Algorithms for Optimal Power Allocation of Wireless Multi-Hop Heterogeneous Networks under Statistical Delay Constraints

Neda Petreska
(joint work with J. Gross and H. Al-Zubaidy)

Fraunhofer Institute for Embedded Systems and Communication Technologies ESK

WoNeCa 2018

Erlangen, 28.02.2018
Wireless Industrial Sensor Networks
Wireless Industrial Sensor Networks

- Provide e2e delay guarantees
- Maximize battery lifetime
- Minimize interference
System Model

- Multi-hop path
- Time slotted system
- Block-fading channels with non-identically distributed, but statistically independent channel gains
Open Questions

- How to analytically define the end-to-end performance guarantees for wireless industrial networks?
  
  ⇒ Consider fading and queuing effects.

- Is an optimal transmit power allocation possible?

- Does the analytical optimum resemble the real system optimum?
Used Method: Stochastic \((\text{min}, x)\) Network Calculus

\[ S(\tau, t) = \prod_{i=\tau}^{t-1} g(\gamma_i) \]

\[ e^{S(\tau, t)} \quad \text{Bit domain} \quad \log(S(\tau, t)) \]

\[ S(\tau, t) = \sum_{i=\tau}^{t-1} \log g(\gamma_i) \]

SNR domain
Analytical Delay Bound

\[ K(s, w) = \frac{M_S(s)^w}{1 - M_A(s)M_S(s)} \leq \varepsilon \]

- \( K(s, w) \): Target delay
- \( M_S(s) \): Mellin transform of the service
- \( M_A(s) \): Mellin transform of the arrival
- \( \varepsilon \): Target delay violation probability
Recursive End-to-End Delay Bound

\[ \mathbb{L} = \{1, 2, 3\} \]

\[ A(t) \rightarrow S_1 \rightarrow S_2 \rightarrow S_3 \rightarrow D(t) \]

Violation probability of the target end-to-end delay \( w \):

\[
K^{\{1,2,3\}}(w) = \frac{M_{S_2}}{M_{S_2} - M_{S_3}} \cdot K^{\{1,2\}}(w) + \frac{M_{S_3}}{M_{S_3} - M_{S_2}} \cdot K^{\{1,3\}}(w)
\]

Transmit Power Minimization Algorithm

Enable delay-aware dynamic power management to

- Extend battery $\Rightarrow$ node $\Rightarrow$ network lifetime
- Reduce interference
- Enable coexistence of several wireless technologies

Use delay bound convexity
Convex Delay Bound: One Hop

![Graph showing delay violation probability vs. time with different SNR levels.

Delay Violation Probability

- SNR=[5] dB
- SNR=[7] dB
- SNR=[10] dB
- SNR=[12] dB

s

10^-8
10^-6
10^-4
10^-2
10^0

s

0 0.005 0.01 0.015 0.02 0.025 0.03 0.035 0.04

N. Petreska (Fraunhofer ESK)
Convex Delay Bound: Multi-Hop

N. Petreska, "End-to-End Performance Analysis for Industrial IEEE 802.15.4e-based Networks", Fachgespräch für Sensornetze, 2017
Power Minimization Algorithm

Apply $\bar{P} = \bar{P}_{\text{max}}$

1. $\kappa^L(s^*, \bar{P}) \leq \varepsilon$ no: no solution
   yes: $\kappa^L \in (\varepsilon - \Delta \varepsilon, \varepsilon)$

2. $\kappa^L \in (\varepsilon - \Delta \varepsilon, \varepsilon)$ yes: return $\bar{P}_{\text{opt}}$
   no: Find link $j$ with smallest gradient $j = \arg\min \kappa_j = \left| \frac{\kappa^L_j - \kappa^L(s, \bar{P})}{\Delta P} \right|$

3. $P_j = P_j - \Delta P$

4. $P_{j_{\text{new}}} < P_{j_{\text{min}}}$ or $\kappa^L(s^*, \bar{P}) > \varepsilon$
   no: Search $s^*$, Compute new $\kappa^L(\bar{P}_j, s^*)$
   yes: $\Delta P > \Delta P_{\text{min}}$

5. $\Delta P = \Delta P/2$

$\bar{P}_{\text{opt}} = \bar{P}_j$
Link Heterogeneity

- Target delay violation probability $\varepsilon = 10^{-3}$.
- Payload size 10 B.
- Transmit power used as a comparison $P_{tx} = 4$ dBm.
- Duration of superframe 30 ms.
Bound-Based vs. Real System Optimum

How well the NC-based power optimization reflects the real system optimum?

![Graph showing the comparison between Bound-Based and Real System Optimum]

- Minimal Battery Duration [#superframes]
- Delay in superframes

- Norm 4 Alg.
- Norm 4 Sim.
- Norm 46 Alg.
- Norm 46 Sim.
- Norm 60 Alg.
- Norm 60 Sim.
- Norm 70 Alg.
- Norm 70 Sim.

N. Petreska (Fraunhofer ESK)
Additional Network Lifetime Extension
Conclusions

- Latency, reliability and energy efficiency - crucial requirements for industrial applications
- Using the (min,x) network calculus we provide
  - a closed form expression for the end-to-end delay bound in multi-hop wireless heterogeneous networks
  - a bound-based optimal power allocation algorithm
- Bound-based power allocation can be used to design reliable and power-efficient wireless industrial networks
Next Steps

- Validate the delay bound in real IEEE 802.15.4e testbed
  - Currently working with ContikiNG and Cooja simulation network
  - Build a multi-hop network prototype and test the power savings under various delay and reliability constraints
- Use the recursive behaviour of the end-to-end delay bound to define a power-efficient routing algorithm

Zolertia motes

TI CC2538
System-On-Chip
Extra Slides
Validation of the WirelessHART Service Curve