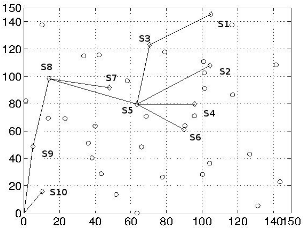

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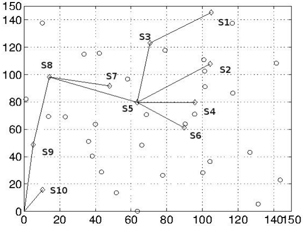

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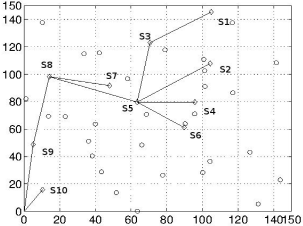

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