Network-Calculus-Based Approach for Optimal Transmit Power Allocation in Wireless Industrial Multi-Hop Networks

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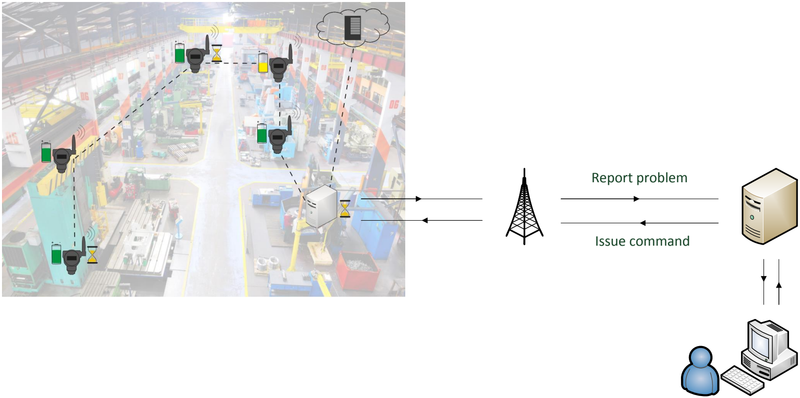
Wireless IoT in Industrial Automation

- IoT comprises heterogeneous wireless networks (WLAN, IEEE 802.15.4e, Bluetooth, ...)
- An IoT network needs:
  - Long battery life
  - Low cost
  - Enhanced coverage $\Rightarrow$ multi-hop
- Typical industrial IoT applications

Application	Latency	Outage prob.
Condition monitoring	> 20 ms	10^{-4}
Predictive maintenance	X s	10^{-3}
Process automation	50 ms - X s	10^{-5}
AGV	15 - 20 ms	$< 10^{-6}$

VDE Positionspapier "Funktechnologien für Industrie 4.0", 2017

Remote Maintenance with IIoT

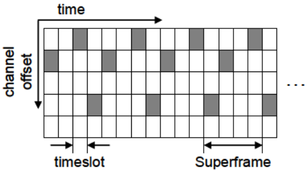


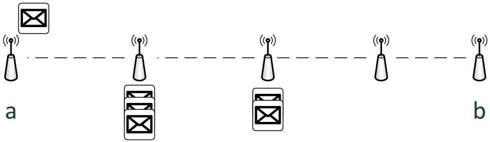
Open Questions

- How to analytically define the end-to-end performance guarantees for wireless industrial networks?
  $\Rightarrow$ Consider fading and queuing effects.
- Which methods to use and how well these methods perform?
- Is an optimal resource allocation possible?
- Does the analytical optimum resemble the real system optimum?

System Model

- Multi-hop path
- IEEE 802.15.4 PHY
- IEEE 802.15.4e TSCH MAC:
  Time Synchronized Channel Hopping
- Block-fading channels with non-identically distributed, but statistically independent channel gains





Goal of the Research

For given target QoS application requirements

- w: delay (given in number of time slots or ms)
- ε: delay violation probability

provide end-to-end delay guarantee and optimize transmit power along a multi-hop path:

- Define the end-to-end delay violation probability
- Determine the optimal transmit power along the path which maximizes battery lifetime and satisfies target QoS (w,ε)

Used Method: Stochastic (min,x) Network Calculus

SNR domain

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

$e^{S(\tau,t)}$

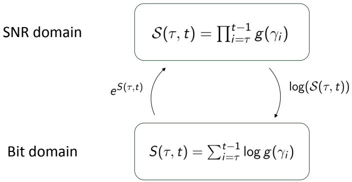
$\log(\mathcal{S}(\tau, t))$

Bit domain

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

H. Al.Zubaidy, J. Liebeherr, A. Burchard, "Network-Layer Performance Analysis of Multihop Fading Channels", IEEE/ACM Transactions on Networking, 2016

Used Method: Stochastic (min,x) Network Calculus



Delay Bound

Quotient of random variables:

$$\mathcal{W}(t) = f\left(\frac{\mathcal{A}(\tau,t)}{\mathcal{S}(\tau,t+w)}\right)$$

Use the Mellin transform:

$$\mathcal{M}_X(s) = \mathbb{E}[X^{s-1}], s > 0$$

$$\Rightarrow K(s,w) = f\left(\mathcal{M}_{\mathcal{A}}(s) \cdot \mathcal{M}_{\mathcal{S}}(s), w\right).$$

Analytical Delay Bound

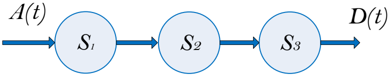
$$K(s, w) = \frac{\mathcal{M}_S(s)^w}{1 - \mathcal{M}_A(s)\mathcal{M}_S(s)}$$

Mellin transform of the service

Mellin transform of the arrival

Recursive End-to-End Delay Bound

$$\mathbb{L} = \{1, 2, 3\}$$



Probability, that the target end-to-end delay w is violated:

$$\mathcal{K}^{\{1,2,3\}}(w) = \frac{S_2}{S_2 - S_3} \cdot \mathcal{K}^{\{1,2\}}(w) + \frac{S_3}{S_3 - S_2} \cdot \mathcal{K}^{\{1,3\}}(w)$$

N.Petreska, H.Al-Zubaidy, R.Knorr, J.Gross, "On the Recursive Nature of End-to-End Delay Bound for Heterogeneous Wireless Networks", ICC, 2015

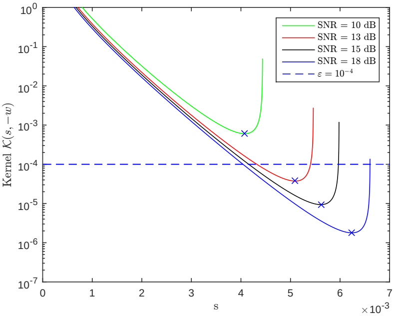
Transmit Power Minimization Algorithm

Enable delay-aware dynamic power management to

- Extend battery ⇒ node ⇒ network lifetime
- Reduce interference
- Enable coexistence of several wireless technologies
- Use delay bound convexity

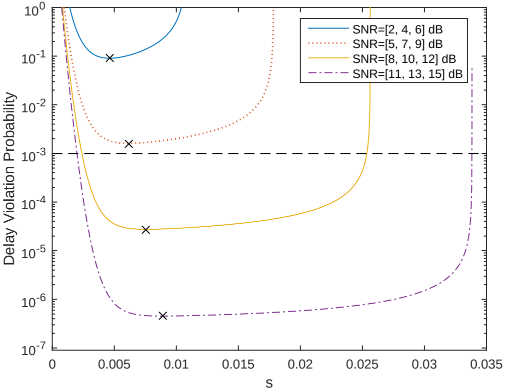
Convex Delay Bound: Shannon Capacity

- The kernel (delay bound) is convex in s and monotone in the average SNR on the link.
- Binary search algorithm in two dimensions
- Instantaneous service: $s_i = N_s \log_2(1 + \gamma_i)$



N.Petreska, H.Al-Zubaidy and J.Gross, "Power Minimization for Industrial Wireless Networks Under Statistical Delay Constraints", ITC, 2014

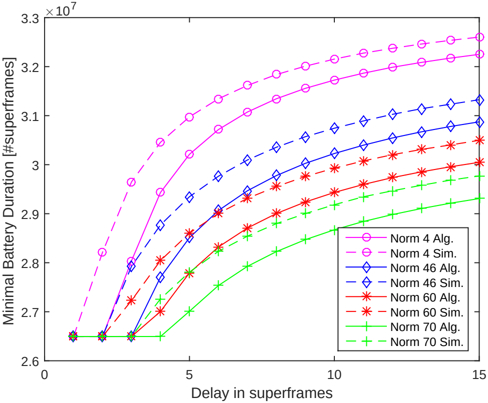
Convex Delay Bound: IEEE 802.15.4-based Networks



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

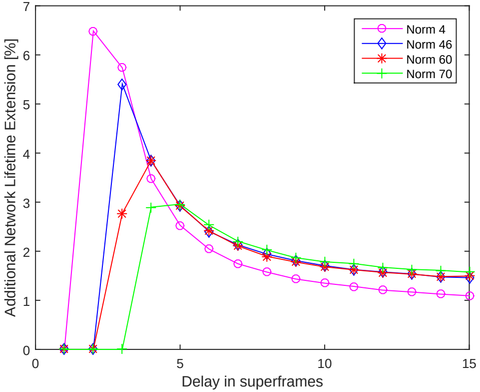
Bound-Based vs. Real System Optimum

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



N.Petreska, H.Al-Zubaidy, R.Knorr, J.Gross, "Bound-Based Power optimization for Multi-Hop Heterogeneous Wireless Industrial Networks Under Statistical Delay Constraints", arXiv:1608.02191, 2017

Additional Network Lifetime Extension



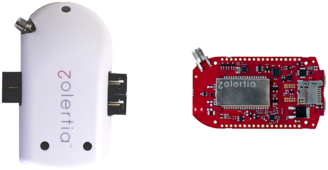
N.Petreska, H.Al-Zubaidy, R.Knorr, J.Gross, "Bound-Based Power optimization for Multi-Hop Heterogeneous Wireless Industrial Networks Under Statistical Delay Constraints", arXiv:1608.02191, 2017

Conclusions

- Latency, reliability and energy efficiency - crucial requirements for industrial IoT
- Stochastic network calculus provides the proper mathematical tools for performance analysis of wireless industrial networks
- 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
- Insignificant difference between the bound-based and the real system optimum was shown for IEEE 802.15.4e-based networks

Next Steps

- Validate the delay bound in real IEEE 802.15.4e network
  - Currently working with Contiki and Cooja simulation network
  - 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



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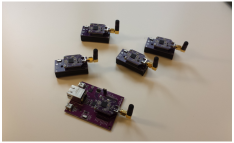

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