Technische Universität Braunschweig

Institute of Operating Systems and Computer Networks

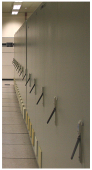
Reliable End-to-End Data Transmission in Wireless Sensor Networks

Wolf-Bastian Pöttner, March 19, 2014

Sines Refinery, Portugal

galpenergia.com

- **35,000** sensors and actuators deployed in Sines refinery
- Connected to the control room **using wires**



Wireless Industrial Monitoring and Control

Motivation

- Monitoring and Control of industrial plants widely based on cables
- Cables have well known **performance and reliability**
- (Petrochemical) Industry physically rearranges plants **regularly**

Benefits of Wireless Networks

- Increased **flexibility** and reduced **cost**

Challenges

- **Bounded end-to-end delay**
- **Guaranteed reliability**

Industrial Processes from a Network Perspective

- (Rather) **Static** network topologies of stationary stations
- **TDMA medium access control** for guaranteed delay
- **Multi-hop** data transport for extended distances
- **Scalability** for large plants

Typical Requirements

- End-to-end delay: max. 1 s
- End-to-end reliability: min. 99 %

How can wireless networks be made reliable enough for monitoring and control of industrial processes?

Outline

Motivation ✓

Fundamentals

- Literature and Technology
- Reliability and Burstiness in TDMA networks

Reliable TDMA Schedules for Real-Time WSNs

- Calculating topologies and schedules
- Measurement results

Distributed Transmission Power Control

- Probe- and attenuation-based Transmission Power Control
- Measurement results

Delay-Tolerant WSNs

Wireless Process Automation in Literature

automation.siemens.com

WirelessHART

- Complex multi-channel design with up to 16 channels
- Wireless extension of the HART field bus
- Primarily for monitoring
- Proprietary centralized network manager

GINSENG

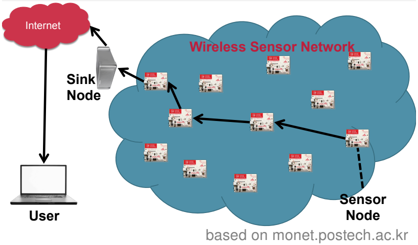
- Predictable single-channel design
- End-to-end solution: sensor to ERP/ERM
- Designed for monitoring and control

T. O'Donovan et al.: *The GINSENG System for Wireless Monitoring and Control: Design and Deployment Experiences*, in TOSN 10, 1, Nov 2013

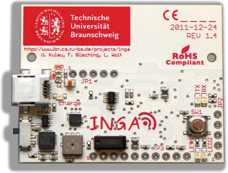
Underlying Technology

Wireless Sensor Networks

- Network of low-power nodes
- IEEE 802.15.4 based radios
- Unstable links, mobility
- Multi-Hop



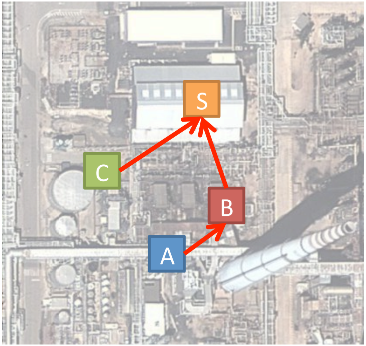
based on monet.postech.ac.kr



Wireless Sensor Nodes

- Based on 8 or 16 bit microcontrollers
- ~16 kiB RAM, ~128 kiB ROM
- Battery powered → short duty cycles

From Topology to TDMA Schedule



Physical Topology

- Location and role of nodes in the field

Logical Topology

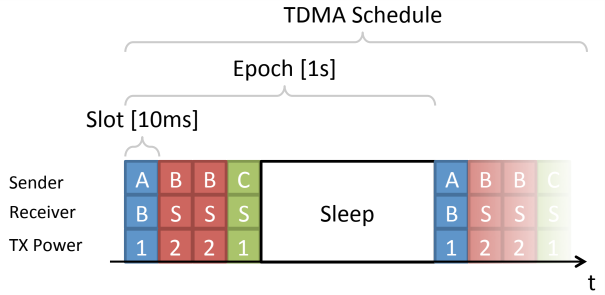
- Multi-hop tree structure rooted at sink

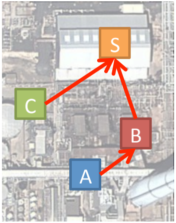
TDMA Schedule

- Based on logical topology, traffic pattern and link reliability

Time Division Multiple Access (TDMA)

- Time is divided into short **time slots**
- Slots are **exclusively** assigned to specific nodes
- Exclusive channel access allows to give timing guarantees





Schedule: Seq. of multiple epochs: $S = \{e_1, \ldots, e_n\}$

Reliability of Wireless Links

Characteristics of Packet Loss Events

- Even on good wireless links, some packets will eventually get lost
- Packet loss events often occur in bursts

Reliability in TDMA Systems

- TDMA schedules have to contain slots for retransmissions
- Worst-case burst loss has to be known in advance

How to determine the number of retransmission slots?

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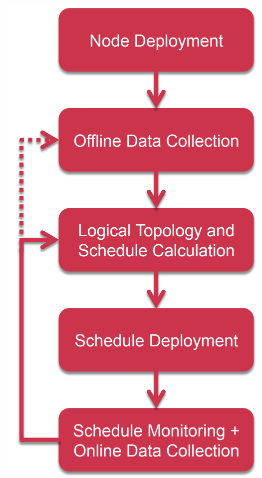
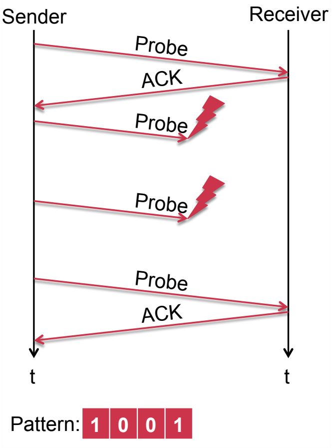
Life Cycle of a TDMA Schedule



Wolf-Bastian Pöttner et al.: *Constructing Schedules for Time-Critical Data Delivery in Wireless Sensor Networks*, in TOSN, 10, 3, Aug 2014

Measuring the Burstiness of Wireless Links



B_{max}

Maximum unsuccessful probes in a row

Here: $B_{max} = 2$

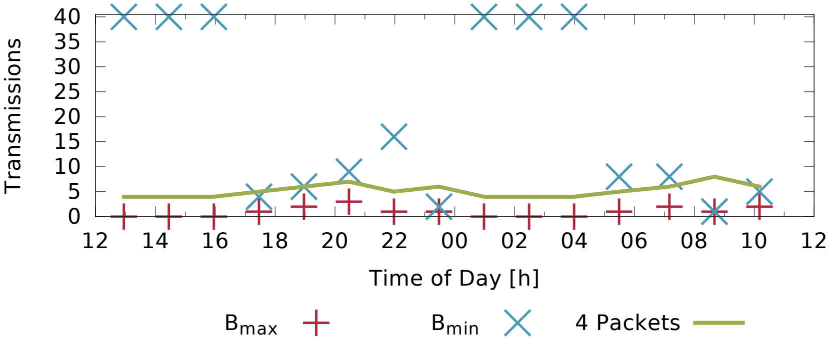
B_{min}

Minimum successful probes after a burst loss

Here: $B_{min} = 1$

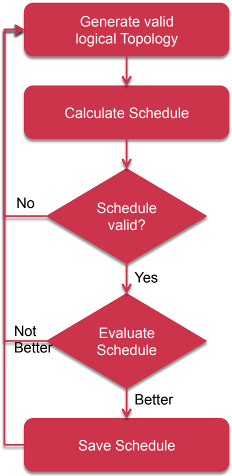
Capturing the worst-case Burstiness of Links

Burstiness of exemplary Link



- Multiple measurements over one “period” of the environment
- **Observed worst-case burstiness** represents link

Calculating Logical Topology and TDMA Schedule



Valid Topology

- Acyclic tree rooted at sink
- Contains all nodes

Valid Schedule

- Based on valid topology
- Follows individual traffic patterns
- Respects B_{min} and B_{max}
- Fulfils application requirements

Best Schedule

- Valid schedule that minimizes ϵ

Wolf-Bastian Pöttner et al.: *Constructing Schedules for Time-Critical Data Delivery in Wireless Sensor Networks*, in TOSN, 10, 3, Aug 2014

Comparing two Schedules

Optimization Goal

- Valid schedule fulfil delay and reliability requirements
- Minimized interference between neighbouring networks

Minimizing Interference

- Approximation through energy signature ϵ
- Minimizing ϵ reduces interference

$$\epsilon = \sum_{i=0}^{k} M_i \cdot D$$

k Slots, Slot Duration D, Transmission Power M_i in Slot i

Wolf-Bastian Pöttner et al.: *Constructing Schedules for Time-Critical Data Delivery in Wireless Sensor Networks*, in TOSN, 10, 3, Aug 2014

Speed of Schedule Calculation

Time for Schedule Calculation

- 5.67 h for 6 nodes and 32 power levels
- Exponential dependency on power levels and nodes

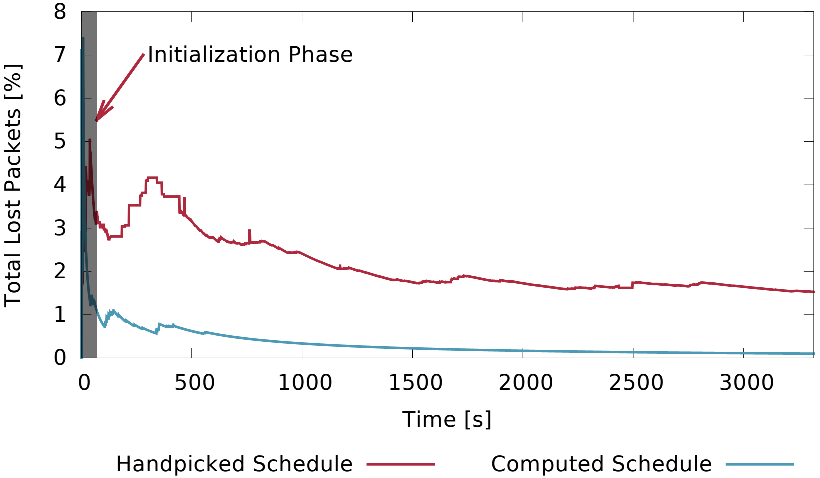
Heuristic discards links that are unlikely to be used

- Unusable links
- Unreliable links
- Limit outgoing link list per node to $T_L = 5$ links

$\rightarrow$ Calculation with heuristic takes 0.054 h (or 3.24 min) for 13 nodes

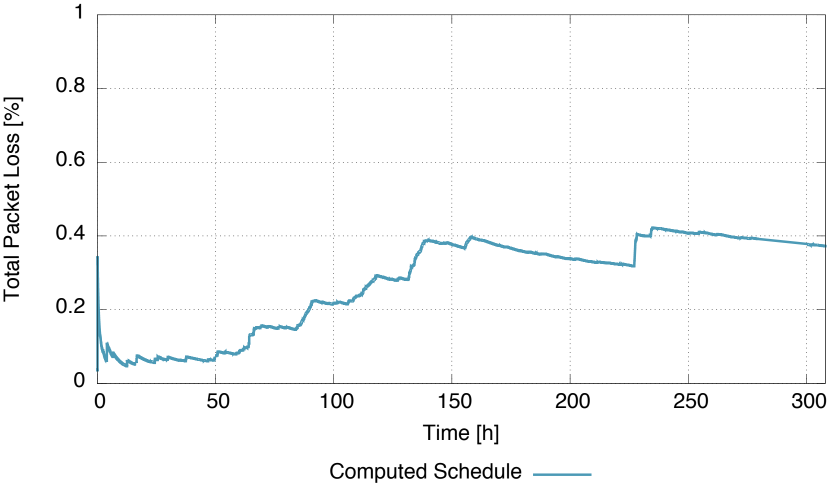
Wolf-Bastian Pöttner et al.: *Constructing Schedules for Time-Critical Data Delivery in Wireless Sensor Networks*, in TOSN, 10, 3, Aug 2014

Results: Reliability in the Refinery



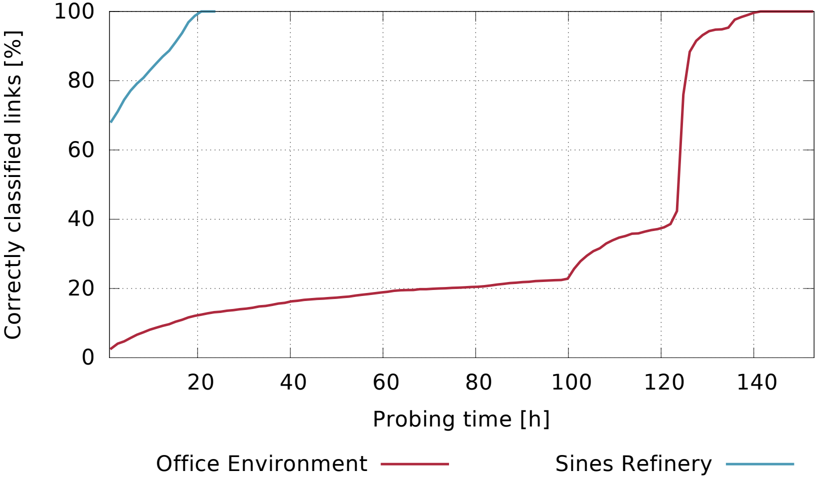
Wolf-Bastian Pöttner et al.: *Constructing Schedules for Time-Critical Data Delivery in Wireless Sensor Networks*, in TOSN, 10, 3, Aug 2014

Results: Long-term Reliability in Office Environment



Wolf-Bastian Pöttner et al.: *Constructing Schedules for Time-Critical Data Delivery in Wireless Sensor Networks*, in TOSN, 10, 3, Aug 2014

Results: Necessary Probing Effort



Wolf-Bastian Pöttner et al.: *Constructing Schedules for Time-Critical Data Delivery in Wireless Sensor Networks*, in TOSN, 10, 3, Aug 2014

Summary of the Results

Reliability

- **Significantly increased** compared to handpicked schedule

Long-term Schedule Validity

- **Valid for > 300 h** in challenging office environment

Probing Effort

- **24 h of probing** enough for industrial setting
- **14 probes** are enough for 99 % accuracy

Interference

- **Reduction of 5 dBm to 20 dBm** at fringe of network

Wolf-Bastian Pöttner et al.: *Constructing Schedules for Time-Critical Data Delivery in Wireless Sensor Networks*, in TOSN, 10, 3, Aug 2014

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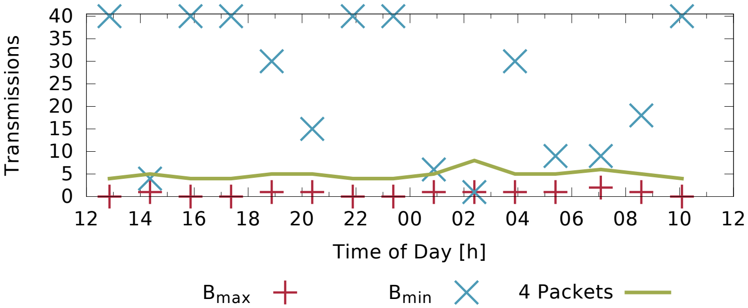
Delay-Tolerant WSNs

How can we lower interference even further when we do not face the worst-case burstiness at the moment?

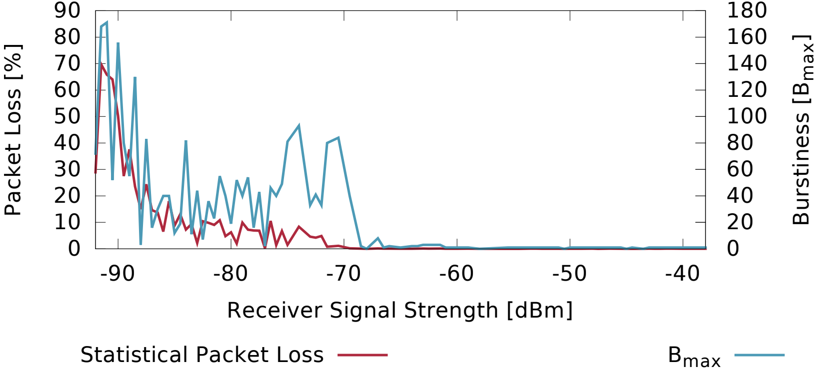
Motivation for Transmission Power Control

- TDMA Schedules are designed for worst-case burstiness
- But: Burstiness of links changes over time



- Potential for **lower transmission power (and interference)** during non-worst-case situations

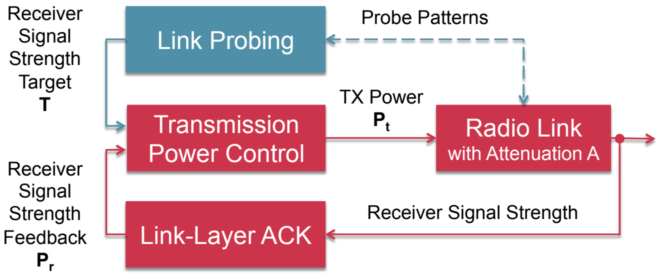
Burstiness with varying Transmit Powers



Burstiness depends on Receiver Signal Strength

Wolf-Bastian Pöttner et al.: *Probe-based Transmission Power Control for Dependable Wireless Sensor Networks*, in IEEE DCoSS 2013, May 2013

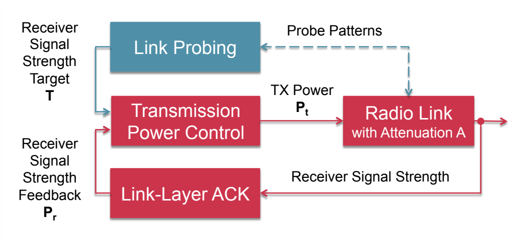
Transmission Power Control



- Attenuation-based Transmission Power Control Algorithm
- Enhanced with continuous link probing

Wolf-Bastian Pöttner et al.: *Piggy-Backing Link Quality Measurements to IEEE 802.15.4 Acknowledgements*, in WiSARN-Fall 2011, Jan 2011

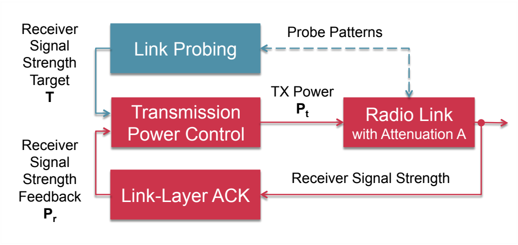
Attenuation-based Transmission Power Control



- Attenuation per packet: $A_i = P_{t,i} - P_{r,i}$
- Smoothed attenuation: $A' = ewma(A_0, \ldots, A_n)$
- Calculate TX power: $P_{t,i+1} = T + A'$

Wolf-Bastian Pöttner et al.: *Probe-based Transmission Power Control for Dependable Wireless Sensor Networks*, in IEEE DCoSS 2013, May 2013

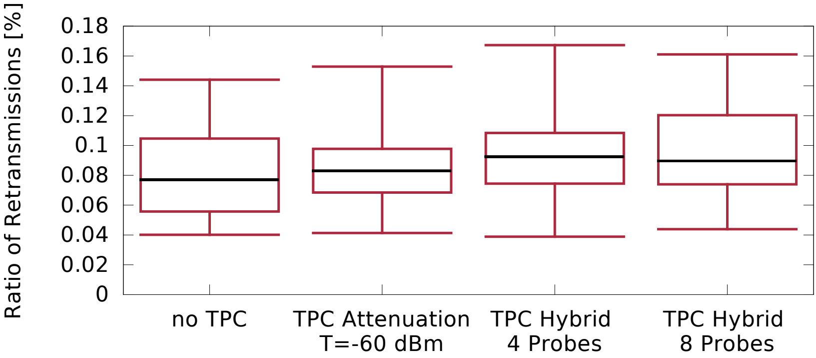
Determining Receiver Signal Strength Target T



- Continuous probing of outgoing links at various TX Powers
- Collection of tuples: $Burstiness_{P_r} = (B_{min}, B_{max})$
- Search for lowest P_r with $Burstiness_{P_r} \leqslant Burstiness_{Schedule}$

Wolf-Bastian Pöttner et al.: *Probe-based Transmission Power Control for Dependable Wireless Sensor Networks*, in IEEE DCoSS 2013, May 2013

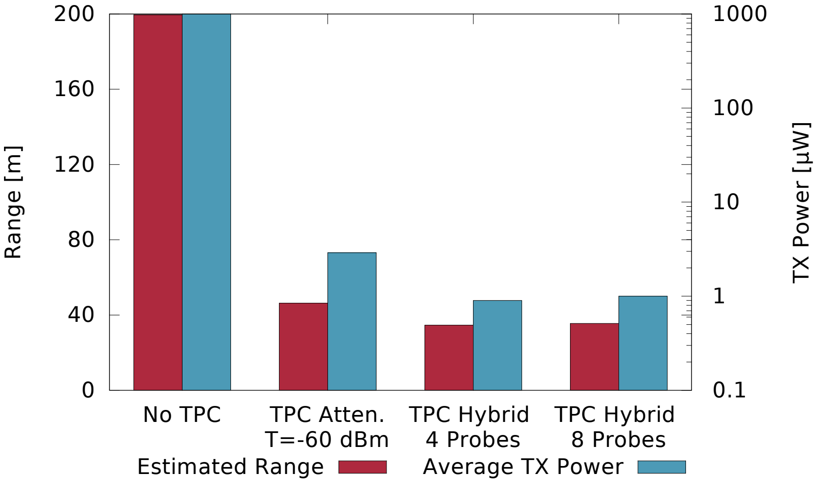
Results: Impact on Reliability



Modest increase of retransmissions, no end-to-end loss

Wolf-Bastian Pöttner et al.: *Probe-based Transmission Power Control for Dependable Wireless Sensor Networks*, in IEEE DCoSS 2013, May 2013

Results: Impact on Interference



Wolf-Bastian Pöttner et al.: *Probe-based Transmission Power Control for Dependable Wireless Sensor Networks*, in IEEE DCoSS 2013, May 2013

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Delay-Tolerant WSNs

What about non-real-time networks?

Network Classes

Timing Constraints:	Hard real-time	Soft real-time	Best-effort with timeout	Best-effort
Application Example:	Industrial Process Control	Industrial Process Monitoring	Webservices via HTTP/TCP	Statistical Data Collection

GINSENG (Hard real-time, Soft real-time)

Delay-Tolerant Networks (Best-effort with timeout, Best-effort)

Delay-Tolerance in (Wireless Sensor) Networks

Store, Carry and Forward Paradigm

- »Store your data until the next contact comes into radio range«
- Asynchronous data transport in self-contained "bundles"
- Use mobility to spread data, efficiently handle failing links
- Routing through space and time; continuous end-to-end paths not necessary

Delay-Tolerant Wireless Sensor Networks

- Use de-facto standard DTN Bundle Protocol in WSNs
- Custom Convergence Layer for IEEE 802.15.4 wireless networks
- **Inherent reliability** through store, carry and forward paradigm

Wolf-Bastian Pöttner et al.: *Flow control mechanisms for the bundle protocol in IEEE 802.15.4 low-power networks*, in CHANTS, Aug 2012

Demonstrating DTWSNs

Application Example

- Long-term statistical weather data collection

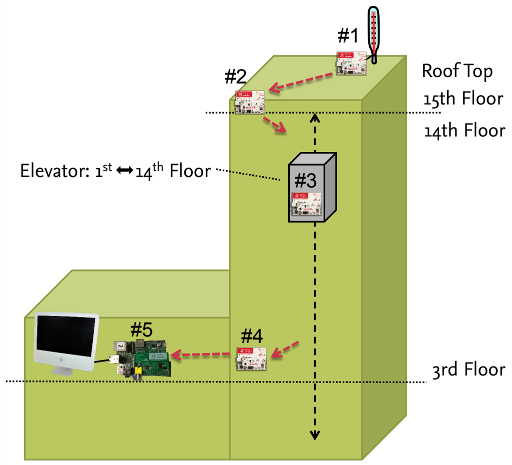
Implementation

- WSN node on roof samples ambient temperature every 200 s
- Data is “muled” downstairs via elevator; exploit existing movement

Benefits of using DTWSN Technology

- Installation of infrastructure not necessary
- Seamless integration into existing DTN
- No end-to-end data loss

Demonstration Setup



Wolf-Bastian Pöttner et al.: *Data Elevators: Applying the Bundle Protocol in Delay Tolerant Wireless Sensor Networks*, in IEEE MASS, Oct 2012

Scientific Contribution (1/2)

Reliable TDMA Schedules for Real-time WSN

- **Computed schedules based on Link Burstiness**
- **Data gathering approach and calculation heuristic**
- *Extensive experimental evaluation*

Distributed Transmission Power Control

- **Transmission Power Control based on Link Burstiness**
- Link-layer ACK reception quality feedback
- *Extensive experimental evaluation*

Scientific Contribution (2/2)

File Systems for Real-Time Applications

- Ring- and FAT-based storage for long-term data collection

WSN Testbed Support in live Industrial Facility

- Remote Reprogramming Infrastructure, WSN - PC interconnection

Bundle Protocol in WSNs

- Convergence Layer for IEEE 802.15.4-based networks
- μDTN: Bundle Protocol Implementation for Contiki OS
- Comparison of flow control approaches
- *Experimental evaluation*

Conclusions

Questions?

Motivation

- Many applications require reliable data transmission, that is (often) not delivered by today's WSN technology

Scientific Contribution of this Dissertation

- Reliable TDMA Schedules for Real-time WSN
- Distributed Transmission Power Control
- File Systems for Real-Time Applications
- WSN Testbed Support in live Industrial Facility
- Bundle Protocol in (Delay-Tolerant) Wireless Sensor Networks

Results

- Reliability can be achieved in real-time and delay-tolerant WSNs