End-to-End Quality of Service Guarantees for Wireless Sensor Networks

Felix Dobslaw

Mittuniversitetet
MID SWEDEN UNIVERSITY

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Mid Sweden University

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Till min älskade familj.
Alexander Leonidas
Johan Ossian
Eirini
♥

Abstract

Wireless sensor networks have been a key driver of innovation and societal progress over the last three decades. They allow for simplicity because they eliminate cabling complexity while increasing the flexibility of extending or adjusting networks to changing demands. Wireless sensor networks are a powerful means of filling the technological gap for ever-larger industrial sites of growing interconnection and broader integration. Nonetheless, the management of wireless networks is difficult in situations wherein communication requires application-specific, network-wide quality of service guarantees. A minimum end-to-end reliability for packet arrival close to 100% in combination with latency bounds in the millisecond range must be fulfilled in many mission-critical applications.

The problem addressed in this thesis is the demand for algorithmic support for end-to-end quality of service guarantees in mission-critical wireless sensor networks. Wireless sensors have traditionally been used to collect non-critical periodic readings; however, the intriguing advantages of wireless technologies in terms of their flexibility and cost effectiveness justify the exploration of their potential for control and mission-critical applications, subject to the requirements of ultra-reliable communication, in harsh and dynamically changing environments such as manufacturing factories, oil rigs, and power plants.

This thesis provides three main contributions in the scope of wireless sensor networks. First, it presents a scalable algorithm that guarantees end-to-end reliability through scheduling. Second, it presents a cross-layer optimization/configuration framework that can be customized to meet multiple end-to-end quality of service criteria simultaneously. Third, it proposes an extension of the framework used to enable service differentiation and priority handling. Adaptive, scalable, and fast algorithms are proposed. The cross-layer framework is based on a genetic algorithm that assesses the quality of service of the network as a whole and integrates the physical layer, medium access control layer, network layer, and transport layer.

Algorithm performance and scalability are verified through numerous simulations on hundreds of convergecast topologies by comparing the proposed algorithms with other recently proposed algorithms for ensuring reliable packet delivery. The results show that the proposed SchedEx scheduling algorithm is both significantly more scalable and better performing than are the competing slot-based scheduling algorithms. The integrated solving of routing and scheduling using a genetic al-

gorithm further improves on the original results by more than 30% in terms of latency. The proposed framework provides live graphical feedback about potential bottlenecks and may be used for analysis and debugging as well as the planning of green-field networks.

SchedEx is found to be an adaptive, scalable, and fast algorithm that is capable of ensuring the end-to-end reliability of packet arrival throughout the network. SchedEx-GA successfully identifies network configurations, thus integrating the routing and scheduling decisions for networks with diverse traffic priority levels. Further, directions for future research are presented, including the extension of simulations to experimental work and the consideration of alternative network topologies.

Acknowledgements

Not all those who wander are lost.
J.R.R. Tolkien

What a journey!

I am very grateful for the challenges therein and the support that I have received. There are some people who deserve a special thanks. Please see your contributions below:

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Acronyms

ARQ Automatic Repeat Request, page 21

DARPA United States Defense Advanced Research Project Agency, page 1

dB Decibel, page 35

ETX Expected Transmission Time, page 17

FEC Forward Error Correction, page 21

GA Genetic Algorithm, page 9

HART Highway Addressable Remote Transducer Protocol, page 1

ISA International Society of Automation, page 22

ISO International Organization for Standardization, page 4

IWSN Industrial Wireless Sensor Network, page 1

LQI Link Quality Indicator, page 58

MAC Media Access Control, page 2

NP Nondeterministic Polynomial Time, page 15

OSI Open Systems Interconnection, page 4

PDR Packet Delivery Rate, page 3

QoS Quality of Service, page 2

RSSI Received Signal Strength Indicator, page 58

SFRT Safety Function Response Time, page 4

SINTEF Stiftelsen for Industriell og Teknisk Forskning, page 12

SNR Signal to Noise Ratio, page 28

TDMA Time Division Multiple Access, page 27

TSMP Time Synchronized Mesh Protocol, page 12

USD United States Dollar, page 2

WirelessHART Wireless HART, page 1

WSN Wireless Sensor Network, page 1

List of Papers

The thesis is based on the following papers, herein referred by Roman numbers:

I **Felix Dobslaw**, Tingting Zhang, and Mikael Gidlund. End-to-end Reliability-Aware Scheduling for Wireless Sensor Networks. *Transactions on Industrial Informatics, IEEE*, 2014. **(published)**

II **Felix Dobslaw**, Tingting Zhang, and Mikael Gidlund. Latency Improvement Strategies for Reliability-Aware Scheduling in Industrial Wireless Sensor Networks. *International Journal of Distributed Sensor Networks, Hindawi*, 2015. **(published)**

III **Felix Dobslaw**, Mikael Gidlund, and Tingting Zhang. Challenges for the Use of Data Aggregation in Industrial Wireless Sensor Networks. *International Conference on Automation Science and Engineering, IEEE*, 2015. **(published)**

IV **Felix Dobslaw**, Tingting Zhang, and Mikael Gidlund. A Reliability-Aware Cross-layer Optimization Framework for Wireless Sensor Networks. **(journal manuscript, under review)**

V **Felix Dobslaw**, Tingting Zhang, and Mikael Gidlund. QoS-Aware Cross-layer Configuration for Industrial Wireless Sensor Networks. **(journal manuscript, under review)**

The author of this thesis is the main author of all included articles and stands responsible for all ideas with their contributions and possible fallacies. Tingting Zhang and Mikael Gidlund acted as advisors and contributed to the articles by discussion, advice, and review comments. All programming, experimental work and authorship involved has been conducted by the main-author. It follows a list of articles published during graduate studies, but not included in the thesis:

1. **Felix Dobslaw**. A Parameter Tuning Framework for Metaheuristics Based on Design of Experiments and Artificial Neural Networks, *In Proceedings of the International Conference on Computer Mathematics and Natural Computing*, Rome, Italy, pages 213-216, WASET, 2010.
2. **Felix Dobslaw**. An Experimental Study on Robust Parameter Settings, *In Proceedings of the 12th Annual Conference on Genetic and Evolutionary Computation 2010*, Portland, USA, pages 1479-1482, ACM, 2010.

3. **Felix Dobslaw**, Aron Larsson, Theo Kanter, and Jamie Walters. An object-oriented model in support of context-aware mobile applications. In *Mobile Wireless Middleware, Operating Systems, and Applications*, pages 205-220, Springer, 2010.

4. **Felix Dobslaw**. Recent Development in Automatic Parameter Tuning for Metaheuristics. In *Proceedings of the 19th Annual Conference of Doctoral Students*, pages 54-63, 2010.

5. **Felix Dobslaw**. Iteration-wise Parameter Learning, In *Proceedings of the IEEE Congress on Evolutionary Computation*, New Orleans, USA, pages 455-462, IEEE, 2011.

6. **Felix Dobslaw**. InPUT : the intelligent parameter utilization tool. In *Proceedings of the fourteenth international conference on Genetic and evolutionary computation conference companion*, GECCO Companion '12, pages 149-156, ACM, 2012.

7. **Felix Dobslaw**, Tingting Zhang, and Mikael Gidlund. Qos assessment for mission-critical wireless sensor network applications. In *Local Computer Networks (LCN), IEEE 38th Conference on*, pages 663–666, IEEE, 2013.

8. Wei Shen, Tingting Zhang, and Mikael Gidlund, **Felix Dobslaw**. SAS-TDMA: A Source Aware Scheduling Algorithm for Real-Time Communication in Industrial Wireless Sensor Networks. In *Wireless Networks, IEEE*, pages 1155-1170, IEEE, 2013.

9. Patrik Jonsson, Torgeir Vaa, **Felix Dobslaw** and Benny Thörnberg. Road Condition Imaging - Model Development. In *Transportation Research Board Conference 2015*, Washington, 2015.

Variable Description

Identifier	Meaning
b_t	The packet buffer state of sensor t
c	network configuration, $c \in I$
$D_{(c,\Omega)}$	Deadline violations considering network configuration c and demand Ω
E	Links in the WSN with possitive link quality
F	Scheduling frame
$\lvert F \rvert$	Number of slots in F
$F_{\underline{\rho}}$	Frame F, guaranteeing $\underline{\rho}$
f_{st}	Transmission allowance from sensor t in slot s in schedule-frame F (boolean)
I	Network configuration space combining R and F
Q	Link quality matrix for the entire network
q_{tp}	Link quality from sensor t to node p in Q (boolean)
R	Routing table
R_t	Parent of sensor t in routing table R (single-path routing)
r_t^o	Parent of sensor t for packets from origin o in routing table R (source-aware routing)
S	Sinks in the WSN
$\mathcal{T}$	Sensors in the WSN
V	Nodes in the WSN, $V = S \cup \mathcal{T}$
Δ	Vector containing the maximum acceptable delay for each sensor
Δ_t	Maximum acceptable delay for sensor t
K	Priority categories
κ	Priority assignment vector
λ	Publish rate vector
λ_t	Publish rate of sensor t
Ω	User defined configuration demand, containing $\underline{\rho}$
Ω'	User defined configuration demand, extending Ω with priority assignment κ
Φ	Packet creation frame
ϕ_{so}	Worst-case anticipated network load
ρ	End-to-end reliability
$\underline{\rho}$	Demanded end-to-end reliability

$\underline{\rho}_t$	Demanded end-to-end reliability for packets from t only
$\vec{\tau}$	SchedEx attempt vector
τ_t	Required attempts for each transmission in order to fulfill $\underline{\rho}$ using SchedEx (single-path routing)
τ_{to}	Required attempts for each transmission in order to fulfill $\underline{\rho}$ using SchedEx (source-aware routing)
ζ_{ts}	Channel over which t is allowed to transmit in slot s (boolean)

Chapter 1

Introduction

Simplicity is prerequisite for reliability.
Edsger W. Dijkstra

In the 1980s, the United States Defense Advanced Research Project Agency (DARPA), with its distributed sensor network program, introduced the wireless sensor network (WSN) as a concept, soon thereafter generating substantial interest in its potential in academia and industry [Lab13]. Two decades later, after three years of negotiations, the first open wireless standard for the automation and control industry, called WirelessHART [Wir08], was introduced in 2007. WirelessHART is the fully compliant wireless extension of one of the most popular wired standards, the highway addressable remote transducer protocol (HART), for communication in industrial automation industries. Approximately 60% of the wireless market within industrial automation could in recent years be attributed to WirelessHART [IDT12].

In 2009, approximately 25 years after the introduction of WSNs, the potentials and challenges specifically concerning industrial environments were concretely outlined as a review of how the existing efforts within the broad WSN technology sector continue to require substantial further development [GH09]. Among the listed most vital but largely unsolved challenges were scalability, reliability and self-configuration, which are topics within the scope of this thesis. In 2013, the first book discussing the state of the art of industrial wireless sensor networks (IWSN) was published [GH13], with Chapter 4 outlining future challenges. The authors concluded that state-of-the-art WSN solutions are suited for condition monitoring with low update frequencies rather than high-frequency process automation with strict deadlines. They stressed the potential cost effectiveness if *real-time* requirements would be addressed in future research. WirelessHART has been applied to industrial applications; however, it has been mainly applied to monitoring or applications with slow sampling rates (*e.g.*, [Che14]). Automation scenarios with actors that act on sensed data in harsh industrial environments are being investigated but are not field-ready as of today [YXW+15]. A re-confirmation of that fact is given in [SRS12], where the state of the art of media access control (MAC) layer protocols is reviewed for *mission-critical* applications. The authors commend the contributions; however, identifying the diverse nature of problems and cases investigated in the literature is one reason and main challenge driving the remaining lack of a more general framework for industrial WSNs. Further, analytical algorithms that, within a short time period, aid the offline feasibility analysis of WSNs before deployment are unavailable but are strongly required.

Scalability and computational efficiency play a superordinated role throughout the thesis. The anticipated industrial environments where WSNs operate are dynamic. Examples include paper mills, oil rigs, and coal mines. Missing a packet deadline may result in a stoppage of production, equipment damage and economic loss or even life-endangering situations. It is therefore critical for a network to react to changes in a timely manner via re-configuration to ensure the demanded quality of service (QoS).

1.1 Benefits of Wireless Sensor Network Technology

The main benefits of using wireless instead of wired communication are its flexibility and cost effectiveness. Wireless sensors can be equipped with batteries and positioned in locations where wire installation is difficult/costly/impossible. The maintenance and extendibility of the existing infrastructures are substantially easier and more cost-effective with wireless sensors that can be exchanged or supported by either temporary or permanent sensors as a response to dynamically changing network conditions under constant quality requirements. A leading global research and advisory company in [Tec13] predicts annual growth rates of the IWSN sector of approximately 15% for the period 2012-2016 and attributes the cost benefits of wireless to be one of the key drivers of the increased influence of the technology. Another advisory company foresees that the current 6% of IWSN market share in the global 0.45 billion USD wireless market will grow to a share of 28% of the predicted 2 billion USD market by 2022 [IDT12]. The total wireless market is projected to approximately double from 2013 to 2020, growing to a 300 billion USD market by 2020 [MM14]. This represents a huge market with a potential to further be exploited by wireless sensor network technology if the current research challenges can be overcome. Despite the projected potential, a bulk of open issues for the deployment of wireless systems in the industrial automation context remain to be solved. This is due to the flexibility and cost advantages obtained when deploying WSNs wherever possible compared with the complex and static wired infrastructure. However, WSNs have their restrictions, most of which are grounded in the openness of the access medium and in a transmission failure rate that largely depends on environmental conditions that are difficult or impossible to control.

1.2 Preliminaries

The problem addressed in this thesis concerns the demand of algorithmic support for end-to-end QoS guarantees in mission-critical WSNs. Here, algorithmic support means the availability of *adaptive, scalable, and fast* algorithms that are compatible with current industrial standards and that *significantly improve* on the quality of end-to-end QoS guarantees for WSNs, which continue to be criticized for being insufficient (*e.g.*, [PD08, PA15, NSG15]). Scalability addresses the need for algorithms of low computational time complexity (the number of required calculations) and space complexity (the required memory), both of which scale with the number of sensors within the network. A scalable algorithm can be used for both small and large network topologies. In this thesis, scalability is evaluated using complexity theory to address the size of the network in terms of transmitting and relaying sensors. Adaptability explains the ability of an algorithm to react to changes in the problem landscape in a timely manner. For WSNs in industrial settings, the problem of providing QoS shall be addressed as a dynamic problem that requires an algorithm that adapts to environmental changes, for instance, with respect to link or channel quality. For an algorithm to be adaptive, it must be fast. In this thesis, adaptability is evaluated based on the execution times of the algorithms.

Two of the most crucial QoS metrics of an IWSN are latency and reliability. Latency describes the travel time of a packet from its source to its destination. Latency varies over time and from packet to packet due to concurrent traffic patterns and dynamic environmental noise.

Because packet delivery cannot be guaranteed deterministically through wireless communication, algorithms must provide their guarantees together with a level of confidence or reliability. Greater reliability can be achieved via preventive actions that ensure high channel quality, such as well-isolated environments, or via the utilization of different types of redundancy (*e.g.*, time, space) in the system. For control applications, maximum latency boundaries must be guaranteed to preempt disasters. Thus, latency guarantees must come with a reliability or confidence. An acceptable maximum latency guarantee is of little value if its reliability goes unmentioned or if it is low, say, below 50%.

End-to-end QoS means that the guarantees hold for a set of communication flows within the network. For instance, a network supporting an end-to-end reliability of greater than 99% must guarantee this reliability for all valid network communication flows. Best-effort protocols, even adaptive and real-time protocols, are not sufficient to address these demands. End-to-end QoS is differentiated from node-to-node QoS in that the latter only includes a single hop to the destination, whereas the former can contain arbitrarily many hops via relaying sensors. Node-to-node reliability is empirically assessed using the packet delivery rate (PDR), and the end-to-end reliability in a multi-hop flow is derived from the PDRs of its node-to-node routes using probability theory.

In this thesis, scheduling and cross-layer algorithms produce transmission schedules to optimally configure the network. A schedule ensures that all scheduled packets can arrive at their destination until the end of its execution. A scheduling algorithm is evaluated in terms of latency based on the total amount of slots that it contains and based on the reliability with which each packet of relevance arrives at the destination after its execution.

1.3 Problem Statements

In applications such as process control, sensor information is looped back into the control system, thereby actively affecting the ongoing progress of, i.e., the production line. Currently, production lines usually work at a certain constant pace, which enforces fixed timing requirements on signalling. Maximizing this pace is often attempted because *time is money* and because a higher pace implies higher productivity. However, especially if humans are involved in the loop, safety regulations must be fulfilled, and factories must ensure certain safety distances or safety function response times (SFRT) for a signal from A to arrive at B as constraints in the network configuration.

Existing research does not satisfactorily address end-to-end reliability guarantees for WSNs, which leads to the first research question addressed in this thesis. No scalable scheduling or routing algorithm providing reliability guarantees with minimal latency has been proposed to date in the literature. Additional details on existing work can be found in Chapter 2.

Question 1. How does one algorithmically support end-to-end reliability guarantees for mission-critical applications using WSNs?

Part of the question is the need for end-to-end reliability guarantees that allow maximum latency boundaries that are compatible with typical process control demands. Addressing latency without considering reliability and vice-versa is trivial. The difficulty lays in the inter-dependency of the two because increasing the performance with respect to one results in a decrease in the maximal possible performance of the other. A user must be able to specify a demand in both dimensions, and the network should be able to, within a short period of time, report whether the constraints can be met. If they cannot be met, the network should be capable of reporting by what margin the demands cannot be met and recommend measures to address the deficiencies. This leads to the next question.

Question 2. Can a generic algorithmic framework for WSN configuration that addresses multiple arbitrary end-to-end QoS criteria be created?

Again, adaptability, scalability, and speed are of great importance here. One aspect to be addressed in the scope of Question 2 is the consideration of dynamicity in the formal problem description. Although the constraints are static, the landscape is highly dynamic. Hence, adaptability is required in such a generic framework. Another aspect is a maximal exploitation of information shared among the physical, data-link, and network layer of the ISO-OSI model. In traditional WSN implementations, a strictly layered approach is applied where, *e.g.*, routing decisions and scheduling decisions are made in a sequence. This also commonly applies to traditional *cross-layer* approaches, for which the different layers exchange information to identify better solutions. As an alternative, decisions can be made jointly using what in this thesis is termed an *integrated* cross-layer approach, which combines problems from multiple layers. An integrated cross-layer configuration extends the scope of the problem to better address the demands by assessing a combined configuration effect that spans multiple layers. To mention one example, a routing tree is formed not only according to a heuristic routing algorithm but also based on the data flows, channel access assignment schedules, and end-to-end latency demands of the network.

Another key aspect of Question 2 is the growing problem complexity when problems are not solved in isolation but jointly. For mission-critical WSNs, both scheduling and routing decisions can be formulated as constrained combinatorial optimization problems. In isolation, the problem variants investigated in this thesis are non-polynomial hard to solve, and joining them significantly increases the problem space, which increases the difficulty in identifying high-performance regions in the problem space in a timely manner. Because the cross-layer approach is a promising concept, it would be of value to numerically verify how much better an integrated cross-layer solution may perform compared with traditional (cross-)layered approaches and how they compare with respect to computational time. Furthermore, QoS demands are diverse, and a solution may not be restricted to a single or to specific metrics. The suggested approach must be agnostic to the QoS assessment function and should allow for the integration of multiple objectives/constraints.

One particularly relevant user feature for mission-critical applications is that of service differentiation. The many data flows within a network often lack equal end-to-end QoS requirements. For example, the latency demand for emergency traffic is, as a rule, significantly shorter than the latency demand for periodic readings. Generally, it is infeasible in practice to configure a network according to the most stringent demand for each end-to-end QoS feature. Therefore, a user must be able to define end-to-end QoS demands on a data-flow basis. Thus, the question to be addressed is

Question 3. How shall service differentiation be implemented in a generic algorithmic framework to ensure multiple end-to-end QoS features?

Part of the question concerns how situations with unmet constraints shall be treated and how to provide qualified information about bottlenecks. The greater the number of constraints is, the more likely this is to happen. Preferably, means of simulating networks that allow users to test topological changes before their deployment should be provided.

The questions formulated in this thesis are based on the concrete demand that has been identified in the literature. Chapter 2, Related Work, contains a thorough justification based on a review of the state of the art.

1.4 Scope

The conducted research is a justification that strengthens the understanding of the problems and the potential of wireless network solutions for industry with a special focus on end-to-end reliability. The thesis proposes low-complexity algorithms and a self-organizing framework for wireless network configuration that is compatible with the relevant industry standards for protocol stacks that apply contention-free scheduling. Contention-free scheduling is the de-facto standard approach to medium access in IWSN (used in, *e.g.*, WirelessHART and ISA 100.11a). Fig. 1.1 illustrates a typical protocol stack for WSNs. This thesis addresses end-to-end QoS,

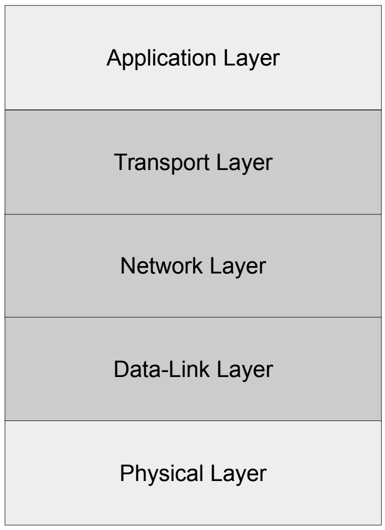

Figure 1.1: The generic WSN protocol stack. The means proposed in this thesis correspond to the dark grey layers.

thus supporting the decision making that occurs at the transport layer for schedule planning, the network layer for routing, and the data link layer for one-hop transmission resource assignment (dark grey areas). Assumptions about the data link layer and physical layer are made based on relevant numbers used in the literature and in industry, *e.g.*, link quality levels or number of available channels. Information from the data link and physical layer is assumed to be supplied for the proposed algorithms to identify valid network configurations given relevant conditions. Application layer demands with respect to end-to-end reliability, maximum tolerable delays, and priority categories are assumed. Simulations of the proposed algorithms on different topologies are then used to verify the achieved/achievable QoS. The algorithms are concretely verified using packet collection scenarios, and they can be extended to achieve a broader applicability, for instance, for networks with arbitrary flow patterns. Though security is a critical aspect for WSNs and the relevant applications, it is not considered in the scope of this thesis.

Fig. 1.2 provides a high-level overview of the QoS metrics that are used to assess the proposed combinations of routing and scheduling algorithms in this thesis. Slot-based scheduling algorithms are investigated, including their extension for data aggregation. Routing algorithms are considered not in isolation but in a cross-layer methodology that addresses both scheduling and routing decisions. Greater reliability is achieved not by redundant multi-path communication but by initially single-path and further multi-flow communication, as explained in Section 4.3.

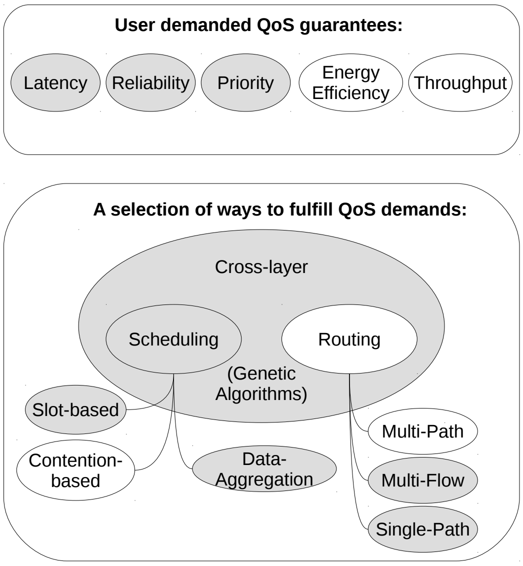

Figure 1.2: A conceptual roadmap of the related work relevant to the provisioning of end-to-end QoS through algorithms. Topics in grey are being addressed in this thesis.

1.5 Contributions

Fig. 1.3 illustrates how the research articles contained in the thesis map to the research questions. Articles I, II and III contribute to Question 1, Article IV contributes to Question 2, and Article V contributes to Question 3. The three research questions have been addressed in a sequential manner, where the last articles build on the knowledge acquired from the work concerning the former articles. The borderlines of the contribution mapping from article to question are not strict. The boxes show the bottom-up order in which the problems have been addressed by extending the

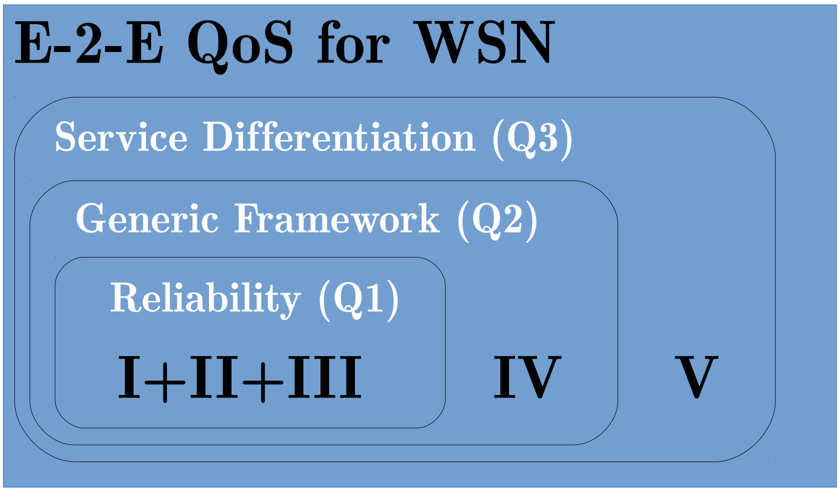

Figure 1.3: An illustration that details the research questions $Q_1 - Q_3$ addressed in the respective papers I-V.

existing solution to include increasingly more aspects. The hierarchical order does not imply that each question addresses a sub-problem of its predecessor; instead, it indicates their order of conduct. The relations are presented and discussed in Chapter 4. This follows a short summary of the articles included in this thesis with their main contributions.

Article I, End-to-end Reliability-Aware Scheduling for Wireless Sensor Networks: SchedEx, a novel slot-based scheduling algorithm extension that guarantees end-to-end reliability, is introduced. The reliability guarantee is proved, the scalability is analyzed using complexity theory, and SchedEx's practical use is verified by using simulations over single sink convergecast scenarios, thus demonstrating its ability to outperform a state-of-the-art approach.

Article II, Latency Improvement Strategies for Reliability-Aware Scheduling in Industrial Wireless Sensor Networks: A lower bound that guarantees the same end-to-end reliability and improves the achieved latency for SchedEx by an average of more than 20% is introduced. The expected latency reduction obtained when utilizing multiple sinks and multiple channels is numerically analyzed.

Article III, Challenges to the Use of Data Aggregation in Industrial Wireless Sensor Networks: Challenges to data aggregation in IWSNs are summarized, and a solution that extends SchedEx is introduced. The results demonstrate the substantial potential of considering packet aggregation already in the scheduling phase and not simply ad hoc in real time using best effort.

Article IV, A Reliability-Aware Cross-layer Optimization Framework for Wireless Sensor Networks: A cross-layer framework based on genetic algorithms (GAs) utilizing SchedEx but spanning both the routing and scheduling decision is proposed. Network configurations that are, on average, more than 30% better than for Articles I and II in terms of latency are shown to be identifiable within seconds.

Article V, QoS-Aware Cross-layer Configuration for Industrial Wireless Sensor Networks: The cross-layer framework from Article IV is extended to consider traffic of sensor-specific priority, publishing rates, and latencies. A sound and complete algorithm that satisfies all given constraints with a sink positioning routine using clustering is presented.

1.6 Ethical and Societal Considerations

Claiming reliability guarantees by proposing scheduling and routing algorithms for IWSN applications that strongly depend on correctness is a sensitive topic. Throughout the course of the conducted research, the author has attempted to be as critical as possible towards positive results and in expressing the results in a manner that does not market their contribution beyond their evaluated scope. Issues of security have not been addressed in the thesis. No intentional intrusion has been assumed to have occurred. A launched product, however, requires an integration of the proposed algorithms together with a security mechanism.

Forming a sustainable society is one of the key challenges both for the current generation and for generations to come. There is a growing demand for technical equipment due to a quickly expanding global middle class. If we are able to reduce the amount of cabling by substituting it with wireless technology, we can come a long way by achieving greater sustainability. This research proposes the use of wireless solutions instead of wired solutions where possible.

One aspect in which the author sees a potential risk of false marketing is the use of the term *determinism*. A system is *deterministic* if and only if it always returns the same output y for a given input x. Functions are by definition deterministic because for a given input, they always produce the same given output: f(x) = y. However, although substantial deterministic behavior is desired in wireless communication, it cannot be achieved, even if it has been claimed (e.g., [DZYD13]) and even if it is one of the outspoken objectives [ÅGB11]. There are no guarantees for packet arrival, and a finite attempt sequence until success can only be performed at a given confidence level. A packet transmitted from A to B arrives after n attempts with a confidence of

p, with $p < 1$; p is never 1. Because p is never 1, the behavior is always probabilistic; therefore, communication over wireless media is not deterministic. Systems that are not deterministic are called *non-deterministic*. Given the measure of confidence, what can be achieved is *predictability*. A rigorous analysis of a topology results in a level at which QoS can be assured, which in return must be validated with respect to the application requirements. Production lines with different speed options that adjust their pace according to the available QoS *resource* can be envisioned where extremely high reliability is vital. Future attention should be directed to an improved assessment and guarantee of QoS features and should thus always be accompanied by a measure of confidence or reliability.

1.7 Thesis Outline

The thesis is organized as follows. Chapter 2, Related Work, explains the basic terms and surveys the state of the art of QoS provisions for WSNs in time-critical applications. Chapter 3 presents a holistic model of the problem, including relevant assumptions. Chapter 4, Solutions and Results, presents the proposed solutions and discusses how they answer the questions posed in this thesis. Chapter 5, Conclusions, concludes the thesis with a summary of the findings, an outlook by the author, and directions for future research.

Chapter 2

Related Work

For the things we have to learn before we can do them, we learn by doing them.
Aristotle

End-to-end QoS constraints in networks are commonly addressed and assessed at the transport layer of the protocol stack. For WSNs, the routing decision at the network layer and the scheduling at the MAC layer have the most considerable impact on the achieved QoS (see the grey areas in Fig. 1.1).

The MAC layer coordinates access to the shared medium, which is a complex task in wireless communication because access to the communication medium can solely be restricted by regulation due to its open nature. Traditional methods of optimizing channel utilization via the MAC layer are intelligent scheduling, the optimization of packet length, the modulation of coding schemes and the adjustment of transmission powers. All network flows are considered in the problem formulation when applying end-to-end QoS metrics. Physical layer features are of pivotal importance to guaranteeing the highest possible link quality between two nodes. However, making the formal problem tangible at the physical layer is not discussed in depth here.

This chapter provides three main contributions. First, the existing research on IWSNs revealing their particular requirements is summarized. This is followed by an overview of the state-of-the-art solutions for scheduling, routing, and cross-layer optimization and configuration in the scope of WSNs. The chapter closes with a description of GAs, a heuristic optimization approach that has been utilized in the presented research to create a generic framework for QoS guarantees in IWSNs.

2.1 Industrial Wireless Sensor Networks

The achievements and challenges concerning IWSNs have led to a first book on the topic being published in 2013, which outlines the existing standards and applications and highlights future challenges [GH13]. Several recent papers have addressed the demands and requirements for the successful application of WSNs in industry (e.g., [YIE11, ÅGB11, NSG15, PA15]). One of the main fields of investigation in this thesis is industrial automation. Typical requirements in industrial automation include real-time communication, safety, security, energy efficiency, backward compatibility, integration, and cost effectiveness. Real-time communication addresses the demand for reliable, timely, and predictable transmissions. Safety concerns the need for automated devices to ensure the safety of humans, environment and property at a site. For many hard industries, power consumption is one of the key expenses, which is why its reduction is a critical objective. The reduction of power consumption further plays a crucial role for WSNs, where sensors may require battery recharging or exchange routines. Solutions must be backwards compatible due to their long lifetime and the requirements of properly integrating with existing infrastructure.

WirelessHART [Wir08] is a protocol stack specification for wireless communication for process monitoring and control that was introduced in 2007. WirelessHART ensures backwards compatibility to the traditional HART protocol, which uses wired communication for the same purpose. WirelessHART relies on a central network manager that is responsible for the network configuration. The network manager depends on continuous updates of live network-related meta-data to make qualified decisions. The network manager controls which routes and schedules are utilized in the network. On the MAC layer, WirelessHART implements TDMA scheduling with channel hopping. Time-synchronized mesh protocol (TSMP) is a prominent TDMA-based MAC layer protocol that supports channel hopping [PD08]. The authors in [PD08] stress the fact that although TSMP is distributable, so far, only centrally managed networks have been able achieve the QoS that is required to support hundreds of nodes in an industrial environment.

Recently, SINTEF in [PA15] reviewed the current standards, technology, and future trends of wireless instrumentation systems for safety critical systems, with a focus on the oil and gas industry. They outlined the financial and non-financial drivers that enable wireless instrumentation, including the avoided costs for cable tray installations, circuit drawings, and an environment that allows easier modifications to the production process. For new facilities (*Greenfield*), the cost savings per wireless instrument is assessed to be approximately 3,300 USD, whereas for existing *Brownfield* facilities, the savings are 2-3 times higher. According to the report, wireless sensor deployment has been limited to non-critical applications and remains insufficiently mature for safety-critical applications due to the lack of a common standard/technology that addresses all requirements, most notably coexistence, openness, protection from cyber attacks and threats, a transparent and quantifiable network performance of the highly dynamic communication landscape, and fulfillment of the general safety standards for instrumentation in industry (e.g., IEC 61508 and IEC 61511). WirelessHART-compliant implementations would require a strict certification procedure for the anticipated functional safety feature of future versions of WirelessHART.

In [Wil08], Willing discusses research areas that are both promising and interesting with respect to the design of protocols and systems in WSNs for industry. Channel fading and external interference are listed as two of the main reasons for the unreliable nature of WSNs, and he notes that the broadly applied view on determinism in the schedulability of real-time streams should be replaced by a probabilistic view on industrial QoS measures that allows for losses. Stochastic network calculus is mentioned as one possible tool for addressing this demand. Güngör et al. in [GH09] described challenges and promising design principles for IWSNs. They requested *self-healing industrial systems*, namely, systems that adjust their communication patterns according to the currently available resources in highly dynamic environments. The use of data aggregation and data fusion as well as cross-layer design are the research areas that the authors assess as being the most beneficial. They mention the demand for analytical tools that accurately predict the QoS properties of a network. Sauer, in [Sau10], argued that the evolution of different technologies for field-level networks, from the field bus to wireless solutions, and their continuous use have a negative impact on innovation. The co-existence of wireless networks is highlighted as one of the main issues to be addressed. In [YIE11], Yigitel et al. investigated the state of the art of QoS-aware MAC protocols and stated that many contributions, instead of guaranteeing a certain QoS level, approach the problem by introducing service differentiation that offers better QoS for a prioritized sub-set of the traffic following best-effort principles. The authors see the main unaddressed questions in supporting multiple applications with different QoS requirements on the same network and dynamically adapting the network topology to the available resources. Cross-layer is mentioned as a promising direction for protocol design. The authors in [ÅGB11] outline future challenges for IWSNs, with safety, security and availability in real-time systems being the main issues that require attention. They also emphasize that a power supply is usually in reach for most deployed sensors, which is why the requirement of energy efficiency may be de-emphasized for many IWSN applications. In [SRS12], the authors review the state-of-the-art WSN MAC protocols for mission-critical applications. They reveal that existing solutions have serious limitations, especially with respect to the availability of analytical tools, energy consumption, flexible use and combination of alternative performance metrics such as jitter or throughput, and moving nodes. They highlight the demand for analytical tools that are able to obtain end-to-end performance bounds for a given scenario and that most efforts are directed towards delay-aware scheduling, leaving reliability to other layers such as the network or transport layer. Huang et al. in [HXS$^+$13] surveyed the evolution of MAC protocols for WSNs by categorizing the approaches into asynchronous, synchronous, frame-slotted, and multi-channel approaches. They reinforced the results from [LSH08, ACDF11] and noted that CSMA-based protocols are not suitable for stringent delay and high reliability demands, thus highlighting the usefulness of TDMA for situations that require maximum channel utilization under high contention such as those in industrial applications. Among the major deficiencies of the reviewed scheduling protocols, the authors mention the lack of considering traffic patterns instead of network topology only, the combined assignment of slots and channels for slot-based scheduling, and strategies for the utilization of unused slots.

Nobre et al., in [NSG15], provided a very recent state-of-the-art overview of scheduling and routing contributions that specifically focuses on WirelessHART. Prevailing open issues concern a more standard way of assessing and comparing the different approaches, including metrics, standard test beds, and considering heterogeneous traffic patterns when addressing different industrial applications. Further, shared-slot scheduling has not widely been researched, and the discussion and analysis of scalability aspects of algorithms should receive more attention, according to the authors.

2.2 Scheduling

Scheduling the allowance of access to the communication medium is implemented at the MAC layer and is commonly based on information on link quality and quality requirements from both the physical and transport layer, respectively. Primarily, MAC protocols can be classified as contention-based or reservation-based protocols. Contention-based protocols work by allowing access to all transmitters of the medium managing access through a combination of collision detection and heuristic avoidance. No global synchronization or topology knowledge is required. Reservation-based protocols avoid collisions by only scheduling non-conflicting transmitters in the same time slot. TDMA is a contention-free protocol, whereas CSMA is contention-based. For contention-free methods, the throughput curve degrades logarithmically in the number of contenders, but in the case of reservation-based methods, the throughput peaks, and the control overhead pays off. For IWSNs, TDMA has been favored due to its reservation-based structure, which makes the guarantee of end-to-end features more tangible.

Slot-based scheduling algorithms in the WSN literature (*e.g.*, [EV10, YLH^{+}14]) follow the same general pattern:

- **While** not all packets delivered
    1. **apply scheduling algorithm** to decide the next slot(s)
    2. **append the slot(s)** to the schedule frame
    3. **update packet buffers** according to the transitions
    4. update meta-data (if required)

Transmission reliability has only recently started to be addressed by including different interference models into the problem formulation. The fact that different interference models are used in the research community makes comparisons of the algorithms difficult [BBS06, CKM^{+}08]. The two most commonly applied interference models are the protocol and physical models. Whereas the protocol model is a stark simplification of reality, thus defining the feature of connectivity between nodes as binary, the physical model is more realistic in that it usually considers link qualities in terms of percent or signal-to-noise ratios to model interference with a finer level of granularity. Incel et al., in [IGK11], surveyed TDMA-based scheduling algorithms for convergecast over tree-based routing topologies and categorized the contributions based on the applied metrics for assessment: the minimization of schedule length, the minimization of latency, the minimization of energy consumption and the maximization of fairness. According to [IGK11], a physical interference model should be preferred over the simplified protocol model and the consideration of QoS because it is more important as the application scope of WSNs widens to industrial applications.

Considering the protocol interference model, the authors in [RL93] provided and proved the validity of an optimum algorithm for addressing the scheduling problem of complexity $O(N \log P)$ for tree networks, where P is the maximum degree within the tree. In [GZH06], Gandham et al. supplied a distributed algorithm that, for convergecast scheduling under the protocol interference model, produces schedules that are no larger than $3N$ in size and demonstrated through simulations that the actual average size is approximately $1.5N$. In [DV09], the authors presented a conflict-free polynomial-time algorithm for the protocol interference model variant of the scheduling problem for multi-hop networks using spatial reuse. Spatial reuse is the concurrent use of the same communication channel and was introduced for TDMA scheduling in 1985 [NK85]. The authors in [NK85] presented several upper bounds for schedule sizes for diverse scheduling problems, including those considering data aggregation for convergecast. Worst-case delay guarantees can be provided using the method proposed in [Nee11], which, however, does not consider end-to-end reliability guarantees. The authors in [FLE06] introduce the decentralized Multi-path Multi-SPEED MAC protocol that provides service differentiation combined with probabilistic guarantees of transport delay and reliability. The protocol is an extension of the well-received SPEED routing protocol for sensor networks [HSLA03]. Different traffic types can dynamically choose different speed options, the choice of which has a large impact on the expected delay. There are situations where the protocol has to step back from the delay guarantee. In [EV10], Ergen et al. proposed two scheduling algorithms, namely, node- and level-based scheduling, for the problem of determining the shortest-length conflict-free assignment of TDMA slots during which the packets generated at each node reach their destination for many-to-one communication in multi-hop WSNs. Both algorithms assume protocol interference and a given interference graph to be known and use arbitrary coloring algorithms to structurally resolve overhearing issues through the creation of a conflict graph. They justified the relevance of the problem by proving it to be NP-complete and derived theoretical upper bounds for the size of the super-frames created by the scheduling algorithms. They further studied the impact of attempting to distribute the algorithms by letting each node identify the network topology and performing the necessary calculations locally. This resulted in delays that were approximately 10-70 times longer than those obtained in a centralized setting, thus showing the practical hardness of distributing the scheduling activity in WSNs.

QoS through scheduling has recently been addressed for very diverse real-time areas, such as in the context of multi-media streaming in wired networks for broadband optimization [LE12], or for IWSNs to reduce latency [ZQYR14]. The authors in [BDWL10] provided a state-of-the-art review of MAC protocols with energy efficiency as the main focus. Because the WirelessHART stack does not specify how scheduling should be implemented, substantial research has been devoted to related problems [FEI+09, SXLC10, ZSJ13, DSDX13]. In [SXLC10], the NP-completeness of the scheduling problem for WirelessHART was proven, with the optimal channel assignment being one of the critical parts. The authors further proposed a heuristic approach that leads to near-optimal scheduling solutions with respect to latency. Instead of applying a multi-path approach, the authors in [DSDX13] proposed a graph-route-based approach for jointly scheduling and routing the packets to the sink to improve reliability. [ZSJ13] provided lower latency bounds for schedules in convergecast scenarios both for the theoretical case of infinitely many channels and for fixed channel scenarios. The complexity of the problem is largely reduced by the fact that only primary conflicts are considered because WirelessHART forbids concurrent spatial reuse over the same channel. The article, however, does not consider packet loss. [FEI+09] attempted to minimize latency via offline scheduling by considering multi-path routing and multiple sinks; however, they did not consider packet loss. The authors in [KSØK14] noted the lack of a protocol for the treatment of wireless sensor actuator networks that includes control loops in the protocol while guaranteeing end-to-end QoS. In [TLB12], Toscano et al. proposed a beacon collision avoidance scheduling protocol that utilizes multi-channel communication. The reliable and interference-free beacon package transmission is a pivotal requirement for a reliable PDR assessment, which in turn is required to guarantee reliable scheduling. The GinMAC protocol for reliable and timely TDMA scheduling was introduced in [SBR10]. GinMAC uses offline dimensioning to attempt a high-quality assessment of the quality fluctuations in the network because wireless links are inherently fluctuating. They verify the approach by TinyOS test-beds with 15 nodes and report that the approach optimizes reliability and co-optimizes both energy consumption and delay. Offline dimensioning times go unmentioned.

Scheduling contributions, such as that presented in [YCK+10], assume a time-consuming offline framework that addresses the distribution of schedule information to the sensors, although it does not consider spatial reuse or multi-channel scheduling in the problem formulation. The scheduler proposed in [MLH+10], also referred to as *Burst* in [SRS12], ensures timely and reliable data delivery for networks that are planned in advance, which is applicable to many IWSN applications. The guarantees are achieved by measuring the maximally received burst length during the testing phase (in the paper, 21 days), using it as a reference for worst-case scenarios to calculate the maximum communication delay. The caveat of Burst is that it requires a long offline learning phase to assess the link qualities and interference patterns of the network, which results in a fixed schedule frame that achieves end-to-end guarantees for networks with topologies that do not vary critically over time. The framework presented in [JK09] is able to reduce the error rates by orders of magnitude using planned re-transmissions, thus acknowledging that the error rate will never be zero, even with the presented scheme. The latter is caused by the nature of wireless communication, as discussed in Section 1.6 in this thesis.

Pöttner et al. [PSB+14] proposed a scheduling scheme for time-critical data delivery in IWSNs. They introduced an algorithm with exponential time complexity to justify the approach by assuming that industrial networks never exceed a size of 24 sensors. This even accounts for the heuristic extension of the algorithm, which prunes the connectivity graph by those links that are unlikely to be scheduled. In the presence of substantial connectivity changes throughout the network, the authors proposed to either re-run the entire offline assessment or use the live collected meta-data, with the risk of overestimating the link quality of certain links. Runtimes were not reported in the study. The authors in [YLH+14] addressed the maximization of end-to-end reliability subject to delay constraints via centralized data-link layer scheduling, which is relevant to safety-critical applications, as an extension of the work performed in [SZZJ10]. They proposed two algorithms, namely *dedicated scheduling* and *shared scheduling*, that outperform *node-based scheduling* and *level-based scheduling*, as introduced in [EV10] with respect to end-to-end reliability. The investigated algorithms were evaluated based on the single-path routing and introduced any-path routing schemes, with routing tables obtained using the expected transmission time (ETX) metric [DCABM05]. The authors contributed the concept of hyper-nodes, which enable a sound theoretical extension of their problem formulation for any-path routing. The authors proposed a two-phase approach to solving the reliability issue via scheduling, with re-transmission being the proposed means to achieving greater end-to-end reliability. First, the chosen scheduling algorithm conducts the scheduling without considering reliability. Second, a schedule improvement algorithm extends the schedule by incrementally repeating the slot that produces the largest increase in the end-to-end reliability of the schedule until a maximum delay has been reached. The authors thoroughly described the simulations of networks with sizes of between 600 and 2000 nodes and demonstrated numerically how single-path routing outperforms any-path routing in terms of end-to-end reliability for all scheduling algorithms, though at a potentially larger energy cost of approximately 36%. The issue of scalability with the incremental approach was outlined as one of the major challenges for future research, together with the co-design of scheduling and routing in a cross-layer. In [SZGD13], the authors proposed a TDMA scheduling algorithm that adapts its schedule according to the network-wide link qualities for networks with unreliable and dynamically changing links. They showed through simulations that the algorithm outperforms node-based scheduling and level-based scheduling from [EV10], comparing the results using different metrics, e.g., delay and throughput. Willig et al., in [WU14], presented different Markov Decision Process-based formulations for the scheduling of TDMA schedules for real-time periodic data updates over lossy channels, assuming centralized network management. They paid special attention to the re-scheduling of failing transmissions and the optimal placement of relaying nodes to minimize the number of missed packets until a deadline.

In summary, no TDMA-based scheduling algorithms exist today that provide the required scalability and ensure end-to-end reliability while being sufficiently flexible to be utilized in combination with an arbitrary interference model. Current solutions do not scale in the number of sensors, which means that for large/flexible networks with hundreds of sensors, the algorithms either will require long execution times that preclude an efficient cross-layer approach or cannot guarantee the demanded QoS.

Data Aggregation

Data aggregation techniques have been surveyed and categorized for arbitrary network topologies [FRWZ07]. The problem of identifying an optimal data aggregation scheme for the collection of sensor readings at a sink of a multi-hop WSN is NP-complete [KEW02]. In the scope of IWSNs, the focus is on lossless aggregation, which means that content cannot typically be aggregated into single values without additional transmission overhead. The relayed content must be formulated in its original form, as opposed to aggregation functions, such as *min*, *max* or *mean*. The relevant information, however, usually does not extend substantially more than a few bytes. Knowing the packet creation timestamp, its origin, and the small sensor reading is usually sufficient for industrial applications to operate according to their requirements.

In [NLG11], Neander et al. proposed the use of data aggregation for networks running WirelessHART in an attempt to reduce energy consumption as a result of the reduced number of transmissions. An unused header byte at the physical layer is used to signal whether a packet is aggregated, which makes the approach backwards compatible. Other noteworthy contributions considering aggregation with respect to security [LGAP13], adaptive slot assignment [Bar12], and interference models [XLS13] have been made. Barnawi in [Bar12] have proposed a TDMA-based aggregation scheme that enables an adaptive scheduling of active sources for convergecast applications. The set of relevant sensors to be scheduled is decided based on a request aggregation scheme. The proposed approach was found to outperform several CSMA-based approaches with respect to energy efficiency and achieved delays.

Existing research suggests that a well-developed data aggregation scheme can lead to significant improvements with respect to the desired objectives. The challenges in achieving the widespread use of data aggregation for IWSNs have not been addressed in depth with respect to QoS demands, and results on the tradeoff between end-to-end reliability and latency have yet to be published. The results presented in this thesis highlight the potential for a broader consideration of data aggregation (see Chapter 4.1).

2.3 Routing

Routing algorithms play a pivotal role in ensuring QoS in wireless networks that often form arbitrary mesh structures, thus supporting arbitrary data flows. Routing algorithms can be roughly classified into on-demand vs. offline routing and single-path vs. multi-path routing. High expectations are tied to the development of multi-path routing, and many recent contributions have applied on-demand routing algorithms. In IWSNs, where end-to-end QoS requirements are stringent, centralized offline routing algorithms are the standard due to their ability to provide global end-to-end guarantees, as opposed to distributed or on-demand algorithms that act based on local information alone. One of the major difficulties when analyzing the impact of routing algorithms is the fact that their contribution in the protocol stack cannot be evaluated in isolation. Networks are highly dynamic, and the quality of a routing decision depends to a high degree on the traffic patterns. Routing algorithms are therefore usually evaluated using different metrics. Much research has been dedicated to the identification of good metrics that capture different features of the routing algorithm to facilitate their direct comparison.

The heavily applied ETX metric for high-quality paths was introduced and investigated in [DCABM05]. It is a simple but efficient metric that includes both asymmetry and link loss in the function to identify high-throughput paths within a network and was shown to perform better than traditional hop-count or one-way reliability metrics. A routing metric for the efficient exploitation of path diversity was introduced in [JD08]. Multiple protocols were used and compared based on the introduced metric, thus promoting it as a viable alternative in various diverse scenarios. The work in [LCS+09] enhances the SPEED scheduling protocol for real-time traffic via a routing protocol that utilizes information on the 2-hop neighborhood, thereby substantially improving the performance in terms of energy utilization and reduced packet loss. EARQ, as presented in [HHC09], addresses the need for reliable communication in IWSNs. It applies redundancy in terms of multi-path transmissions only if reliability is assessed to be substantially increased and the reduction in energy efficiency is modest. [MAB+14] investigated the collaborative relaying of failed transmissions from source-destination pairs using reactive forwarding via alternative paths. The proposed approach achieved better results than did conventional time-diversity re-transmission for those scenarios with periodic traffic in adaptive and reactive relaying settings.

Radi et al. in [RDBL12] reviewed the state of the art on the topic of multi-path routing in WSNs. The authors assessed the need for a better integration of multi-path with cross-layer knowledge from, e.g., the MAC layer, to achieve more accurate path quality estimations. Further, the authors declared multi-constrained QoS multi-path protocols to be an open research issue. In [JM96], a dynamic on-demand source routing protocol that allows multi-hop ad-hoc networks with mobile nodes to be self-organizing and self-configuring was presented. The ReInForM routing algorithm [DBN03] sends multiple copies of packets to ensure user-defined reliability given a flow from a source to the sink node. ReInForM uses local topology knowledge and channel error rate information only by applying a randomized forwarding scheme.

The authors in [GLSJ12] investigated the impact of multi-channel communication compared with adaptive routing over networks with link dynamics in single and multi-hop networks. Their results revealed that both approaches lead to similar end-to-end reliabilities in dense topologies, whereas multi-channel use yields better performance in terms of both average end-to-end delay and reliability. Interestingly, a recent study in [YLH+14] demonstrated that single-path routing outperforms multi-path routing in all settings. The choice of routing and scheduling algorithm seems to highly dependent on the investigated scenario.

Routing decisions in the literature are commonly made based on heuristic measurements of link qualities. These metrics fail to address the dynamic traffic patterns depending on the application-layer requirements and created through the deployed schedules to ensure the end-to-end QoS. The existing research fails to address the need for a scalable, generic, QoS-aware routing metric that incorporates information from other layers.

2.4 Cross-layer and Service Differentiation

Networks sub-divide the different responsibilities into layers. In practice, at the least, the physical, MAC, network, transport, and application layers are commonly distinguished. Lower level layers offer services to the higher level layers to achieve high cohesion due to the modular structure, which simplifies the exchange of distinct layer implementations for optimization purposes. Cross-layer optimization / configuration eases these layer boundaries to improve performance by making distinct layers directly share and exchange information. Thus, a better overall performance in the network can be achieved. An example of cross-layer optimization is to co-optimize a routing table on the network layer together with the schedule frame for medium access at the data-link layer.

Another example is the use of link quality information from the physical layer for decisions at the network and MAC layers to ensure that only the most suitable routes are selected and internal interference is minimized by scheduling sensors with high mutual connectivity to transmit over different channels or in different time slots. The overall performance can thus be significantly improved.

The cross-layer concept can further be extended to include information from the physical layer on packet reception rates and signal strength. One major drawback of cross-layer optimization is that it decreases the interchangeability of the different layer implementations because it tightens them using additional assumptions. This, in turn, makes them more dependent on one another, for instance, when they are optimized for application-specific measures.

Diverse cross-layer solutions for WSNs operating under diverse combinations of physical, data link, network and transport layers have been presented in the literature (e.g., [LZG04, BM05, GAA08, SF10, CHJ$^+$13]). These solutions address different objectives such as energy preservation through mobile chargers in urban network installations [CHJ$^+$13], throughput maximization in multi-hop networks [LZG04, BM05], and reliable event transport in wireless sensor and actuator networks [GAA08]. Al-Anbagi et al., in [AAEKM14], surveyed the cross-layer approaches for QoS in WSNs, including those relevant to industrial applications and service differentiation. Their view is that the heavy weight on contributions in the IWSN literature is on low power consumption and secure protocols for non-delay-critical monitoring applications. They identified a large research gap with respect to WSNs and QoS, including the consideration of different traffic types, a consistent QoS for adaptively changing network conditions, the consideration of scalability in the proposed solutions, and a common standard for QoS handling procedures. They identified the use of physical-layer information in the MAC and network layer and their cross-layer interaction in the optimization as a key driver towards the eventual goal of a cross-layer protocol that allows developers to specify QoS requirements in a flexible manner. Shi et al. proposed a cross-layer solution spanning the physical and data link layer, where the problem lays in the control of the transmission powers of the transceivers, with the main objective of maximizing energy efficiency [SF10]. The ExOR protocol for multi-hop routing in [BM05] solves the routing and scheduling problem a posteriori and thus does not make predictions about channel qualities but uses topology information together with actual reception acknowledgements to negotiate the ongoing path of the travelling packets towards their sinks. This approach requires a non-negligible communication overhead and does not scale well for dense networks. By building a cross-layer between the physical and data link layers in [LZG04] and applying adaptive modulation coding, the authors demonstrated that the connection diversity obtained with their combination of automated repeat request (ARQ) and forward error correction (FEC) through re-transmission can be compared with the diversity obtained through multi-path or alternate routing because channel quality varies substantially over time. Re-transmission can thus represent a cheaper variant to routing via different paths. The authors in [GAA08] proposed an adaptive transport layer protocol that ensures what they called *event reliability*, rather than end-to-end reliability for wireless sensor and actuator networks. Event reliability was assessed to be more relevant than end-to-end reliability because in sensor and actuator networks, communication is both continuous and concurrent and is most relevant on a flow basis for the sensor-actuator flows. Soldati et al. in [SZZJ10] addressed joint routing and scheduling as an optimization problem with the objective of maximizing end-to-end reliability for real-time communication, given strict delay bounds for a single packet in two simple test topologies. They proposed a Markov Chain model in combination with a greedy algorithm that incrementally maximizes the reliability of packet arrival by repeating the best suited slot in the existing schedule super-frame until the packet deadline. They concluded that the reliability gain is minimal, usually below 3%, for multi-path routing compared with single-path routing. The existing work addresses the TDMA scheduling for WirelessHART by improving QoS in a cross-layer approach, where a reliable routing graph is first established, and the link scheduling is added in a subsequent step [HZM$^+$11]. Saifullah et al. in [SXLC11] introduced an optimal and heuristic real-time flow scheduling algorithm for fixed-priority scheduling in WirelessHART networks to maximize reliability at runtime while ensuring that all packets arrive at the sink before their deadline if possible. The algorithms are tested on WirelessHART-compliant networks with feedback control loops. Their proposed heuristic algorithm usually performs close to optimal while being faster than the optimal algorithm.

The PriorityMAC protocol for IWSNs was proposed in [SZG13, SZBG14]. PriorityMAC attempts to decrease the packet delay of high-priority packets by hijacking the dedicated transmission bandwidth of low-priority traffic. The authors therefore introduced four fixed traffic categories (TC1-TC4) to describe how PriorityMAC acts in the different scenarios. PriorityMAC is evaluated both in theory based on the average expected arrival times and in practice through simulations and experiments in a test-bed network with 20 sensors. Using PriorityMAC, high-priority traffic misses (T1 and T2) could be reduced by over 90% compared with WirelessHART MAC. The approach does not provide bounds or delay guarantees, nor does it include the routing decision in the algorithm. The international society of automation

(ISA) suggests a 6-class priority model, with a clear distinction among monitoring, control and safety traffic. However, the model is limiting in that timing constraints are tightly coupled with the importance of packets (i.e., high-importance traffic with low latency demands cannot be modeled).

Diverse cross-layer approaches have been presented in the literature. A generic QoS-aware cross-layer framework that is flexible in terms of quality demands, adaptive and scalable, has yet to be proposed.

2.5 Genetic Algorithms

Because of Articles IV and V, where the use of a GA is proposed as a basis for the generic cross-layer framework, GAs are introduced as a general machine learning tool to address different types of optimization/constraint-satisfaction problems.

GAs are population-based optimization algorithms that enforce an artificial evolution with the objective of finding solutions to hard optimization problems. The evolution in a GA is based on the maintenance of a population, the creation of diversity, a selection mechanism, and a process of genetic inheritance [FM08]. Each individual is represented by a *genotype*, namely, its genetic representation. Each genotype must injectively translate into a *phenotype*, which is the solution to a problem. The GA clones and manipulates the genotypes of *fit* individuals by utilizing recombination and mutation operators. Fitness is defined as the quality of the phenotype with respect to a measure, a so-called *fitness function*. Selection restricts reproduction to those considered capable of inducing progress to the offspring with respect to the objective of the artificial evolution. GAs have been shown to be efficient for addressing multi-objective problems, rugged problem landscapes, non-continuous functions and in instances where other optimization methods become stuck in local optima of multimodal problems (see, e.g., [MTK96]). Important to the success of a GA is the choice of a meaningful fitness function, a suitable genotypical representation of the problem and operators that both drive diversity and preserve successful patterns (*building blocks*) in offspring to make the population evolve into valid and fit regions of the solution space. The process has shown to be effective in finding fit individuals in a relatively short time, given that the parametric choices of the algorithm are well balanced and in accordance with the problem. Thus, utilizing heuristics such as GA requires fine tuning and a thorough investigation of the formulation of the problem and its formal constraints to tailor it to the GA [MJ91, SS09]. Further, the correct combination of parameters, such as the mating scheme and selection strategy, must be chosen for each new problem individually because there is no general optimal algorithm and, thus, no general optimal setup for an algorithm that is optimal for each problem (there is *no free lunch* [WM97]). Omitting this fact can lead to frustration or a misunderstanding of why a GA does not perform well at times: this is not necessarily because GAs are not suitable for the problem but because they have not been appropriately calibrated.

GAs for slot-based scheduling [NL03, Cha04, WSHT05, JZX07] and routing [KFV11, BK12] in WSNs have been proposed. A GA-neural network hybrid was introduced in [NL03] and has been shown to improve on a neural network only approach in terms of latency for convergecast scenarios. The authors in [Cha04] introduced a GA with a binary matrix representation and a penalty mechanism to enforce latency constraints. [WSHT05] rejected the binary matrix representation from [Cha04] and instead proposed an integer-based representation with permutation crossover operators. The authors in [WSHT05] further enhanced the fitness assessment to consider slot utilization. When applying the investigated methods, they received minor improvements in quality. Runtimes are not mentioned, nor was how the reference optimally sized frames for the four investigated highly connected networks were found. Network lifetime optimization for static WSNs was addressed with the GA-Particle Swarm Optimization hybrid introduced in [JZX07].

Jang, in [Jan12], investigated various meta-heuristics to find configurations that minimize energy consumption by WSNs and found GAs that obtained the best convergence times. The authors in [GFBN14] surveyed and analyzed 40 papers that addressed solutions to the flexible manufacturing system scheduling problems using GAs, thus revealing both the opportunities and diversity in using the approach. In [FDRSS13], the authors investigated a routing problem for vehicular networks utilizing a multi-objective GA and verified their results by using the NS2 simulator. They concluded that the slight increase in protocol complexity obtains performance improvements in terms of end-to-end delay. In [LG13], the authors introduced a GA to optimize WSN configurations by considering throughput, delays, and power levels. They proposed a utility function that weights the three metrics using the utility function as the fitness function for a proposed tailored GA scheme that combines routing and scheduling. The scheduling does not consider the repetition of unsuccessful transmissions, and scalability and performance are not addressed in the paper. The results are compared with those of exhaustive search on small topologies. Shakshuki et al., in [SMS14], applied GAs to increase WSN lifetimes by identifying near-optimal routes for relaying mobile agents in harsh radio environments.

None of the previous work considers end-to-end reliability, and no studies propose the use of a GA as a foundation for a generic cross-layer framework for WSN, as proposed in this thesis.

Chapter 3

Models and Assumptions

Every problem is a gift - without problems we would not grow.
Anthony Robbins

3.1 A Centralized Optimization Model

WirelessHART [Wir08], the wireless standard with the largest industry market share, employs centralized routing and scheduling, which requires a proportion of central knowledge to be maintained at all time. This requires the collection of global meta-data such as link quality levels and battery drain at the so-called *network manager*. One of the advantages of a centralized framework is that a global model solves issues that cannot be solved by local optimization or configuration models that lack non-local connectivity information, for instance, for a network-wide realization of fairness or priority with predictable bounds. Until today, no distributed solutions that address all aspects relevant to industrial applications, including reliability, security and real-time requirements, had been proposed [PD08, PA15, NSG15]. In industrial applications, where packet payload consists of small sensor readings and commands, meta-data are commonly being collected together with the payload to facilitate central decision making.

Fig. 3.1 conceptualizes the framework, which is compatible with WirelessHART, anticipated in this thesis. The network manager operates in a loop in which it continuously obtains meta-data readings from the WSN and enforces changes in topology and medium access in response to meet the QoS demands. A network manager in this thesis is composed of four modules:

- **Model Filter:** Receives the meta-data, interprets it, and updates the WSN model accordingly. The filter identifies error patterns and ensures that the model is

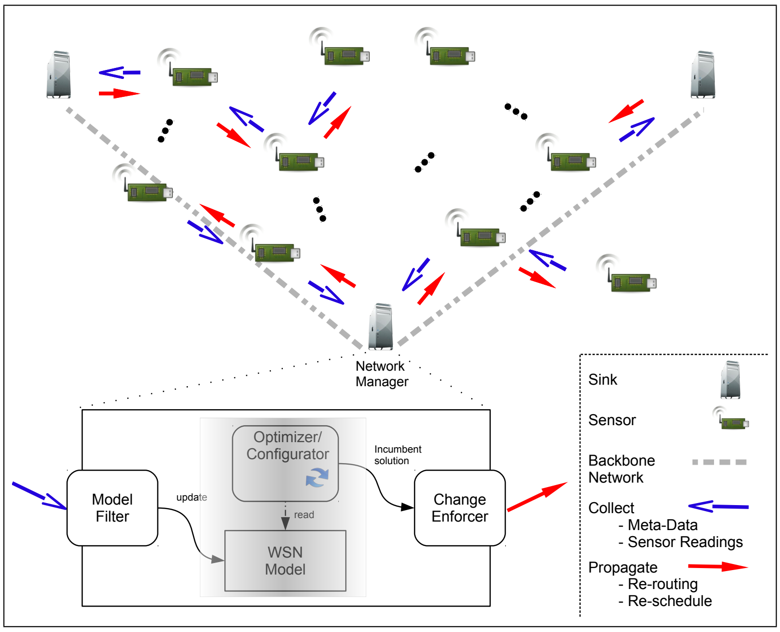

Figure 3.1: The anticipated centralized optimization framework for convergecast with one sink serving as the network manager, which is responsible for ensuring the demanded end-to-end QoS guarantees by an appropriate network configuration. The framework is composed of a model filter for the collected meta-data, the internal WSN model for which the optimizer identifies network configurations that fulfill the QoS requirements, and the change enforcer, which decides on and propagates suggested changes.

protected from temporary fluctuations.

- **WSN Model:** The abstraction of the WSN, used for the simulations on which the optimization algorithm is running.
- **Optimizer/Configurator:** The algorithm that attempts to ensure the QoS demands at all times.
- **Change Enforcer:** Evaluates the performance gain of the configurations with respect to the current setup, the QoS requirements, and the cost for deployment. Initiates changes if worthwhile.

The drawbacks of centralized approaches in the context of WSNs are timeliness and scalability. Meta-data must be collected and integrated into the optimization model, which takes time. A problem that must be addressed is scalability because of the cumulative workload close to sinks. Regardless, a centralized framework can be combined with decentralized decision making where possible, for instance, in exceptional or emergency situations.

Instead of modeling communication channels by considering real application-specific data or distributions that attempt to model reality, channels are assumed to be modeled empirically based on the data that are measured and collected from the live network. Topological real-time information may change significantly over time. Neither a distribution nor real data can explain the real interference that appears in the network. It is assumed that information concerning link quality levels is available to the configuration algorithms proposed in this thesis. Link quality variations occur due to internal and external network interference. External interference is due to factors that are uncontrollable by the network, including moving machines, humans, and noise due to machine activity. Internal interference occurs when multiple sensors in the network transmit concurrently, thereby disturbing one another. The algorithms in this thesis assume that the provided link qualities consider external interferences.

3.2 Evaluation and Experimental Setup

The research questions were posed in a sequential manner, and that is also how they were addressed in the presented research. The proposed algorithms were evaluated through simulations in a simulator written in Java. The simulator is based on random processes, where transmission success depends on the assumed link quality levels. The simulator was made conceptually compliant with WirelessHART supporting time division multiple access (TDMA) and multi-channel communication. All link quality levels were extracted from the Rayleigh fading interference model, thus emulating the noise of the environment. The quality of the algorithms was verified in terms of *complexity theory* and *runtime measurements* to ensure a principle feasibility for networks characterized by different structures and sizes. Another metric used throughout the thesis and the included articles is *distance to optimum* sizes of the schedules. A schedule ensures that all packets arrive at the destination after its execution given a reliability demand. Because execution times of the proposed algorithms significantly improved over those measured by other newly published methods, the *times faster* metric has been used to illustrate the relative improvement. In the constraint satisfaction problems in later papers that address cross-layer configuration and priority handling, the *number or proportion of sensors* in the network fulfilling all constraints has been used as a measure as well.

The investigated networks were convergecast scenarios, where n sensors must transmit data to m sinks. Network sizes of 50 to 800 sensors were investigated, considering single- and multi-sink scenarios as well as up to 15-channel communication. Rayleigh fading was applied with signal-to-noise (SNR) levels of 50 and 60 dB and differentiated transmission and interference ranges.

Chapter 4

Solutions and Results

Es gibt nichts Gutes, außer man tut es.
Erich Kästner

This chapter contains an extended summary of the contributions from the articles included in this thesis with respect to the posted research questions in Section 1.3. The research questions are repeated in the respective section for the reader's convenience.

4.1 Q1: End-to-end Reliability

Question 1. How does one algorithmically support end-to-end reliability guarantees for mission-critical applications using WSNs?

The generic slot-based algorithm extension SchedEx is introduced in Articles I-III. Article I details how SchedEx adds the feature of end-to-end reliability guarantees to existing slot-based scheduling algorithms. The principle idea is to consider time redundancy in the assigned slots for the creation of the schedule frame. End-to-end reliability can then be obtained by integrating a reliability-ensuring routine into an existing scheduling algorithm. SchedEx is an implementation of that idea. Article II improves the latency of the produced schedules by a tighter bound and widens the problem scope. Article III further extends SchedEx to the use of packet aggregation. SchedEx not only supports end-to-end reliability but also, given the features of multiple channel use, multiple sink use, and packet aggregation, offers a flexible framework, in terms of scheduling algorithm choice, that explicitly aims to minimise schedule size and thereby latency. Article I contains a comparison to a state-of-the-art reliability-guaranteeing algorithm, which demonstrates SchedEx as being orders of magnitude faster to execute. The latency results for scenarios of low end-to-end reliability (≤ 0.999) are competitive, whereas the ones for high-reliability situations (≥ 0.99999) outperform the alternative algorithm in terms of both latency and runtime.

Article I investigates a special case of wireless networks, namely, convergecast topologies, where all data flow towards a single sink. SchedEx's correctness is proved for arbitrary concurrent data flows. A significant improvement in scalability over existing algorithms is achieved via the utilization of a novel local upper bound for the minimum required number of repetitions per link.

It follows the formal problem description[1]:

$$\min_{x} \quad o(x) = |F|, \forall x = (R, F) \in \mathcal{I} \tag{4.1}$$

subject to

$$c_0 : \qquad \underline{\rho} \leq \rho \tag{4.2}$$

$$c_1 : \qquad r_{tt} = 0 \tag{4.3}$$

$$c_2 : \qquad \sum_{p \in V} r_{tp} \leq 1 \tag{4.4}$$

$$c_3 : \qquad r_{tp} = 1 \Rightarrow (t, p) \in E \tag{4.5}$$

$$c_4 : \qquad f_{st} = 1 \Rightarrow f_{sp} q_{pt} = 0 \tag{4.6}$$

$$c_5 : \qquad f_{st} f_{st'} = 1 \Rightarrow q_{tp} q_{t'p} = 0 \vee \tag{4.7}$$

$$\sum_{t \in \mathcal{T}} f_{st} r_{tp} = 0 \vee \tag{4.8}$$

$$ch_{ts} \neq ch_{t's} \wedge r_{tp} + r_{t'p} \leq 1 \tag{4.9}$$

The formal objective is to identify a minimum size schedule frame that fulfills all of the given constraints. c_0 is the global reliability constraint, $c_1 - c_3$ are routing constraints, and $c_4 - c_5$ are scheduling constraints. SchedEx ensures end-to-end reliability at the MAC layer by allocating redundant transmission slots for the scheduled communication links of the schedule frame, thereby trading latency for reliability. The application-specific end-to-end reliability demand, $\underline{\rho} \in [0, 1]$[2], which SchedEx ensures for all data flows in the network, therefore plays a crucial role in terms of the size of the final schedule frame. SchedEx requires a routing table as input that, for each transceiver with packets waiting in the buffer, depicts the respective receiver.[3] SchedEx allocates sufficiently many slots for each transmission until the probability of success for each end-to-end packet transmission reliability ρ throughout the schedule frame is equal to or larger than $\underline{\rho}$, according to Proposition 4 from Article I.

[1]The meaning of each variable is given in the Variable Description list in the beginning of the thesis, and a detailed explanation of the variables can be found in Articles I and II.

[2]Usually in the range $[0.9, 1]$

[3]First, SchedEx is formulated for single-path routing only but is generalized in Article IV to source-aware routing, which allows the specification of the receiver of a packet based on both packet source and transmitter. Additional information can be found in Section 4.2.

The maximum required number of re-transmissions is influenced by the link quality q_{tr} of each active transceiver-receiver pair (t, r) in the network. Here, Proposition 4 is repeated as Proposition 4.1 for the reader's convenience:

Proposition 4.1. *Given a network with a single-path routing table R, sinks $\mathcal{S}$, transceivers $\mathcal{T}$, link quality matrix Q, and a total of $k_1, \ldots, k_{|\mathcal{T}|}$ packets passing each transceiver $t, 1 \leq t \leq \mathcal{T}$ on their way towards any of the sinks via multi-hop routing, the end-to-end reliability of $\underline{\rho}$ can be guaranteed if n_t repetitions are executed for each route from t to R_t for each packet over the entire network according to the following:*

$$n_t = \left\lceil \frac{\log(1 - \underline{\rho}^{\frac{1}{|\mathcal{T}| \cdot k_t}})}{\log(1 - q_{tR_t})} \right\rceil, \forall t \in \mathcal{T} \tag{4.10}$$

R_t is the parent of t in routing table R. The SchedEx *updatePacketBuffer* routine is presented here as Algorithm 1. It is an implementation of step 3 in the general congestion-based scheduling scheme presented in the Related Work chapter, Section 2.2. The routine utilizes a controlled packet move delay guarded by the counter vector c (line 3) for each scheduled transceiver $t \in \mathcal{T}$ to ensure the demanded end-to-end reliability. Vector τ defines the required number of attempts $\tau_t = n_t$ for each transceiver $t \in \mathcal{T}$ to ensure that link reliability does not fall below $\underline{\rho}$ according to (4.1). This is guaranteed by the initialisation of delay counter c_t through τ_t.

Each time a transmission attempt in t has been registered in a slot, the counter for t is decremented (line 2). The scheduler moves a packet from the transmitter buffer to the receiver buffer once the counter has been hit τ_t times. Thereafter, the counter is re-initialised by τ_t.

Algorithm 1: $updatePacketBuffers(t, \mathcal{S}, b, c, \tau)$
Input: Scheduled Transmitter $t \in \mathcal{T}$, Sinks $\mathcal{S}$, Buffer State b, Counter Vector c, Repetition Vector τ

```
1: if b_t > 0 then
2:     c_t-- // count down attempts for transmitter t
3:     if c_t = 0 then
4:         b_t-- // remove packet from transmitter buffer
5:         if R_t ∉ S then
6:             b_{R_t}++ // add packet to receiver buffer
7:         c_t ← τ_t // update counter
```

SchedEx is utilized as follows. The chosen scheduling algorithm SA, extended by reliability awareness through SchedEx (Algorithm 1), is executed on the network manager. The link quality matrix Q with lower bounds is derived (*e.g.*, using [FGJL07]), and the routing table R is created using an arbitrary routing algorithm. SchedEx is run once at network start time to derive a schedule solving the optimization problem in (4.21). This schedule is then deployed. SchedEx is re-run in response to routing and link quality changes that violate the end-to-end reliability constraint $\underline{\rho}$.

Article II introduces and proves the correctness of a tighter network-wide bound, which is further proven to be globally optimal for SchedEx. Article I narrows the scope to single-sink scenarios, whereas Article II explores scenarios with a sink-based backbone network, where all packets are to be transmitted to any of the sinks. These types of network architectures are also called hybrid because they combine wired and wireless sensors in one topology. Article II further introduces concurrent communication via multiple channels to enable more realistic evaluations in the industrial context, where up to 15 channels are utilized via WirelessHART. SchedEx, in Article II, was evaluated through numerous simulations for various convergecast network topologies, including hybrid topologies. Articles I and II present the scheduling performance in terms of schedule frame size per end-to-end reliability demand and compare them with an existing incremental algorithm from the literature [YLH^{+}14], which is explained in greater detail in Article I and chapter 2.2. With respect to time complexity, SchedEx obtains a higher performance than does the incremental algorithm, and it achieves similar performance in terms of end-to-end latency in the version presented in Article I; in addition, it achieves a consistently higher performance in the improved version from Article II. SchedEx extends the complexity of any given slot-based scheduling algorithm by a constant factor, which is the maximum number of repetitions required for the poorest link used in the routing table $\max \tau_t, \forall t \in \mathcal{T}$. The incremental algorithm has a quadratic complexity of $\Theta(|\mathcal{T}||F|^2)$ and therefore scales poorly in both the size of the network and the reliability demand. SchedEx is therefore assessed to scale well according to the requirements in Question 1. In practice, SchedEx performs significantly faster than the worst-case scenario, as opposed to the incremental algorithm, which requires a two-step schedule creation process. The second *incremental* step introduces quadratic growth in complexity. It further always requires the worst-case number of steps. The advantage in terms of complexity is reflected by round-trip times in the simulations, which are, on average, more than an order of magnitude faster for SchedEx (see Fig. 4.1). With the optimal bound introduced through Article II (Proposition 1), SchedEx performs 20% faster than does Article I for topologies following the same distribution. The scheduling performance in terms of latency further consistently outperform the incremental algorithm in any of the investigated scenarios (see Fig. 4.2). The improvement is due to a better distribution of the reliability burden over the network according to the following proposition[4].

Proposition 4.2. *Given a network with a single-path routing table R, sinks $\mathcal{S}$, transceivers $\mathcal{T}$, link quality matrix Q, and a total of $k_1, \ldots, k_{|\mathcal{T}|}$ packets passing each transceiver $t, 1 \leq t \leq \mathcal{T}$ on their way towards any of the sinks via multi-hop, the end-to-end reliability of $\underline{\rho}$ can be guaranteed if n_t repetitions are executed for each route from t to R_t for each packet over the entire network according to the following:*

$$n_t = \left\lceil \frac{\log(1 - \underline{\rho}_t)}{\log(1 - q_{tR_t})} \right\rceil, \forall t \in \mathcal{T} \tag{4.11}$$

with

$$\underline{\rho}_t = \underline{\rho}^{\frac{1}{k}} \tag{4.12}$$

[4]Proposition 1, Article II

and

$$\hat{k} = \sum_{t \in \mathcal{T}} k_t \tag{4.13}$$

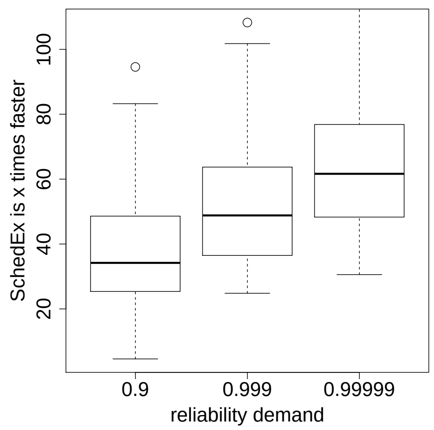

Figure 4.1: SchedEx's performance relative to the reliability-aware incremental framework from [YLH+14]. SchedEx is more than one order of magnitude faster, and the higher the reliability demand, the larger the difference.

SchedEx was tested using four scheduling algorithms from the literature, namely, Node-based Scheduling, Level-based Scheduling (both [EV10]), Dedicated Scheduling, and Shared Scheduling (both [YLH+14]), and evaluated against the incremental approach from [YLH+14]. The results in Article I suggest that SchedEx does not favor algorithms according to their nature; rather, it improved algorithm performance rather equally among the algorithms, unlike, *e.g.*, the incremental algorithm which favors Dedicated Scheduling and Shared Scheduling over the other algorithms (see Fig. 4.3). The best latency performance could be achieved using Node-based Scheduling with a simple coloring scheme, which is notable considering that Node-Based Scheduling has by far the lowest time complexity of the four tested scheduling algorithms.

SchedEx executes within tens of milliseconds and offers feedback to the network manager regarding the latency performance that can be expected. Depending on the time slot size, the schedule frame size can be calculated and matched against the application requirements. When there is no violation of timing constraints, the schedule can be deployed. Otherwise, the margin by which the constraint cannot be met provides a means to assess whether a topology can be tweaked or whether the network configuration cannot be realistically adjusted to suit the problem. In the former case, a tweaking of up to 50% latency improvement may be achieved by cross-layer optimization framework proposed in the Article IV, as presented in the next section. In the latter case, a re-organization of the network may be required; this is further discussed in Section 4.3.

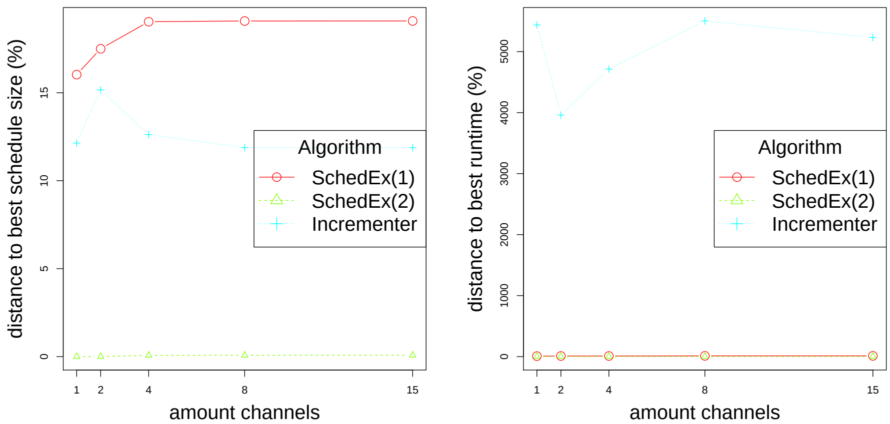

Figure 4.2: The average impact of the number of available channels on the scheduling performance (left) and runtime (right) for the three reliability-aware approaches. SchedEx(2) produces the shortest schedules throughout the investigation. The Incrementer is the algorithm presented in [YLH+14].

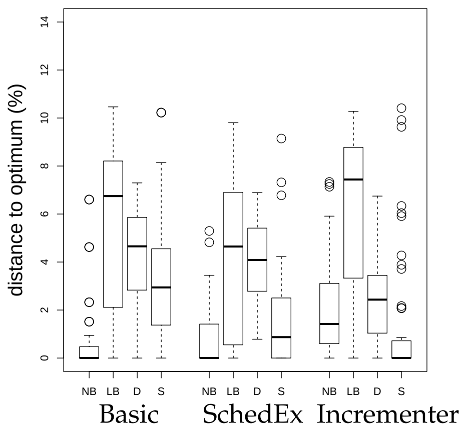

Figure 4.3: The distance to the optimum distribution for all four scheduling algorithms given the following three methods: Basic (no reliability), SchedEx, and Incrementer. Comparing SchedEx and the Incrementer, it becomes obvious that the Incrementer favors Dedicated and Shared Scheduling in terms of performance. SchedEx, in contrast, does not exhibit significant differences in the performance achieved for the Basic scenario, which suggests that the choice of scheduling algorithm does not have a large impact on the performance.

The simulations can be put into the industrial context by considering the wireless industrial communication standard WirelessHART, which offers a minimum time slot size of $10ms$. Given convergecast topologies with 50 sensors that act as sources and relays, a channel model with a signal-to-noise ratio of 60 dB on the receiver side of each receiver, and given a single sink, SchedEx in Article I can achieve the routing of all packets at an end-to-end reliability of $\underline{\rho} = 0.99999$ in a schedule frame spanning 14.3 seconds of round-trip time. Article II reports schedule frame round-trip times as small as 1.83 seconds compared with 2.11 seconds for the incrementer algorithm for a backbone of four deployed sinks and utilizing four channels. SchedEx(2) obtains the schedule in 2 milliseconds, whereas the incrementer requires approximately 45 milliseconds.

One of the features of SchedEx that has not been promoted in the publications is that SchedEx guarantees an end-to-end reliability $\underline{\rho}$ for arbitrary mesh networks for which the flows, including sources and sinks, are known in advance. Additionally, SchedEx can be customized to support different reliability levels $\underline{\rho}_t$ for packets from any transceiver t in the network. That way, periodic sensor readings and emergency signalling can be differentiated, as reflected in the number of dedicated slot allocations made in the final schedule for the different flows. However, for IWSNs, it is common to request a single global end-to-end reliability demand for all packet transmissions in the network, which is why this feature may be of theoretical interest only. Regardless, in Article V, this feature has been added and is further discussed in Section 4.3.

Article III discusses the challenges in the use of aggregation techniques in IWSNs. The article introduces an adjustment of SchedEx that allows for packet aggregation. It illustrates the opportunities with packet aggregation in the industrial context where sensor readings are small in size by suggesting a conservative aggregation scheme that allows x packets to be aggregated into a single packet, using WirelessHART as an example[5]. The extension requires a slight adjustment of relay logic, which is implemented in the buffers of intermediate sensors in multi-hop networks. Within a schedule frame, sensors only use their transmission right if all expected packets have arrived or if no additional packets can be transmitted in one transmission. The SchedEx algorithm requires a slight adjustment to cover aggregation (see Algorithm 2). The difference in the original version from Article I is the updating of the relay counter w_t in line 7 and the consideration of p_t packets being relayed in aggregation (lines 4 and 6).

The calculation of $\hat{k}$ is further extended according to the following formula, including the maximum number of original packets that can be aggregated into a single aggregated packet, $\hat{a}$:

$$\hat{k} = \sum_{t \in \mathcal{T}} \left\lceil \frac{k_t}{\hat{a}} \right\rceil \tag{4.14}$$

Applying packet aggregation to the topologies from Article II significantly improved the schedule frame size, thus reducing latency by 65% down to 4.26 seconds for the

[5] with an aggregation of up to $x = 4$ packets

Algorithm 2: $updatePacketBuffers(t, \mathcal{S}, b, c, \tau)$

Input: Scheduled Transmitter $t \in \mathcal{T}$, Sinks $\mathcal{S}$, Buffer State b, Counter Vector c, Repetition Matrix τ, Maximum Aggregation $\hat{a}$, Relay Packet Counter Vector w

c_t-- // count down attempts for transmitter t
if $c_t = 0$ **then**
  $p_t \leftarrow \min(b_t, \hat{a})$ // cache the packets
  $b_t \leftarrow b_t - p_t$ // remove packets from transmitter buffer
  if $R_t \notin \mathcal{S}$ **then**
    $b_{R_t} \leftarrow b_{R_t} + p_t$ // add packets to receiver buffer
    $w_{R_t} \leftarrow w_{R_t} - p_t$ // decrement packet relay counter
  $c_t \leftarrow \tau_t$ // re-initialize attempt counter

SchedEx, extended for aggregation by coerced waiting.

previously mentioned scenario with a single sink. Fig. 4.4 illustrates the performance improvement for SchedEx with aggregation of up to 2 and 4 packets compared with no aggregation. For up to 2 packets, the latency can be reduced by approximately half while still guaranteeing the same end-to-end reliability level $\underline{\rho}$. Additional simulations that combine packet aggregation according to Article III, together with a hybrid topology containing four sinks and the availability of four communication channels as of Article II, reduced that number to 0.85 seconds instead of the original 14.3 seconds from Article I (94% reduction). These numbers may suffice for many closed-loop control applications.

SchedEx, as introduced in Article I and extended in Articles II and III, offers the flexibility to adjust the schedule to the WSN according to the reliability requirements of the application. The introduction of multiple sinks, multiple channel use (both from Article II) and packet aggregation (Article III) only requires slight adjustments in the calculation of the repetition bound and the packet update procedure of the algorithm. SchedEx satisfactorily addresses the need for a scalable reliability-aware scheduling algorithm. What remains missing is the extension of the problem formulation to mesh networks and arbitrary flows, which requires only modest adjustments to the problem formulation.

4.2 Q2: Generic QoS-aware Framework

Question 2. Can a generic algorithmic framework for WSN configuration that addresses multiple arbitrary end-to-end QoS criteria be created?

The existing efforts documented in Chapter 2 do not suffice to address this question because they do not offer scalable algorithms that identify scheduling and routing configurations fulfilling the typical QoS demands for IWSNs. Further, the solutions are either very problem specific or contain assumptions that often cannot be met in reality. Article III introduces a cross-layer optimization framework for WSNs, thereby addressing several aspects of Question 2. Even Articles II and III introduce improvements of the SchedEx schedule algorithm extension, thus demonstrating its adaptability with respect to feature extensions and problem space adjustments. Arti-

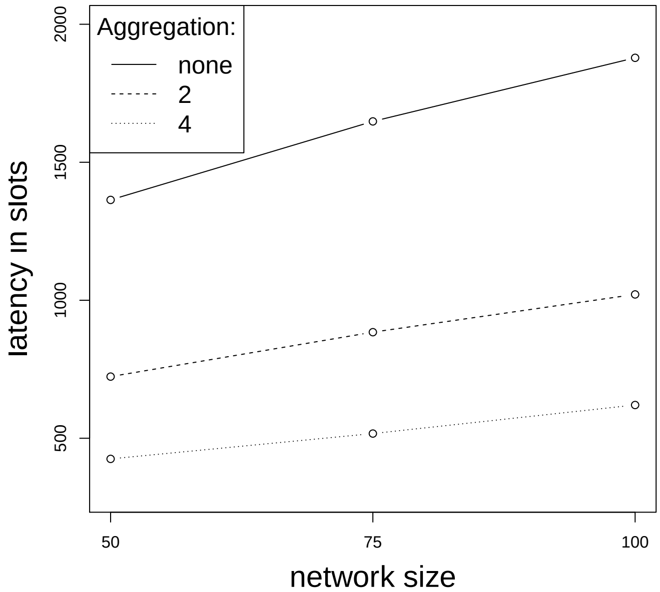

Figure 4.4: The aggregated average required frame size for the topologies to submit all packets to the sink given an end-to-end reliability constraint of 99.999% using SchedEx and a maximum aggregation of four packets. The improvements for an aggregation of 2 and 4 packets are significant.

cle V, building on Article IV, then extends the scope to additional QoS requirements, including publish rates, deadlines (discussed in this section), and service differentiation by priority (discussed in the next section).

The framework in Article IV extends the work from Articles I and II by including the routing decision in the problem formulation, which is why it was categorized as an *integrated* cross-layer approach. The framework is considered an *integrated* cross-layer approach because it jointly assesses the quality of both the routing table r from the network layer and the schedule frame F from the MAC layer as a combined solution, (r, F). The advantages of cross-layer approaches were discussed in Chapters 1 and 2.

The proposed framework is based on a metaheuristic, a GA, that provides a pluggable structure for the integration, (dynamic) substitution and exchange of evaluation functions and assessment criteria. The framework does not make any assumptions on the evaluation function, which means that it could incorporate any evaluation function with any assessment metrics required by the application. A GA can be considered a flexible heuristic that can be tailored to the application requirements using experimental design techniques such as parameter tuning [BBLP05]. This flexibility also extends to the problem formulation, *e.g.*, in the scope of WSNs. An integration of further layers into the problem formulation can be achieved by extending the representation using additional details. GAs are more suitable than other meta-heuristics or bio-inspired algorithms, such as ant colony optimization, because a change in the environment or network produces an instantaneous adaptation instead of a slowly converging adaptation of the algorithm [LG13]. The handling of topology-specific constraints can be achieved by tailoring the problem representation and genetic operators to the specific needs of the application. The proposed GA is conceptualized in Fig. 4.5. Details about the GA, including the operators and the initial population, can be found in Article IV. The GA operates on routing tables, which means that all changes in individuals of the population are reflected by changes in their routing table. For fitness assessment, SchedEx from Article I is applied because SchedEx offers a scalable means of identifying reliability-aware schedules for a supplied routing table. The framework then attempts to minimize the latency per user-defined end-to-end reliability demands. It does this by using random mutation and crossover between the individuals of the GA population to evolve them into better individuals with respect to the fitness function.

Article IV further introduces and investigates a routing approach that is more general than single-path routing, namely, *source-aware* routing. Single-path routing is often applied in the literature due to its simplicity and computational feasibility (*e.g.*, [EV10, YLH$^+$14, DZG14]). However, real-world WSNs offer more sophisticated protocols at the network layer. Source-aware routing is investigated, where relaying sensors decide the next receiver of each packet according to its source of origin. Fig. 4.6 illustrates the diversity of paths for source-aware routing (right), where each edge type represents a different source, compared with the simple one-parent routing for all packets to be routed via a single path (left). Source-aware routing is a more general alternative and may produce a more efficient traffic distribution and, thus, a resolution of bottlenecks without significantly increasing the routing complexity.

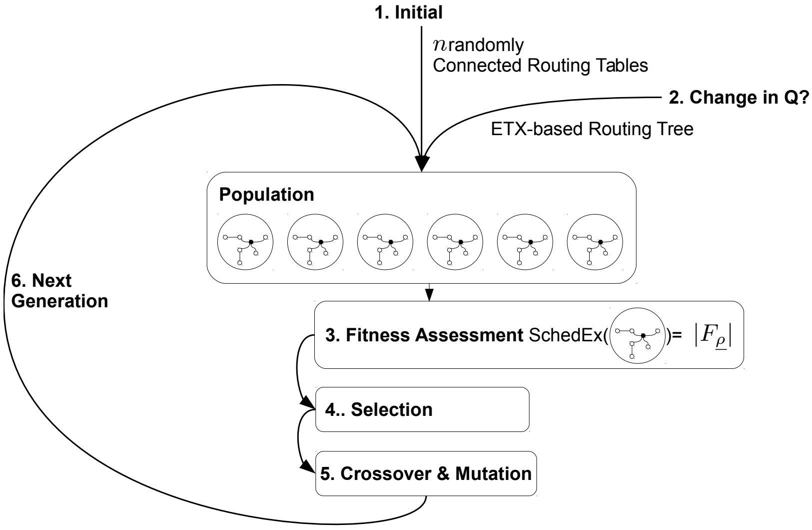

Figure 4.5: The GA algorithm loop for identifying valid and well performing network configurations that consist of a source-aware routing table and a slot-based schedule.

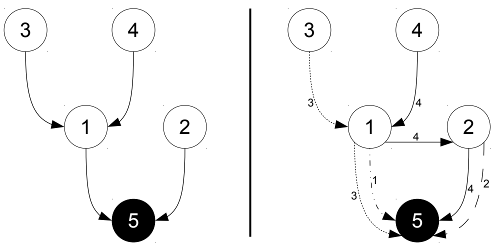

Figure 4.6: Single-path routing (left) vs. source-aware routing (right). For source-aware routing, transmissions are dedicated to a certain receiver, according to the source of the packet.

The problem formulation from Article I had to be adjusted to cover source-aware routing. The routing table is a map r that, for each combination of transceiver $t \in \mathcal{T}$ and packet *source* or *origin* $o \in \mathcal{T}$, provides the receiver, or *parent*, r_t^o, that each packet from o over t is to be routed to in a single hop. What distinguishes single-path routing from source-aware routing is that $r_t^o = r_t^{o'}$ for all $o', o' \in \mathcal{T}$ in single-path routing. The existing routing constraints are substituted by the following:

$$c_1 : \quad \exists\, t_1, \ldots, t_k \Rightarrow r_{t_i}^o = t_{i+1} \wedge r_{t_k}^o \in \mathcal{S} \tag{4.15}$$

$$c_2 : \quad r_t^o = p \Rightarrow q_{tp} > 0 \tag{4.16}$$

Even the scheduling decisions are effected by the inclusion of source-aware routing, and c_4 has to be re-formulated as in:

$$c_4 : \quad f_{st} f_{st'} = 1 \Rightarrow q_{tp} q_{t'p} = 0 \vee \tag{4.17}$$

$$\sum_{t \in \mathcal{T}} f_{st} r_t^o = 0 \vee \tag{4.18}$$

$$\zeta_{ts} \neq \zeta_{t's} \wedge r_t^o \neq r_{t'}^o \tag{4.19}$$

For more details about the formality changes, see Article IV.

The inclusion of routing in the problem formulation significantly increases the chance that valid network configurations can be identified. Source-aware routing enables a more sophisticated and tailored scheduling and routing configuration that, on average, provides a 9% reduction in latency compared with single-path routing (see Fig. 4.7). In particular, when multiple channels are utilized, which often is the case for IWSN, the GA with source-aware routing identifies better configurations than with single-path routing alone.

Article IV must further extend the proposition for the calculation of n_t because of the dependence of the reliability calculation on the transceiver t and origin of the packet at hand o, due to the potentially different receivers, according to

$$n_t^o = \left\lceil \frac{\log(1 - \underline{\rho}_t)}{\log(1 - q_{tr_t^o})} \right\rceil, \forall t, o \in \mathcal{T} \tag{4.20}$$

In addition, the SchedEx algorithm is further extended to cover source-aware routing, as presented in Algorithm 3. Single-path routing is a special case, for which $\tau_{to}\tau_{to'}, \forall o, o' \in \mathcal{T}$. Instead of a repetition vector, a repetition matrix τ is required that contains, for each transceiver t and origin o, the correct number of demanded repetitions n_t^o to receiver r_t^o in τ_{to} according to (4.20). Each buffer b_t is further represented as a customizable queue that allows removal, enqueuing and head peeking using the *pop*, *enqueue*, and *peek* routines. SchedEx further allows for the setting of varying individual reliability constraints $\underline{\rho}_t$ for each sensor $t \in \mathcal{T}$. As a consequence, service differentiation could be realised; however, this is not considered in Articles I-IV (but in Article V; see the next section).

Article V outlines the conceptual framework that illustrates the solution from a network perspective, which is explained in Section 3.1 in this thesis. The dynamicity

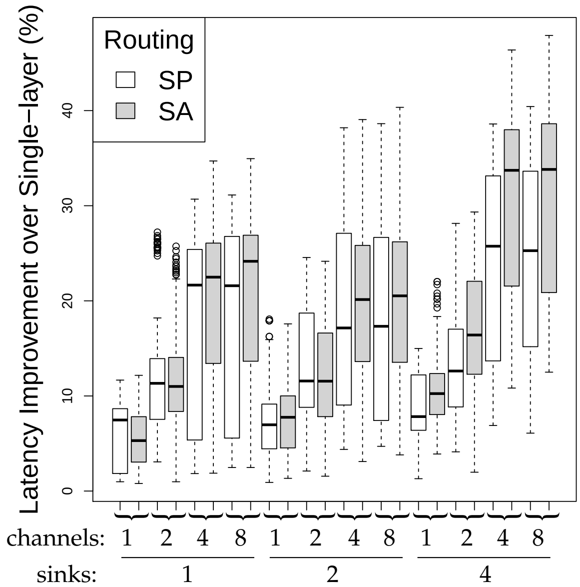

Figure 4.7: The improvement of the cross-layer GA over SchedEx based on heuristic routing. Source-aware routing can successfully be utilized, resulting in on average 9% better results if applied by the GA compared with single-path routing.

Algorithm 3: $updatePacketBuffers(t, \mathcal{S}, b, c, \tau)$

Input: Scheduled Transmitter $t \in \mathcal{T}$, Sinks $\mathcal{S}$, Buffer State b, Counter Matrix c, Repetition Matrix τ

```
φ ← b_t.peek() // get next packet
o ← φ.origin // get packet source
c_to-- // count down attempts for transmitter t and origin o
if c_to = 0 then
    b_t.pop() // remove packet from transmitter buffer
    if r_t^o ∉ S then
        b_{r_t^o}.enqueue(φ) // add packet to receiver buffer
        c_to ← τ_to // update counter
```

The SchedEx algorithm in support of source-aware routing [DZG14].

of the network is addressed by running a quickly converging centralized global optimizer with knowledge about the entire network, which is triggered by the network manager. The article does not attempt to solve the problem of link quality assessment nor the dissemination or distribution of network control packets (*meta data*), which is a potential area for future work, as mentioned in Chapter 5.

Article IV suggests an injection of heuristic routing tables into the artificial evolution when the link qualities in the network change drastically. This bootstrapping approach is chosen as a starting point for the GA for finding increasingly better solutions. In particular, considering dynamic environments, the problem of stale data in the evolution can be efficiently solved in this manner as long as rapid algorithm convergence is assured. The main challenge for a GA design in real-time environments is to identify an evaluation function that executes in a sufficiently short period of time and is run many hundreds (if not thousands) of times per second to quickly converge towards well-performing regions of the problem space.

The proposed GA establishes high-quality network configurations, more than 20% better than those reported in Articles I and II, in less than one second. Article III reveals that the framework leads to, on average, improvements of 31% over the layered results from Article I in less than 60 seconds. As a consequence, there is a chance that the integrated cross-layer framework can successfully be applied to topologies that miss the user requirements concerning heuristically created routing tables according to Articles I-III. This is because network dynamics cannot be addressed by a heuristic assessment of only a part of the solution, *e.g.*, the routing table, as performed in layered approaches. The convergence curves for the GA with single-path and source-aware routing can be observed in Fig. 4.8.

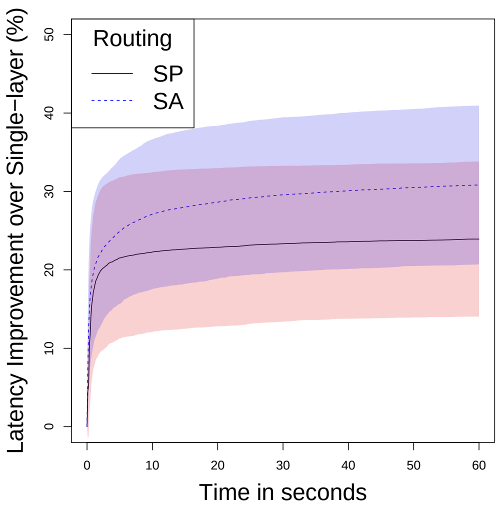

Figure 4.8: The average convergence improvement of the cross-layer GA over SchedEx using heuristic ETX-based routing.

The GA is a suitable candidate for cross-layer optimization that includes routing and scheduling in the network configuration and assesses them in an integrated manner. The framework produces network configurations within seconds, thus guaranteeing the end-to-end reliability requirement $\underline{\rho}$ for all traffic in the network and improves the performance in terms of latency compared to the use of SchedEx utilized on heuristic-based routing tables by more than 20%. Once the algorithm has been implemented, the extension to multiple objectives and constraints can easily be achieved, as discussed in the next section.

Article V extends the generic framework to consider the publish rate λ_t, maximum tolerable delay Δ_t, and end-to-end reliability $\underline{\rho}_t$ on a sensor-basis for each transceiver $t \in \mathcal{T}$ in the problem formulation. The article names the framework *SchedEx-GA*. The objective in Article IV has been re-defined to minimize the number of deadline violations with the following problem formulation:

$$\min_{c} o_{\Omega}(c) = |D_{(c,\Omega)}| \tag{4.21}$$

subject to

$$c_0 : \qquad \underline{\rho_o} \leq \rho_o \qquad \textit{Reliability}$$
$$\ldots$$

Constraints $c_1 - c_4$ remain as in Article IV. The objective function in (4.21) attempts to identify a cross-layer configuration $c = (r, F)$ that minimizes the number of deadline violations $D_{(c,\Omega)}$ given the user-defined configuration demand $\Omega = \{\underline{\rho}, \Delta, \lambda\}$:

$$D_{(c,\Omega)} = \{\phi | \phi \text{ from } o \in \mathcal{T}, c = (r, F), \searrow^{\phi} - \nearrow_{\phi} > \Delta_o\}. \tag{4.22}$$

$D_{(c,\Omega)}$ contains all packets ϕ from any sensor $o \in \mathcal{T}$ created throughout the schedule frame F, for which the deadline has been violated. $\nearrow^{\phi}$ denotes the creation time of ϕ, and $\searrow^{\phi}$ denotes its time of arrival at a destination sink. Article V therefore introduces the *packet creation frame* Θ for a given schedule frame F. Θ can be derived to account for a worst-case anticipated network load, as in

$$\theta_{f_{so}} = \begin{cases} 1 & \text{if } \lfloor i_o + s \mod \lambda_o \rfloor = 1, \\ 0 & \text{else,} \end{cases}$$

with offset i_o being the initial time slot with the opportunity to transmit a packet for o. By customizing i_o, packets from different sensors can be synchronized with *happens - before* relations considering individual time slots and deadlines for each transceiver. The deadline for each packet ϕ from transceiver o in slot s is then calculated as $s + \Delta_o$. An example of a creation frame can be found in Table I in Article V. Article V also introduces the concept of logical sensors, which is required for sensors that publish content with different reliability, publish rate or deadline demands. Logical sensors realise a logical sensor split for the physical sensors to allow for a differentiation within the problem formulation. Fig. 4.9 exemplifies a two-way split.

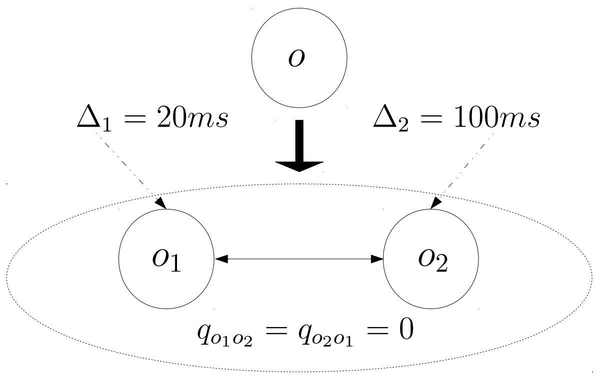

Figure 4.9: An example of a logical sensor split in o for two different service levels Δ_1 and Δ_2.

Article V further extends the reliability demand from Article I in c_0 using sensor-specific publishing rates. The concept of a network-wide end-to-end reliability used in Articles I-IV may not be appropriate for the varying requirements among the sensors in IWSNs. An *event* or *packet-based* end-to-end reliability $\underline{\rho}_o$ for the successful arrival of each packet of origin o better suits the network with unaligned and arbitrary publishing rates. Article V introduces end-to-end reliability $\underline{\rho}_o$, in which the end-to-end reliability considers all h_o hops for the packets from source o traveling to sink s (see Fig. 4.10). To guarantee $\underline{\rho}_o$, the following must hold:

$$\prod_{i=1}^{h_o} \rho_i \geq \underline{\rho}_o, \forall o \in \mathcal{T} \tag{4.23}$$

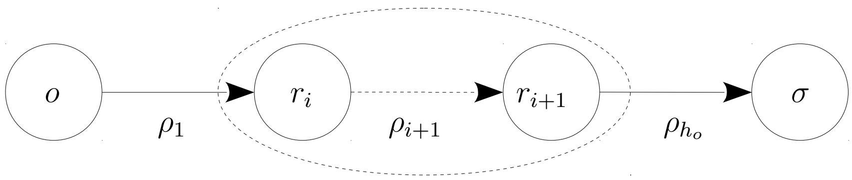

Figure 4.10: An exemplified routing path for all packets from origin o to sink σ, passing by i relays. The transmission on each link i must ensure the reliability ρ_i to fulfill the sensor-specific end-to-end demand of $\underline{\rho}_o$, according to (4.23).

Constraint (4.23) can be guaranteed by Proposition 1 in Article V for all flows from each transmitter $o \in \mathcal{T}$ to their destination $\sigma \in \mathcal{S}$ in support of multi-hop routing. The proposition tailors SchedEx to event transmission reliability as follows:

Proposition 4.3. *Given a network with sinks $\mathcal{S}$, transceivers $\mathcal{T}$, a routing map r, a link quality matrix Q, and a total number of h_o hops to $\sigma \in \mathcal{S}$ for each sensor $o \in \mathcal{T}$ according* *to routing map r, an end-to-end reliability $\underline{\rho}_o$ for the arrival of each packet starting from o to its sink can be guaranteed if n_t^o repetitions are executed for each sub-route passing $t \in \mathcal{T}$ according to*

$$n_t^o = \left\lceil \frac{\log(1 - \underline{\rho}_{to})}{\log(1 - q_{tr_t^o})} \right\rceil, \forall t, o \in \mathcal{T} \tag{4.24}$$

with

$$\rho_{to} = \underline{\rho}^{\frac{1}{h_o}}. \tag{4.25}$$

The *updatePacketBuffers* routine in its developed form from Article V is presented

Algorithm 4: $updatePacketBuffers(t, \mathcal{S}, b)$
Input: Scheduled Transmitter $t \in \mathcal{T}$, Sinks $\mathcal{S}$, Buffer State b
1: $\phi \leftarrow b_t.peek()$ // get next packet
2: $o \leftarrow \phi.origin$ // get packet origin
3: $\phi.attemptCounter$-- // count down attempts for ϕ
4: **if** $\phi.attemptCounter = 0$ **then**
5: $\quad b_t.pop()$ // remove packet from transmitter buffer
6: $\quad p \leftarrow r_t^o$ // get receiver
7: $\quad$ **if** $p \notin \mathcal{S}$ **then**
8: $\quad\quad b_p.enqueue(\phi)$ // add packet to receiver buffer
9: $\quad\quad \phi.attemptCounter \leftarrow n_p^o$ // re-init attempt counter

as Algorithm 4 in this thesis. For each scheduled transmitter t, *updatePacketBuffers* is executed to ensure that only those packets ϕ of origin o are considered to have been successfully transmitted by transmitter t to the next relay or sink, for which the transmission attempt counter $\phi.attemptCounter$ has registered n_t^o attempts (line 4). In contrast to the original SchedEx version, the attempt counter is now specified on a packet basis, instead of a transmitter basis, for consistency. Whenever a new packet arrives at a transmitter, it becomes included in the existing transceiver queue, potentially before all other packets.

The basic GA implementation in Article V is an extension of that in Article IV. Study 1 of Article V investigates how SchedEx-GA, using source-aware routing, can address topologies of size 50 with deadlines and publish rates in the range of $250 - 5000ms$ and reliability demands in the range of $0.9 - 0.99999$. Fig. 4.11 verifies the impact of using multiple channels and multiple sinks in the scenarios. For more than 4 channels, no significant improvement can be achieved; however, the use of multiple sinks makes the number of deadline misses converge towards zero. SchedEx-GA significantly minimizes the number of deadline violations within tens of seconds. For those frames created using the fitness assessment in Article IV, deadline violations are close to 100% for all scenarios because the fitness function is unable to consider deadline misses and therefore optimizes for the wrong metric.

To address Question 2 in its entirety, considering *arbitrary* QoS constraints, additional and broader studies are required, particularly with topologies of different

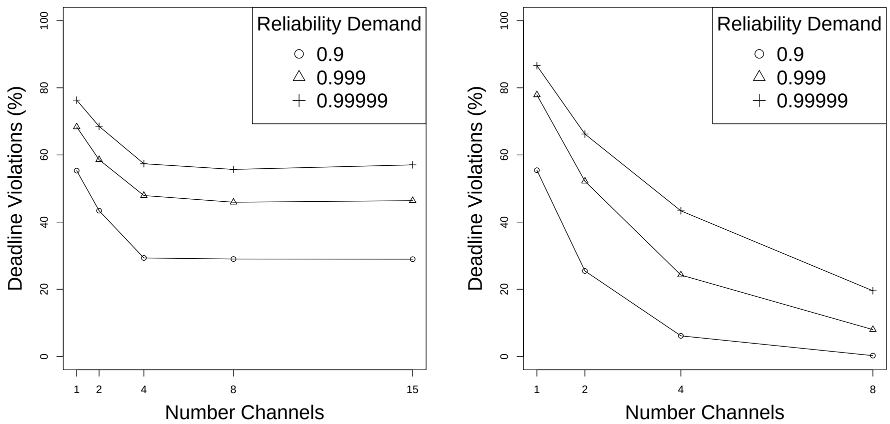

Figure 4.11: The average impact of the number of channels (left) and sinks (right) on the number of deadline violations.

nature. However, the integration of end-to-end reliability, arbitrary publish rates and delays have successfully been implemented in SchedEx-GA through Articles IV and V.

4.3 Q3: Service Differentiation

Question 3. How shall service differentiation be implemented in a generic algorithmic framework to ensure multiple end-to-end QoS features?

Article V extends the generic framework in Article IV by adding service differentiation support. This support utilises the flexibility of the GA and incorporates the handling of both sensor-specific periodicity and deadlines in the form of formal constraints, whereas priority handling is ensured by explicit rules for the packet buffer queues of the sensors. This criterion can be customized, depending on the needs of the specific application.

The user-defined configuration requirement triplet $\Omega\{\underline{\rho}, \Delta, \lambda\}$ has been discussed in the previous section. Article V further extends the QoS demand to include arbitrary priority categories. To address priority, a priority queuing scheme for the packet buffers of each intermediate sensor must be established. The priority scheme is used hierarchically in the class of priority categories K=$\{1, 2, \ldots\}$, with packets of category κ always being placed higher up in the transmission queue than those for κ' if $\kappa < \kappa'$ $\forall\kappa, \kappa' \in K$. The problem formulation is extended and can be customized using a penalty to assign higher priority to packets of lower packet category. Ω is therefore extended to a quadruplet Ω'=$(\underline{\rho}, \Delta, \lambda, \kappa)$ to include the sensor specific priority assignment κ_o for each sensor $o \in \mathcal{T}$. The set of violations per category $D_{(c,\Omega',\kappa)}$

packet category	deadline (ms)	distribution (%)
1. emergency	250	20
2. closed loop control	500	30
3. monitoring	$1000-5000$	50

Table 4.1: The packet categories, their deadlines, and distributions for the simulations.

is further defined as in

$$D_{(c,\Omega',\kappa)} = \{\phi|\phi \in D_{(c,\Omega)}, \phi \text{ from } o \in \mathcal{T}, \kappa_o = \kappa\} \tag{4.26}$$

which leads to the priority-aware objective function:

$$o_{\Omega'}(c) = \sum_{\kappa \in K} p_\kappa |D_{(c,\Omega',\kappa)}|. \tag{4.27}$$

Here, p_κ is a penalty for each service-level category $\kappa \in K$. The simulation results are compared on those topologies investigated in Article I. With respect to priority, K=$\{1, 2, 3\}$ has been chosen according to Table 4.1 in the investigation. Three priority levels are assumed that must be respected in the constraints and at each relaying node, namely, emergency signalling, close-loop control, and monitoring. To penalize deadline violations of different categories proportional to the importance of their arrival, penalties p_1=1e^6, p_2=1e^3, and p_3=1 are chosen to reduce the risk of multiple low category packets being preferred in the scheduling over even a single higher service level packet. It should be noted that the use of these three classes is for the simplicity and presentability of the results. The proposed priority model allows for the arbitrary application-specific assignment of sensors to priority classes. The packet category is randomly assigned to the sensors in a topology according to the distribution in column 3 of Table 4.1. The distribution has been chosen to emulate a fictive industrial site.

The fitness function in (4.27) attempts to reward high-priority packet arrivals. Compared with the results of (4.21), it becomes obvious that the consideration of priority in the objective function makes a difference. A series of simulations was conducted to obtain performance differences of the fitness functions. For monitoring packets, there is no significant performance difference, whereas for control and emergency packets, a deadline violation reduction of 16% and 35%, respectively, could be obtained when using the objective function (4.27). This result strengthens the decision to include priority in the objective function, therein showing a significant impact on the deadline violation ratios and their distribution among the categories.

For a user to be able to assess how far off the current best solution in the evolution is from the requirement, user feedback about the margin by which the requirements are missed shall be visualized. A graphical assessment tool has been used to provide an easier interpretation of the results throughout the study. For a given user-defined QoS demand Ω' and number of utilized channels ζ, the GA converges within a short period of time, and the bottlenecks in the network can be visualized as exemplified in Fig. 4.12. The requirements can then be changed and tested with, *e.g.*, a larger number of sinks to find a solution that fulfills all constraints. A user sees whether the

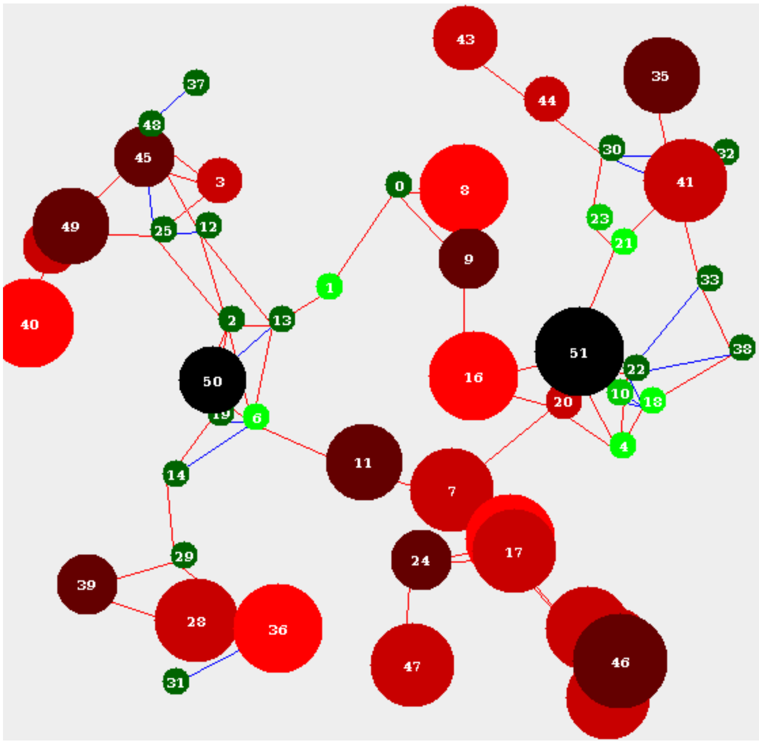

Figure 4.12: An example of visualizing sensors with deadline misses (red), those without (green), and sinks (black). The size of the sensors stands in relation to the number of missed packets, and the lightness of the colour illustrates its urgency. For the given case, a sink deployment in the lower-right corner could be investigated to resolve the deadline misses there.

current best solution is succeeding based on the colouring. If the algorithm fails, the output identifies the locations of the bottlenecks in the network. As a consequence, the user may attempt a re-design using additional relay or sink deployment by considering the clues. The network can be tested by only small and directed corrections in the physical network. Using modeling techniques, such as surrogate modelling, simulations could even be conducted without interfering with the physical world by extrapolating link qualities from other links in the link quality matrix Q.

The approach, as presented so far, cannot be guaranteed to identify network configurations that fulfill all requirements. A user could attempt to tweak the network using the graphical feedback; however, this may be cumbersome. The graph in Fig. 4.11, however, suggests that the number of violations converges towards zero for all reliability demands as a function of the number of deployed sinks. The problem is therefore re-formulated in Article V from minimizing the deadline violations to asking for the minimum number of sinks necessary to fulfill all QoS demands Ω' given a certain number of channels for a topology, as in

$$\min_{c} o_{\Omega'}(c) = |\mathcal{S}| \tag{4.28}$$

A constraint that now requires no violations be permitted is added:

$$c_5 : \quad \searrow^{\phi} - \nearrow_{\phi} \leq \Delta_o, \forall \phi \text{ from } o \in \mathcal{T} \quad \textit{Deadline} \tag{4.29}$$

Constraint c_5 requires that each packet ϕ from any sensor $o \in \mathcal{T}$ created throughout the time frame be transmitted before its deadline $s + \Delta_o$.

Algorithm 5, which guarantees that a valid solution can be found for (4.28), is proposed in Article V. The framework is initially run with one sink, positioned in the weighted center of the topology based on K-means clustering, and generates a record if the best candidate after termination results in packets missing their deadline. If not, the algorithm stops and returns the result that one sink is required to fulfill the requirements. Otherwise, the number of tested sinks is doubled, and the process is repeated. Once a sufficient number and positioning of sinks has been identified in this manner, we identify the minimum number of sinks that satisfies the constraints (line 14). Algorithm 5 executes in $O(\log N)$, where N is the number of sinks between the last non-successfully tested number of sinks and the first identified successful number of sinks. Algorithm 5 is both correct and complete. It is correct because once a solution has been found, it is valid, and it is complete because all valid solutions satisfy the stopping criteria. The algorithm always terminates because there are as many sinks as sensors in the worst case, with sinks positioned on top of the sensors. This is a rather theoretical case in which no gain in using wireless technology is reached; it is solely mentioned to prove the important termination criterion.

Algorithm 5: $findMinNumberSinks(N, \mathcal{T}, \zeta_{MAX}, \Omega')$

Input: Initial Number of Sinks N, Transceivers $\mathcal{T}$, Utilized Channels ζ_{MAX}, Application Constraints Ω'

1: $IsSatisfied \leftarrow FALSE$
2: **while not** $IsSatisfied$ **do**
3:     **if** $N > |\mathcal{T}|$ **then**
4:         $N \leftarrow |\mathcal{T}|$
5:     $\mathcal{S} \leftarrow K\text{-}means(N, \mathcal{T})$
6:     $Q \leftarrow AssessLinkQualities(\mathcal{S}, \mathcal{T}, \zeta_{MAX})$
7:     $c \leftarrow SchedEx\text{-}GA(\mathcal{T}, \mathcal{S}, Q, \zeta_{MAX}, \Omega')$
8:     **if not** $c.hasDeadlineViolations()$ **then**
9:         $IsSatisfied \leftarrow TRUE$
10:     **else if** $N = |\mathcal{T}|$ **then**
11:         **return** ∞ // no satisfactory solution can be found
12:     **else**
13:         $N \leftarrow 2N$
14: $N \leftarrow findMinNumberSinks(N, \mathcal{T}, \zeta_{MAX}, \Omega')$
15: **return** N

The Iterative Sink Search Algorithm, initiated with $N = 1$.

The result for Study 2 in Article V shows that the required number of sinks nearly doubles for each demanded level of reliability $\underline{\rho}_o$. A decreased performance can be anticipated for the utilization of multiple channels (*e.g.*, comparing 8 and 15 channels), which can partly be explained by the greater computational burden for the scheduling algorithm. The number of required sinks without aggregation, namely, 6.14, is on average 1.81 times larger for $\underline{\rho}_o = 0.999$ than the 3.4 sinks for $\underline{\rho}_o = 0.9$; moreover, the 10.1 sinks required for $\underline{\rho}_o = 0.99999$ is 2.97 times larger.

reliability	0.9	0.999	0.99999
channels	**required number of sinks**		
1	4.3 ± 1.16	8.2 ± 1.55	17 ± 4.32
2	3.3 ± 1.42	5.8 ± 0.79	9.4 ± 2.59
4	3.2 ± 1.03	5.3 ± 1.16	8.1 ± 0.88
8	3 ± 0.94	5.5 ± 0.97	7.8 ± 0.79
15	3.2 ± 0.79	5.9 ± 1.2	8.2 ± 1.23

Table 4.2: The average number of sinks per utilized channel required to guarantee all deadlines to be met for the given reliability demand for topologies of size 50.

Article V, in Study 2, further investigated the use of aggregation based on Article III with a relaxed waiting scheme because of the stringent deadlines. Packets never wait to be transmitted; however, up to x packets could be sent in aggregation, which should substantially increase the performance according to Article III. Fig. 4.13 summarizes the results. The decrease in the demanded number of sinks when applying aggregation is noteworthy, with an average improvement of ca. 10%. However, because the scenario in Article V is substantially more constrained than the one in Article III, no improvements in the range of $60 - 90\%$, as reported in Article III, could be obtained.

Article V addresses the problem of service differentiation and reveals the hardness of the problem by determining the required numbers for moderately harsh and realistic scenarios in industrial environments. The proposed approach delivers user feedback that can be interpreted and used for an improvement in QoS by adjusting the infrastructure in simulations where possible and without the requirement of physical intervention in the network. The scalability of the approach is not discussed at the heart of the Article, which makes it non-applicable to real-world situations where network changes occur within seconds and where feedback must be provided in seconds. However, where the algorithm has time, say, between 10 and 300 seconds, to calculate a result, an integration may be promising. In addition, the simulations are conducted with a standard stationary PC from 2007; therefore, the results should be obtained substantially faster with new hardware because GAs are made fully parallelizable by distributing each candidate solution of the population to a dedicated CPU. The approach is flexible in that it allows a user-defined definition of all service requirements. A generalization from the centralized to decentralized model, where each logical sensor must report to a specific sink, can easily be achieved by adding an additional constraint that interprets all packets arriving at the wrong sink as violating the deadline. Thus, the SchedEx-GA framework addresses Question 3 by proposing a generic solution to the problem of service differentiation and the flexible integration of multiple QoS features.

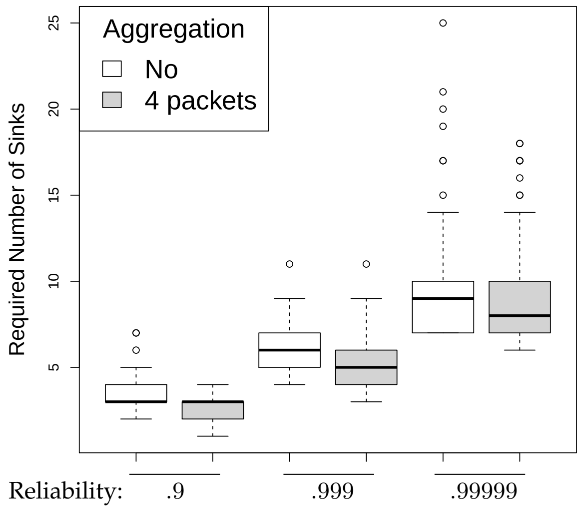

Figure 4.13: A box-plot visualizing the impact of aggregation, summarized over all channel models. Aggregation gives an improvement of in average ca. 10%.

Chapter 5

Conclusions

Though the road's been rocky it sure feels good to me.
Bob Marley

This thesis focuses on an investigation of WSNs for their use in mission-critical applications and their corresponding limitations. The author strongly believes that wireless technology will continually imply a remaining risk of failure that is greater than that of wire-based solutions. The choice of wireless over wired technology is a choice *favoring* flexibility and cost effectiveness while trading off reliability. Determinism in the physical world cannot be achieved, and wireless presents a further departure from determinism compared with wired solutions. The algorithms and frameworks discussed in this thesis offer means to optimize, analyze, and better explain remaining uncertainties to the user for wireless sensor and actuator networks. Compared with the existing work in the literature, the proposed algorithms substantially improve on the scalability, adaptability, and computability for the provisioning of end-to-end QoS guarantees in WSNs.

The main contributions are summarized as follows. With the introduction of SchedEx (Article I), a scalable, end-to-end reliability-aware TDMA-scheduling algorithm extension, an important contribution to reliability-aware scheduling for WSNs, has been made. SchedEx has been extended for multiple channels and multi-sink scenarios (Article II) and is justified by a performance improvement of one order of magnitude compared with the original single-sink, single-channel configuration. The utilization of data aggregation with SchedEx has been investigated and demonstrated that the integration contributes substantially to the closing of the gap to a feasible solution to end-to-end reliability for real-world scenarios (Article III). SchedEx has been further integrated into a GA-based cross-layer framework to solve configuration problems spanning routing and scheduling under end-to-end QoS requirements (Article IV). The approach achieved an improved performance of 31% in terms of latency compared with the isolated use of SchedEx in Article II. The proposed integrated cross-layer is a self-healing and adaptive approach and can be adjusted to consider alternative or additional QoS requirements by the substitution of the fitness function. The framework is further extended to support flow-specific individual deadlines for each logical sensor, thus supporting service differentiation by implicitly weighting more urgent traffic and assigning it a higher priority in packet buffers throughout the network (Article V).

In future studies, rather than using single-path routing and single-channel utilization when investigating scheduling algorithms, source-aware routing shall be taken as a reference. The increase in complexity is modest, whereas the performance gain can be noteworthy. Newly proposed methods should be found to outperform the existing ones, given assumptions that are closer to *real-world* scenarios than those used in much of the current literature. An openly available data set with realistic scenarios would greatly simplify the comparison of algorithms.

Scheduling and routing problems in the scope of WSNs are computationally hard due to the large set of possible alternative solutions. The requirement for probabilistic guarantees further substantially increases the complexity of the configuration problem and affects the possible QoS for the topology of interest. Nevertheless, wireless sensor and actuator networks open new markets. For industrial control applications, wireless may well be a suitable solution. The likelihood and potential consequences of a failure can be numerically obtained and weighted against each other. The algorithms proposed in this thesis contribute to the revelation and counteracting of failures in WSNs.

5.1 Research Conduct

In the early stages of the studies, it became clear that the use of a cross-layer solution would be preferable over a MAC-layer- or network-layer-only approach because of the interdependence of routing and scheduling with respect to end-to-end reliability assessment. To investigate the difficulty of end-to-end reliability, the schedule minimization problem was formulated as a cross-layer Integer Program, including schedule and routing as variables. For test topologies with a size of 20, even finding initial solutions took tens of minutes; for topologies with sizes above 30, the program was canceled without success after a week of execution time. Neither scalability and performance were in line with the objective.

As a next step, the use of GAs for the same cross-layer problem considering end-to-end reliabilities was investigated. The first attempt was to calculate the end-to-end reliabilities representing the reachability graph of the topology with all of the packets created in a TDMA super-frame as a finite-state machine. The formal description was implemented, and multiple fitness functions were used to evaluate the individuals in the population to find a good compromise between reliability and latency. The approach scaled poorly because of the exponential complexity of the reachability graph of the network. For networks with more than 10 sensors, the GA would require multiple seconds to evaluate a single generation, which showed that the approach would not be feasible. Graph pruning of states with reachability probabilities below a threshold (e.g., 0.1 %) could reduce execution time by more than half; however, the scalability issue remained, and pruning introduced another level of uncertainty.

A simulator-based approach was taken next, where the end-to-end arrival probability was no longer calculated but estimated using inferential statistics [Nav06]. The GA could infer the number of required repetitions per assessment for a user-defined reliability demand with the *confidence interval of the proportion*. The minimum sample size is determined for a user-defined *confidence level* α (more precisely, $1 - \alpha$) and maximum error ϵ. The minimum required number of stochastic independent runs is then

$$n = \hat{p}\hat{q}\left(\frac{z_{\alpha/2}}{\epsilon}\right)^2, \tag{5.1}$$

assuming that the error follows a standard normal distribution. The z-score $z_{\alpha/2}$ is the quantile that an observation X falls inside the $]-\infty, z_{\alpha/2}]$ interval. Because $\hat{p}$ and $\hat{q}$ in $\hat{p} = 1 - \hat{q}$ for the derivation of the confidence interval are unknown, $\hat{p} = \hat{q} = 0.5$ can be assumed to maximize the acceptable variance $\hat{p}\hat{q}$ and guarantee that n is never underestimated. This results in the proportion $\hat{p'} = \frac{X}{n}$ of packets that arrive at a sink for each simulation. According to the central limit theorem, the proportion sampling formula gives us an estimate of the end-to-end reliability. For example, at least 9.604 runs have to be executed to receive a sample mean $\hat{p'}$ that is within the $[\hat{p'} - 0.01, \hat{p'} + 0.01]$ interval with 95% confidence (given that $\alpha = 0.05$ and $\epsilon = 0.01$). However, because reliability demands are usually high, the confidence interval was required to be narrow, which resulted in tens of thousands of repetitions per assessment to ensure the required accuracy of the results. As a consequence, a heuristic approach was taken, where each assessment received 100 simulation runs, knowing that the results could be very imprecise. A GA, however, probes the same instance multiple times if it succeeds to the next generation due to randomness. In the long run, the hypothesis was that the bad solutions are obliterated. The approach produced good convergence for topologies of up to 30 sensors. However, at later stages of the algorithm execution, to receive high-performing solutions, the number of repetitions per assessment had to be increased again for all instances of the population, which made the final convergence a time-consuming process. A solution that should be deployed further had to be tested with the correct confidence demand, which was also time consuming. The approach was abandoned because it did not scale to sufficiently large WSN topologies.

Eventually, a step back was taken to identify a scalable scheduling algorithm to ensure end-to-end reliability guarantees. The work in [YLH$^+$14] inspired the author to investigate whether a lower-bound for end-to-end reliability guarantees could be identified. For that reason, the existing scheduling algorithms together with reliability-aware scheduling algorithms were implemented. As opposed to the existing work, the focus was not on receiving an exact end-to-end reliability but ensuring that a user-defined minimum constraint could be fulfilled. This eventually resulted in SchedEx, as presented in Article I. Throughout the research, the simulator was extended to obtain multi-channel support, multi-sink support (hybridisation, Article II), data aggregation (Article III), source-aware routing (Article IV), and sensor-specific publish rates (Article V). The algorithmic correctness was verified by unit tests for all relevant aspects, including the link quality calculation and correct schedule creation for the different algorithms based on reference solutions from the literature (*e.g.*, from [EV10, YLH+14]). The approach was further investigated through simulations on various settings using multiple channels and multiple sinks and theoretically being extended using a tighter bound to calculate the minimum required number of repetitions per scheduled link. This resulted in Article II.

The reliability-aware scheduling was put in a broader context for the creation of a generic framework that utilizes scheduling algorithms solely as a feature. This framework should first be verified to produce satisfying results for integrating routing and scheduling decisions and is thus sufficiently flexible to be extended for service differentiation. The choice fell on a GA-based framework, which is a naturally pluggable construct. With the initial experience from simulation-based investigations, the choice was to reduce the search space complexity by having only the routing table represent the genotype while using the SchedEx algorithm over a fixed scheduling algorithm to deterministically obtain valid reliability-aware schedules within short time periods. The problem therefore included the identification of both the routing table and the schedule. The results were presented in Article IV, where the cross-layer was demonstrated to improve on the performance of SchedEx over shortest path routing.

Until then, all packets were assumed to be created at the beginning of each frame, and the deadline of each packet was at the end of each frame, which is a very limiting assumption. The network simulator was therefore extended to allow for the periodic creation of packets according to sensor-specific publish rates defined by the user. The use of packet creation plans was formalised in Article V. A fitness function was introduced to minimize the number of packets missing their deadline per schedule frame. The model was further extended to arbitrarily customizable priority categories, incorporated the fitness function and transceiver queue ordering, to schedule higher priority packets before lower priority packets. In an extended study in Article V, sinks were added incrementally to form a backbone in the hybridised wired/wireless network configuration until all demanded QoS requirements could be fulfilled. At network deployment time, the framework could therefore offer automated suggestions for network extensions/adjustments. A stage of experimental verification could not be reached during the studies.

5.2 Future Work

The introduction of wireless control may require/allow for a rethinking of how things are done today. Currently, production lines (usually) operate at a constant pace, demanding a given QoS from the communication system to maximize productivity. The pace is often dependent on the machinery and work force. Constance simplifies profit calculations. In these situations, there will always remain the risk that lost packets will negatively impact productivity, break machinery, or harm employees due to the fluctuating conditions of the communication medium. As an alternative, a factory where wireless is consciously chosen over wired communication could pessimistically adapt the production pace to the communication system, which would substantially increase reliability despite producing other potential expenses such as higher energy use by the motors of machinery that adaptively change their pace or a period of reduced production rate. In power plants, the flexibility advantages may not be justified, especially with respect to the potential consequences and risk assessment. For paper mills, a successful and cost-effective implementation may very well be in reach.

The algorithms proposed in this thesis contribute to the creation of a scalable and adaptive QoS-aware framework for mission-critical applications in support of WSNs. Nevertheless, important research questions outside the scope of this thesis must be addressed in future work to provide decision makers with a complete solution/product for the appropriate configuration of a network, all the way up to the application layer. Possible directions for future research are detailed below.

5.2.1 Centralized Optimization Framework

The conceptual centralized optimization framework in Fig. 3.1 has four major compartments embedded inside the network manager: The WSN model, the Optimizer, the Model Filter and the Change Enforcer. The main contributions of this thesis are regarding the WSN model and the Optimizer. A discussion on the Model Filter and Change Enforcer is not within the scope of the thesis. However, scalable solutions for both the Change Enforcer and the Model Filter are a requirement for a generic framework. The scalable assessment and collection of link quality spanning the entire network is another area that requires attention from the research community because centralized network management is the status quo and may be around for a long time to come.

Model Filter

A Model Filter ensures that only relevant PDR information is used to update the internal PDR of the WSN Model on the gateway. The Model Filter can even be partly decentralized in that not all delivery rates are reported to the gateway but are aggregated at the sensor. The sensor could even receive the main responsibility of maintaining valid packet reception rates to its neighbors and report changes to the gateway whenever the packet reception rate varies by more than a pre-defined threshold. That information could then be forwarded to the gateway via, *e.g.*, piggybacking.

Change Enforcer

An important question to be addressed is the point in time where a schedule update shall be deployed into the topology. Every schedule deployment comes with a substantial control overhead, which requires time that is taken from, *e.g.*, production.

Being forced to regularly re-deploy the schedule may slow production significantly because of the many halts. A way to approach the problem is to examine the possibility of partial schedule adjustment, where the majority of the schedule remains stable, and only those links that are affected by a substantial quality decrease are effected, for instance, by a re-routing of the content to another neighboring relay node. Identifying such solutions under the consideration of network dynamics may not always be possible; however, where possible, it may result in a more efficient re-deployment.

Link Quality

A major un-addressed challenge is the assessment of channel quality and its collection at the network manager, which requires a training/startup phase where PDRs are measured based on beacon reception statistics among the sensors. Further, because connectivity varies over time, an efficient strategy for the collection of link qualities throughout the lifetime of the network must be in place.

Assessment For SchedEx and the generic framework to operate properly in practice, reliable node-to-node link quality readings must be available. In Article I, it is explicitly stated that SchedEx requires lower bounds for the link qualities between all links used throughout the network lifetime. A PDR, if based on link quality indicator (LQI), received signal strength indicator (RSSI), or another metric received from the physical layer, does not suffice as a means of defining the lower bound because it usually describes a weighted average, which is what can be expected but not what can be guaranteed. Therefore, for networks with heavy link quality variations, a more sophisticated method that rarely or never underestimates the link quality is required. Fig. 5.1 illustrates the need for an offset when making assumptions based on empirical data.

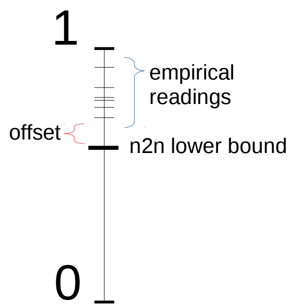

Figure 5.1: To provide valid end-to-end guarantees, the lower bounds for node-to-node PDRs that are used as a basis for scheduling and routing must consider an offset due to the stochastic nature of the channel.

Further, a quick assessment of channel quality over n channels requires an n-times longer training phase. The existing research addresses this problem [FGJL07], even for the case of packets of different sizes [JR15]. Further, in its presented version in the included articles, SchedEx assumes all channels to be of equal quality, which is a limiting assumption. After the assessment of all channel qualities, a selection mechanism is required for the choice in each slot. This also requires both transmitter and receiver to be in sync with the channels at all time.

Collection SchedEx and the GA-based framework are centralized approaches in that they require global connectivity knowledge over the entire network topology to operate. This knowledge has to be collected, which has not been addressed in the articles. Further, the link quality levels have to be constantly reported to the gateway, which requires a control overhead that is not discussed explicitly in the presented research. Without a timely update of link quality levels throughout the network, the gateway cannot produce reliable schedules.

Another natural problem from which centralized approaches suffer is the scalability issue introduced by the use of multiple channels for the assessment of link quality. Assessing and collecting the node-to-node link quality levels between all nodes in the network is already difficult in the one-channel scenario; however, this becomes substantially more difficult when considering up to 15 channels. This can be exemplified by an empirical testing of up to 5000 links in a 50-node network for one channel (50×50), compared to a maximum of 75,000 links for the 15-channel scenario ($50 \times 50 \times 15$). These numbers are extremes, but they hint at the extent of the problem. Methods of experimental design and heuristics combined represent ways to address this problem of exponentially increasing complexity. Approaches such as smart piggy-backing may be investigated, especially because sensor readings are usually of small size, and the payload can be extended by link quality readings in a smart manner.

5.2.2 Network Model - Decentralization

In this thesis, the focus is on QoS for convergecast data flows. For automation and control scenarios, it is crucial that the collected readings arrive in a timely manner at the gateway because of their potential impact on actuators. Given the result from our proposed integrated cross-layer framework, future work must extend the existing work to address the entire loop, including actuators and arbitrary concurrent control flows. Alternatively, a decentralized implementation can be supported by the setup, wherein the flows directly connect sensors and actuators. Regardless, global connectivity information would have to be gathered at a central gateway, as in Fig. 3.1. Given that control metadata are still collected centrally, the proposed framework can be used to identify optimal concurrent flows within the entire network. As a consequence, the control and processing topologies are not equal; they are separated in a way that control information flows in a centralized manner, whereas application data flow in a decentralized manner. Actuators could then be directly connected by wires to the gateway. Alternatively, they can be connected to a wireless sensor that reacts based on the sensor information received by all sensors, of which it requires status information to act. A next challenge is an extension of the formulation for the WSN model, where flows must be manageable in strict orders or dependency graphs. For instance, a flow from sensor t_1 to actuator a_1 is always followed by a control flow from actuator a_2 to actuator a_3. Additionally, conditional flows should be supported, where a flow from sensor t_1 to actuator a_1 either triggers a flow from actuator a_1 to a_2 or alternatively a_3, depending on the value of the packet from t_1. Information should also be forkable, where readings from certain sensors directly go out to multiple receivers subscribing to information in a decentralized setting. In general, a more sophisticated method of modelling flows would be required. The author does not see any reason why SchedEx should not be extendable to that general scenario.

The articles presented in this thesis utilize redundancy in terms of time, where failing transmissions are repeated over the same static pre-defined connection with respect to a given schedule frame. Other redundancy methods, such as redundant sensor nodes that substitute existing nodes once their batteries are drained (seamless hand-over), and multiple or alternative path routing could be investigated.

5.2.3 Joining/Leaving Sensors

In industrial settings, the placement of sensors and actuators usually requires thorough planning, which is vital for the success of the application. This is also why joining or leaving sensors is not a common situation, except where the existing ones are substituted by redundant sensors that measure the same data. Joining and leaving sensors degrade end-to-end QoS, which is why they will be substituted by superior routing and/or scheduling alternatives at an early stage if available. There are surely scenarios where this is relevant; however, in the industrial automation sector, it is here assumed that *important* sensors will remain in the network throughout their lifetime. Otherwise, readings would be lost in their entirety. In addition, because the focus is on mission-critical applications, all sensors are supposed to be important.

5.2.4 Co-Existence

Co-existence of multiple wireless networks sharing the same channels is another challenge and is left un-addressed in this thesis. The existing research has only started to address the challenges of managing channel access for independent wireless networks [WP14]. Especially with the upcoming opportunities related to the Internet-of-Things and Cyber-Physical Systems [WKT11], addressing co-existence is an important requirement if strict end-to-end QOS features such as jitter and reliability are demanded.

5.2.5 Experiments

One of the greatest limitations of the conducted research is that only preliminary experiments with real sensors have been conducted. The preliminary results confirm the correctness of the reliability guarantee in an office-like environment. A next step is to extend the conducted experiments and to investigate the guarantees in an industrial setting. The correctness and scalability of the introduced algorithms have been verified through numerous simulations. However, a real deployment of the proposed generic framework requires multiple non-trivial practical questions to be addressed, including the questions mentioned in this chapter.

Channel models other than Rayleigh fading used throughout all simulations shall be investigated. The issue is not the correctness of SchedEx; it is the evaluation of real industrial deployments to obtain an idea of the potential QoS that can be supported over channels that are largely affected by environmental noise. The investigated signal-to-noise ratios of 50/60 dB used for the simulations were considered to be stable, which is not a generalizable assumption in the industrial context.

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