MULTI-HOP NETWORK DESIGN UNDER IEEE 802.15.4 FOR IOT APPLICATIONS

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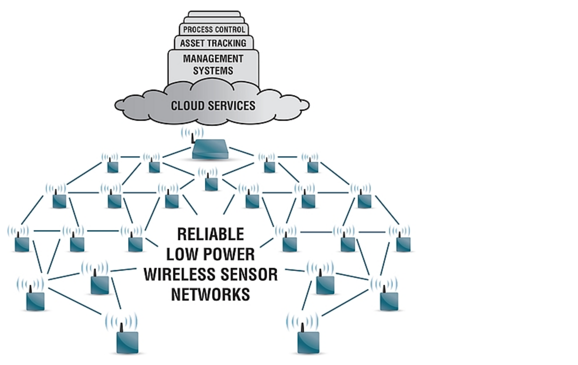
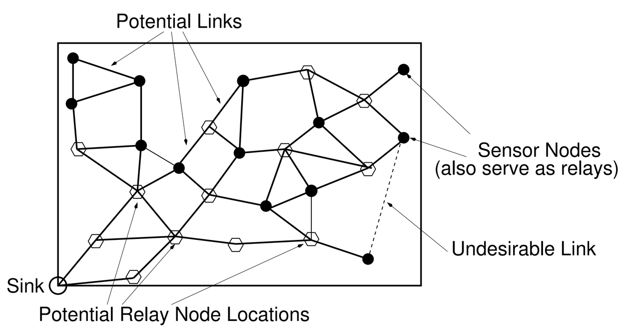
Wireless Sensor Networks and IoT



- Wireless sensor networks essential component of the 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



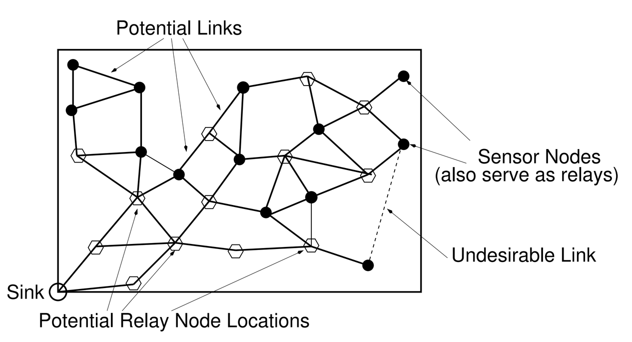
- Given: sensor locations, sink location, potential relay locations, *fixed* transmit power of the nodes
- There is a graph of "good" links
- Problem: select a set of potential relay locations to place relays
  - Obtain a multihop wireless network with some desired properties, e.g., min number of relays $P[\text{end-to-end delay} \leq d_{\max}] \geq p_{\text{del}}$

Traffic Rate Regimes

- **Very light traffic regime**
  - Environment/resource monitoring
  - Measurements required at multiple seconds or minutes
  - Essentially no inter-node contention
  - In this regime, Target p_{del} ⇒ 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.

Network Design for Very Light Traffic



- 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* ⇒ Need **approximation algorithms**

ILP Formulation

- Γ^k: the set of minimal node cuts for a source node k

$$\min \sum_{j \in R} y_j \quad (1)$$

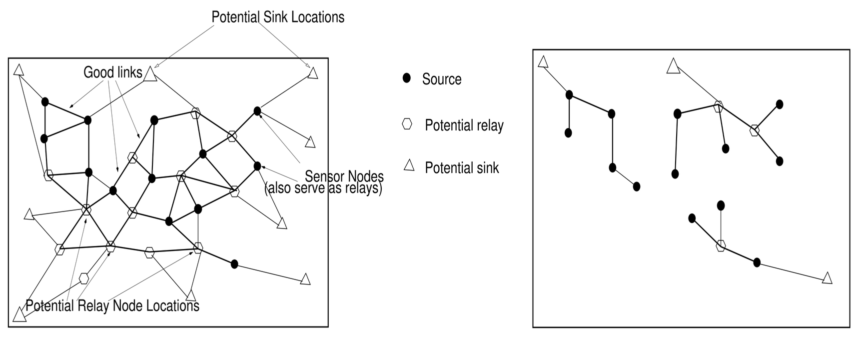
Subject to:
$$\sum_{j \in \gamma} y_{j,k} \geq 1 \quad \forall \gamma \in \Gamma^k; \forall k \in Q \backslash \{0\} \quad (2)$$
$$y_j \geq y_{j,k} \quad \forall j \in R; \forall k \in Q \backslash \{0\} \quad (3)$$
$$\sum_{j \in V \backslash \{k,0\}} y_{j,k} \leq h_{\max} - 1 \quad \forall k \in Q \backslash \{0\} \quad (4)$$
$$y_{j,k} \in \{0,1\} \quad \forall k \in Q \backslash \{0\}; \forall j \in V \backslash \{k,0\} \quad (5)$$
$$y_j \in \{0,1\} \quad \forall j \in R \quad (6)$$

Theorem: Opt. value of the objective function for the ILP = Opt. solution to the design problem

Poly-time Heuristic

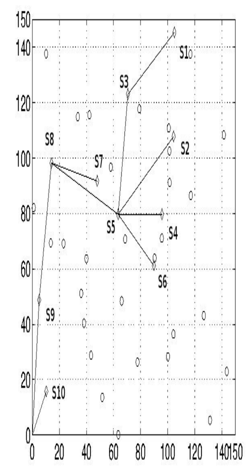
- Sequence of shortest path computations from the sources to the sink
  - Start with a shortest path tree (SPT) on the entire network graph
    - ∗ Any source-sink path longer than $h_{\max}$ ⇒problem infeasible
  - Prune relay nodes from the feasible solution sequentially
  - Each time, compute a new SPT over only the remaining nodes
  - Until hop constraint is violated
- 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

Multi-Sink Network Design



- Cost of each *potential* sink location, c_s
- Cost of each *potential* relay location, c_r
- 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 set cover based greedy heuristic
- Fast run-time; close to optimal solutions in practice

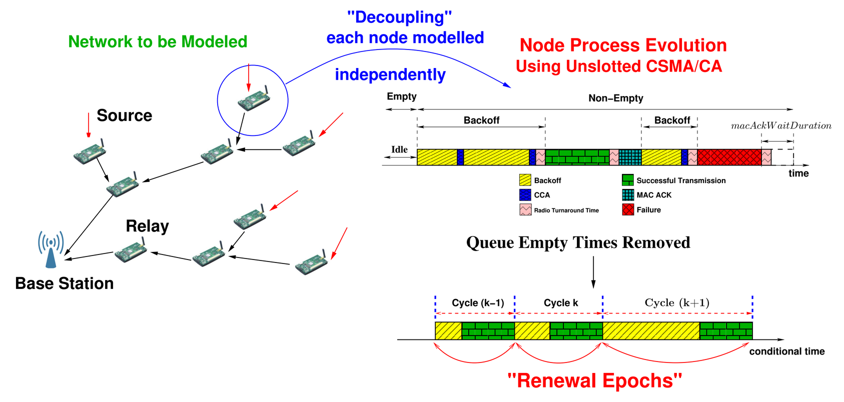
Beyond Very Light Traffic



- 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 λ pkts/s
- Find largest λ s.t. packet drop probability at a link is at most a target $\overline{\delta}$

- Develop an analytical model for IEEE 802.15.4 CSMA/CA multihop networks
- Use the model to obtain constraints on arrival rates and topology to meet QoS

802.15.4 CSMA/CA Network Analysis



- Decoupling: Stochastic process at each node modeled independently, isolating it from the rest of the network
  - treating the rest of the network as environment
  - environment modeled by its unknown time averaged statistics
- Recoupling: The individual node processes are coupled via fixed point equations involving their unknown time averaged statistics

Fixed Point Eqns.:No Hidden Nodes

$$\eta_i = \frac{\beta_i}{\beta_i + \sum_{j \neq i} \overline{\tau}_j^{(i)}}; \; c_i = \left(1 - e^{-12\, T_s \beta_i}\right)$$

$$\overline{\tau}_j^{(i)} = \frac{\beta_j \times b_j \times q_j}{1 - q_j + q_j \times b_j}; \; \gamma_i = l + (1 - l)p_i$$

$$\alpha_i = \frac{(1 - \eta_i)(1 - c_i)\beta_i T_{tx}}{\eta_i + (1 - \eta_i)c_i + (1 - \eta_i)(1 - c_i)\beta_i T_{tx}}$$

$$p_i = \frac{R_i^{(3)} + R_i^{(4)}}{\eta_i + (1 - \eta_i)c_i}; \; R_i^{(4)} = (1 - \eta_i)c_i$$

$$R_i^{(3)} = \eta_i \left(1 - \exp\left\{-12\, T_s \left(\sum_{j \neq i} \overline{\tau}_j^{(i)}\right)\right\}\right)$$

$$\overline{B}_i = 78 + 158\alpha_i + 318\alpha_i^2 + 318\alpha_i^3 + 318\alpha_i^4; \; r_i = \gamma_i(1 - \alpha_i^5)$$

$$\overline{Z}_i = \overline{B}_i(1 + r_i + r_i^2 + r_i^3)$$

$$\overline{Y}_i = (1 - \alpha_i^5)T(1 + r_i + r_i^2 + r_i^3)$$

$$\frac{1}{\sigma_i} = \overline{Z}_i + \overline{Y}_i; \; b_i = \frac{\overline{B}_i}{\overline{B}_i + (1 - \alpha_i^5)T_{\text{tx}}}$$

$$\beta_i = \frac{1 + \alpha_i + \alpha_i^2 + \alpha_i^3 + \alpha_i^4}{\overline{B}_i}$$

$$q_i = \frac{\nu_i}{\sigma_i}; \nu_i = \lambda_i + \sum_{k \in \mathcal{P}_i} \theta_k; \theta_i = \nu_i(1 - \delta_i)$$

$$\delta_i = \alpha_i^5(1 + r_i + r_i^2 + r_i^3) + r_i^4$$

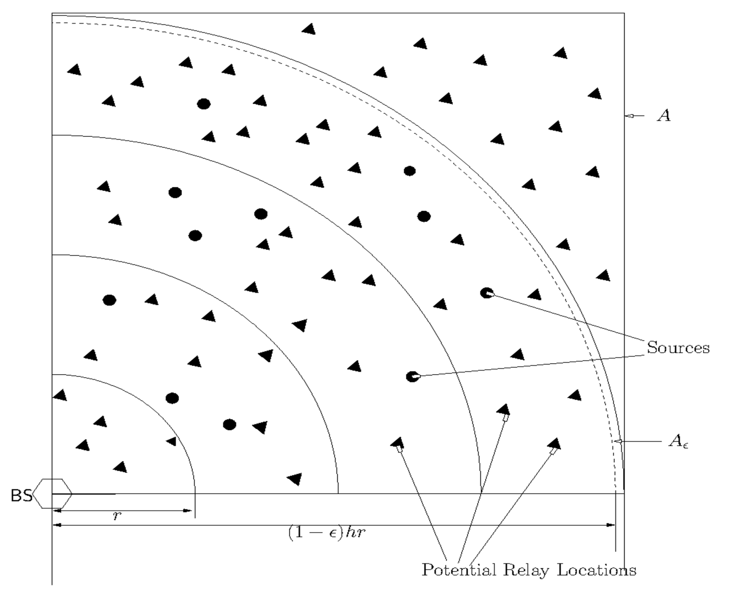
Light Traffic Design: NH Nodes

- 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; $B(\cdot,\cdot)$ has an explicit formula
  - Taylor expansion around the detailed fixed point ⇒ simpler scalar fixed point
  - The scalar f.p. analyzed using monotonicity arguments, and concepts from Real Analysis (Lipschitz continuity, contraction principle, Mean Value Theorem)
- Notice that $\lambda \sum_{i=1}^{m} h_i$ is the total *offered* packet rate that the medium must carry
- Example: For default protocol parameters, with T = 262 symbols, and $\overline{\delta}$ = 2%, we get $B(\overline{\delta}, T) = 95.2$ packets/sec
- Consequence: A Shortest Path Tree is **approximately throughput optimal**

Average Case Analysis: Setting



- n potential locations i.i.d. uniformly over A
- m sources i.i.d. uniformly over A_ϵ
- Yields $\mathcal{G}^r(\omega)$: RGG consisting of links of length $\leq r$
- $\mathcal{X} = \{\omega : \omega \text{ is hop count feasible}\}$
- For $n \geq n_0(\epsilon, \delta, h_{\max}, r)$, $Pr[\mathcal{X}] \geq 1 - \delta$
- $N_{algo}(\omega)$: # relays in the outcome of the algorithm on $\mathcal{G}^r(\omega)$
- $R_{Opt}(\omega)$: # relays in an optimal solution to the design problem on $\mathcal{G}^r(\omega)$
- Define average case approximation ratio

$$\alpha \triangleq \frac{E[N_{algo}|\mathcal{X}]}{E[R_{Opt}|\mathcal{X}]}$$

Average Case Analysis: Results

Lemma 1:

$$E[N_{algo}|\mathcal{X}] \leq m\left[h_{\max} - \frac{1}{(1-\epsilon)^2 h_{\max}^2} - \sum_{j=2}^{h_{\max}-1} \frac{j^2}{h_{\max}^2}\right] - m + m\delta(h_{\max} - 1) \triangleq \overline{N}$$

Lemma 2:

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

where, $n_i = \min(i, h_{\max} - i)$

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

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