Maximizing Network Lifetime of WirelessHART Networks under Graph Routing

Chengjie Wu, Dolvara Gunatilaka, Abusayeed Saifullah*, Mo Sha^, Paras Tiwari, Chenyang Lu, Yixin Chen

Cyber-Physical Systems Lab, Washington University in St. Louis
Missouri University of Science & Technology *
Binghamton University ^
Wireless for Process Automation

Emerson
• 5.9+ billion hours operating experience
• 26,200+ wireless field networks

$944.92 million by 2020
[Market and Market]

Offshore
Onshore

Killer App of IoT!

Courtesy: Emerson Process Management
Industrial Wireless Challenges

- Reliability
- Real-time
- Control performance
- **Energy efficiency:** need long battery life in harsh environments!
WirelessHART

- **Industrial reliability**
  - Multi-channel TDMA MAC
  - Over IEEE 802.15.4 PHY
  - **Redundant routes**

- **Centralized network manager**
  - collects topology information
  - generates routes and transmission schedule
  - disseminates to field devices
  - re-computes routes when topology changes

*Industrial wireless standard for process monitoring and control*
Graph Routing

- Handle link and node failures through path diversity
- Graph route of a flow
  - a primary path
  - a backup path for each node on the primary path

Transmissions per hop
- Two transmissions on the primary link – dedicated TDMA slots
- One transmission on the backup link – shared CSMA/CA slot
Energy Cost of Reliability

- Graph routing improves reliability at cost of energy
- Measurement: +57% reliability at $1.7 \times \text{energy}$ compared to single-path source routing [EWSN'15]
Challenges

- Maximize network lifetime under graph routing
  - Industry demands multi-year battery life
  - Efficient routing in response to wireless dynamics

- Unique challenges for WirelessHART networks
  - **Centralized multi-path** graph routing
  - Transmissions in **dedicated** and **shared** slots
Contributions

- Problem: network lifetime maximization under graph routing
  - Network lifetime = time till first node runs out of battery
  - NP hard

- Three approaches
  - Optimal integer programming
  - Linear relaxation of the integer programming
  - Efficient greedy heuristic

- Implementation on a WirelessHART testbed
Analyzing Power Consumption

- Model based on WirelessHART standard
- 1-2 transmissions on primary path
- 3rd transmission on back path
  - Small probability, but receiver must turn on and listen.
- **Load**: power consumption / battery capacity
Objective: max min node lifetime → min max load

Graph route as constraints
- An incoming primary link → an outgoing primary link
- An incoming primary link → an outgoing backup link
- An incoming backup link → an outgoing backup link

Optimal solution
- High computational cost → cannot scale to large networks
Linear Programming Relaxation

1. Relax binary decision variables to real numbers
2. Linear Programming $\rightarrow$ real number solutions
3. Round real numbers to integer solutions based on threshold
4. Incrementally find the largest threshold with valid routes

- Implemented in GNU Linear Programming Kit (GLPK)

- Near optimal solution with affordable computational cost.
Greedy Heuristics

- Compute routes for flows in the rate monotonic order

- For each flow: find the graph route with minimum load
  - Load per node = power consumption / battery capacity
  - Incrementally add nodes with the smallest load to primary path and update neighbors’ load
  - Then select backup path with minimum load

- Iterate until no further improvement

- Polynomial complexity
Evaluation

- Implemented on a WirelessHART testbed (69 TelosB motes)
  - WirelessHART stack (multi-channel TDMA + routing)
  - Network manager (scheduler + routing)
- Simulations based on testbed topology
Compare to Optimal (Small Network)

- Lifetime normalized to optimal solution from Integer Programming
- 10 nodes, 20 links
- **SP**: Shortest Path
- **RRC** [Han 2011]
- **GH**: Greedy Heuristic
- **LP**: Linear Programming

**GH & LP within 80% of optimal**
LP and GH lead to longer network lifetime
GH needs less time than LP
Conclusion

- Industrial wireless networks is a killer app for IoT
  - Driven by industrial standards such as WirelessHART
  - Deployments rolling out worldwide

- Graph routing enhances reliability at high energy cost → energy efficiency is critical!

- Three approaches to maximize network lifetime
  - Integer Programming: optimal
  - Linear Programming Relaxation: faster
  - Greedy Heuristic: fastest solution for run-time adaptation

- Implemented with WirelessHART on testbed