A Research Roadmap for 6TiSCH towards DetNet

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***Abstract*—Current implementations of the 6TiSCH stack, such as in the operating system Contiki-NG, mainly focus on best-effort traffic. Deterministic flows, in contrast, require strict guarantees in terms of latency, reliability, and robustness. While these requirements are not yet fully addressed in practice, RFC 9030 already specifies functions that extend 6TiSCH with deterministic capabilities, laying the foundation for further enhancements. This paper outlines a research roadmap to advance 6TiSCH towards DetNet. We first highlight the role of cross-layer optimization across routing, scheduling, and channel assignment to balance conflicting objectives such as latency, energy, and reliability. Next, we discuss modeling approaches for reliability and robustness, including mechanisms such as retransmissions, replications, and falsification-based stress testing. Finally, we address real-world validation through hardware experiments and propose extensions to Contiki-NG, focusing on buffer design improvements and enhanced routing through Generalized Multiprotocol Label Switching (GMPLS).**

***Index Terms*—IEEE 802.15.4, IETF 6TiSCH, IETF DetNet, Contiki-NG, multi-objective optimization, cross-layer design, reliability, robustness**

I. INTRODUCTION

Delay-sensitive networking is gaining increasing importance across diverse application domains. Examples include Industry 4.0 and smart grid infrastructures, where timely message exchange is essential to ensure correct system operation. A promising foundation for such applications is the IETF 6TiSCH protocol stack, which builds on the IEEE 802.15.4 standard and is well suited for low-power IoT systems. Its Time-Slotted Channel Hopping (TSCH) mode provides reliable, low-latency communication and thereby establishes the basis for soft real-time applications.

Earlier standards such as WirelessHART and ISA100.11a, both based on IEEE 802.15.4, are tailored to industrial applications and demonstrate the demand for wireless networks with low latency and high reliability. However, their proprietary nature limits flexibility. In contrast, 6TiSCH provides an open and extensible foundation that can evolve to meet both academic and industrial requirements. Building on this foundation, standardization bodies, including the IETF DetNet and RAW groups, are actively working to extend 6TiSCH with deterministic capabilities [1]. In this work, we use the term deterministic networking to denote the envisioned goal of providing strong guarantees on latency, reliability, and robustness, even if such guarantees cannot yet be fully achieved in wireless settings due to lossy connectivity and the unpredictability of the radio medium.

This work outlines a research roadmap to enable deterministic networking in 6TiSCH, structured around three main objectives. First, we investigate the intersection of cross-layer and multi-objective optimization, an area that has received little attention so far. In particular, we analyze whether joint designs can improve latency, energy efficiency, reliability, and schedulability. Second, we address reliability and robustness: while mechanisms such as retransmissions and replications are well known, their integration into a unified optimization model remains an open challenge. To quantify robustness, we also apply falsification by optimization techniques. Third, we validate our approaches on real hardware using the nRF52840 platform, which requires targeted extensions to the Contiki-NG operating system to support the envisioned techniques.

The remainder of this paper is structured as follows. Section II provides background and problem statement, Section III reviews related work, Section IV presents our research roadmap, and Section V concludes.

II. BACKGROUND AND PROBLEM STATEMENT

A. Background on 6TiSCH

The 6TiSCH stack, specified in RFC 9030 [2], provides IPv6 connectivity over the TSCH mode of IEEE 802.15.4. Representative implementations include the Contiki-NG operating system [3] and the OpenWSN protocol stack [4]. In TSCH, time is divided into slots which are grouped into repeating slotframes. Each slot schedules a transmission on one of 16 frequency channels, typically with a duration of 10 ms. RFC 9030 distinguishes between routing and scheduling for best-effort and deterministic traffic. Best-effort traffic commonly relies on the RPL routing protocol together with distributed scheduling schemes such as minimal TSCH [5] or Orchestra [6]. Deterministic traffic, in contrast, is provisioned along Tracks [2], i.e., directed paths with reserved resources. Two variants exist: serial Tracks, which rely on retransmissions, and complex Tracks, which additionally support replication and elimination.

Channel hopping, as defined in IEEE 802.15.4 [7], further improves reliability by iterating over the set of available frequencies H. In each timeslot, the physical channel is selected as

$$CH = H\big[(ASN + o) \bmod |H|\big],$$

where ASN is the global slot counter, o the channel offset of the link, and $|H|$ the length of the hopping sequence.

By assigning distinct channel offsets o to nodes within interference range, transmissions are distributed across different channels, mitigating interference and multipath fading. Resource allocation in 6TiSCH thus involves not only reserving paths, timeslots, and buffers, but also assigning channel offsets. This is typically handled in a centralized fashion, either through a Path Computation Element (PCE) [2] or via Software-Defined Networking (SDN) approaches [8]. IETF DetNet also aims to provide end-to-end deterministic paths across heterogeneous networks, for instance between a 6TiSCH low-power and lossy network and an Ethernet backbone.

B. Problem Statement

Our work primarily addresses time-triggered traffic, in which sources periodically transmit packets to a sink node. Each flow is specified by its period, latency bound, bandwidth demand, and a reliability target in terms of end-to-end packet delivery ratio (PDR). For deterministic networking, the PDR is expected to be close to one. The objective is to allocate all flows without violating these constraints. This constitutes a classic network planning problem, where the goal is to schedule as many flows as possible. We define the fraction of successfully scheduled flows as the schedulability rate and aim to maximize it. Beyond this primary metric, we also consider energy consumption, average latency, and reliability.

III. RELATED WORK

Cross-layer optimization has been widely studied in wireless mesh networks. Prior work includes delay-aware routing and scheduling [9], joint formulations of routing, scheduling, and channel assignment [10], and, more recently, cross-layer approaches for 6TiSCH that integrate scheduling, RPL, and queue management [11]. Our own earlier work [12] compared schedulability rates between isolated and joint routing and scheduling. Related challenges have also been investigated in the context of time-sensitive networking, including models for time-triggered Ethernet [13], models for large-scale deterministic IP networks [14], and heuristics for 1+1 protected DetNet flows [15]. Multi-objective optimization in 6TiSCH networks has been explored through traffic-aware scheduling that balances reliability, latency, and energy [16], as well as RPL extensions for Smart Grids that incorporate latency, residual energy, and link quality [17]. Similar concepts appear in WirelessHART, where multiple energy-related metrics are optimized to extend network lifetime [18].

Reliability in 6TiSCH has been explored mainly through the PAREO family of mechanisms, including ARQ, replication and elimination, and overhearing, which improve robustness at moderate energy cost [19]. To mitigate out-of-order delivery caused by replication, reordering algorithms have been proposed [20]. Similar principles are employed in WirelessHART through graph routing, where packets are transmitted along a primary path with retransmissions and duplicated across alternative paths [21].

IV. PROPOSED ROADMAP

In this section, we outline our research roadmap. First, we explore the benefits of a cross-layer design from a multi-objective optimization perspective and describe our planned contributions in this area. Second, we address reliability and robustness, which are central to deterministic networking. Finally, we consider real-world deployment through planned hardware measurements and extensions to Contiki-NG. Fig. 1 provides a graphical overview of the proposed roadmap, highlighting the interplay between the different objectives and serving as a reference while reading the work packages.

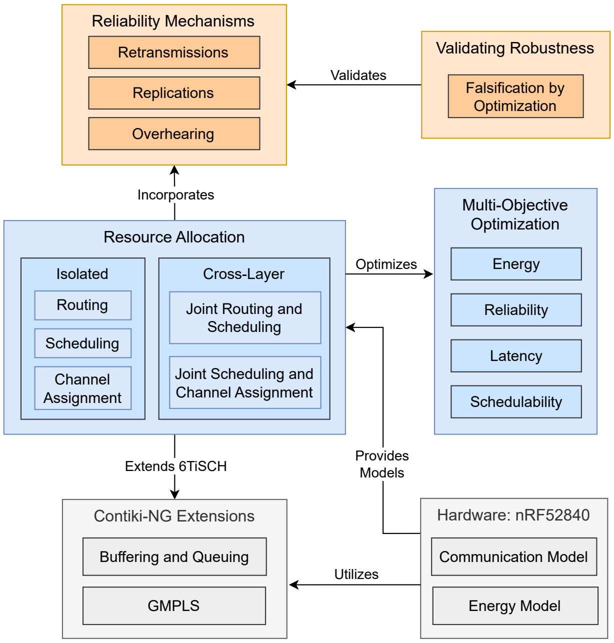

Fig. 1: Research roadmap towards DetNet in 6TiSCH. It illustrates the interplay of cross-layer optimization, reliability and robustness validation, and real-world evaluation. Arrows indicate dependencies between dimensions.

A. Objective 1: Multi-Objective Cross-layer Optimization

1) Optimization Problems and Metrics: Three combinatorial optimization problems arise when allocating resources in 6TiSCH networks: routing, scheduling, and channel assignment. Each problem affects different metrics:

- **Routing:** Influences network lifetime through load balancing, latency through path length, and reliability by selecting high-quality links.
- **Scheduling:** Affects latency and jitter, while also controlling bandwidth through timeslot allocation and energy consumption through duty cycles.
- **Channel assignment:** Reduces interference and thus avoids collisions, which lower reliability and throughput and cause energy-wasting retransmissions.

Traditionally, routing, scheduling, and channel assignment are solved in isolation. While this enables highly specialized and efficient models, it also restricts the overall search space and may exclude promising alternative solutions. Once routes are fixed, scheduling is limited to these paths, and channel assignment is constrained by both routing and scheduling, which can reduce overall solution quality. Cross-layer optimization addresses this limitation by jointly formulating two or more of these problems, thereby expanding the search space and avoiding premature restrictions. In combination with multi-objective formulations, this approach allows explicit and systematic modeling of trade-offs between latency, reliability, and energy efficiency, providing a more flexible basis for analysis and design than isolated methods.

In our research, we will evaluate to what extent joint formulations can outperform separate ones and identify the scenarios in which separate approaches remain more viable. Since all three problems are NP-hard and the number of variables and constraints grows rapidly, runtime is a key concern. To this end, we will employ Integer Linear Programming and Constraint Programming as modeling frameworks.

2) Joint Routing and Scheduling: We first consider the joint routing and scheduling (JRaS) problem, which offers two main benefits. First, it can improve flow schedulability: strict latency bounds depend on both routing and scheduling, and a joint formulation may therefore increase the number of admissible flows. Second, it enables multi-objective optimization of network lifetime and flow latency. Since routing mainly determines network lifetime and scheduling determines latency, their joint optimization allows exploration of trade-offs along the Pareto front. In future work, we therefore aim to analyze the trade-offs between lifetime, latency, and schedulability through a multi-objective optimization model.

3) Joint Scheduling and Channel Assignment: We next consider the joint scheduling and channel assignment problem (JSaCA), which offers several benefits. First, JSaCA directly affects schedulability. Channel assignment is crucial for avoiding collisions: in a DetNet setting, a flow should not be scheduled if it would inevitably collide with another. Ensuring collision-free operation therefore requires careful allocation of timeslots and channels, both of which can be optimized jointly in JSaCA. Second, JSaCA enables minimization of channel utilization, i.e., the number of distinct channels used. This is relevant in practice; for example, if parts of the 2.4 GHz spectrum are occupied by Wi-Fi, the corresponding channels may need to be blacklisted for IEEE 802.15.4 channel hopping. We expect that channel utilization can benefit from JSaCA, since it allows adjustments in both time and frequency. Third, JSaCA also lends itself to a multi-objective formulation: besides maximizing the number of accepted flows, we can simultaneously minimize channel utilization and latency, and explore the resulting trade-offs.

Interference modeling remains a central challenge. To estimate link quality, we rely on the log-normal path loss model described in Section IV-C1. Common approaches to interference modeling include the k-hop and signal-to-noise-plus-interference ratio (SINR) formulations [22]. The SINR formulation is more realistic, as it accounts for the capture effect and permits multiple concurrent transmissions. The k-hop formulation, by contrast, is simpler and excludes all nearby concurrent transmissions, even when they would be feasible. Despite this conservatism, it has two advantages. First, in a DetNet context, avoiding collisions at all costs justifies a cautious model in which only one channel is active within a neighborhood. Second, the k-hop formulation integrates more naturally with Integer Programming and Constraint Programming. For these reasons, we currently consider the k-hop approach more practical for our setting.

4) Other Joint Problems: We deliberately exclude two joint formulations from our current work, while acknowledging their potential for future research. First, the joint routing and channel assignment problem (JRaCA) is not considered, as it cannot be formulated as naturally as JRaS or JSaCA. Channel assignment depends on timeslot allocation during scheduling, which typically lies between routing and channel assignment. Consequently, routing and channel assignment cannot be combined in a straightforward manner. Still, routing clearly influences the spatial structure of the network, which affects interference and thus channel assignment.

Second, routing, scheduling, and channel assignment may be combined into a single formulation. Such a model would offer full visibility of the search space and allow all metrics to be optimized simultaneously. The drawback, however, is the almost inevitable runtime explosion. This raises an interesting research challenge: how to design scalable models that remain applicable to realistic network sizes. In this context, we consider decomposition techniques such as column generation a promising direction. Yet, developing such models remains a substantial challenge.

B. Objective 2: Reliability and Robustness Modeling

To make 6TiSCH networks dependable and suitable for DetNet, two key properties are required: reliability and robustness. In the following, we define these concepts and outline our planned contributions.

1) Reliability Optimization: Reliability is the ability of a system to perform as required, without failure, for a given time interval under specified conditions [23]. In networking, it can be quantified by metrics such as the PDR. In 6TiSCH networks, reliability can be improved mainly through retransmissions and replications. Retransmission refers to resending packets along the primary path, while replication establishes one or more disjoint backup paths, as described in RFC 9030 [2], thereby providing temporal and spatial redundancy. Replication can also be combined with overhearing: since wireless communication is inherently broadcast, neighboring nodes may overhear a transmission. If the intended receiver fails to acknowledge the packet, an overhearing node can immediately forward it instead of waiting for the next retransmission opportunity. This mechanism reduces latency when used, while saving energy when not required.

Building on our previously described work on multi-objective cross-layer optimization, we extend the models to also incorporate retransmissions, replications, and overhearing. Our primary objective is to maximize PDR. Minimizing jitter is also important, since retransmissions and replications can introduce latency variations between flows. Due to the stochastic nature of the wireless medium, link quality is inherently imperfect and packet losses may occur. To capture this effect, we rely on the log-normal path loss model described in Section IV-C1. To the best of our knowledge, no work integrates retransmissions, replications, and overhearing in a unified optimization model.

2) Robustness Analysis via Falsification: Robustness is the ability of a system to maintain correct functionality under conditions beyond its specified operating range [24]. To evaluate the robustness of the reliability mechanisms introduced in Section IV-B1, we stress test them under dynamic disturbances such as moving obstacles, external interference, or malfunctioning nodes. As a first step, we aim to identify the most common causes of errors and their frequency of occurrence. Based on these insights, we plan to systematically measure the robustness of our 6TiSCH network.

For this purpose, we adopt the approach of falsification by optimization (or planning) [25]. In this method, one or more disturbances are deliberately generated and optimized to challenge the system, thereby testing their impact on key performance metrics such as PDR and latency. By exploring a broad spectrum of scenarios, we can derive failure distributions and quantitatively assess the robustness of the network. Falsification by optimization has been widely applied in domains such as automotive, aerospace, and other cyber-physical systems. However, in the context of communication networks, its use remains largely unexplored, making our investigation a novel contribution in this field.

C. Objective 3: Real-world Validation on Contiki-NG

To validate cross-layer optimization and reliability mechanisms, we require a real-world deployment comprising both a hardware platform for network construction and a software stack implementing 6TiSCH. The following subsections describe these components in detail.

1) Experimental Evaluation on the nRF52840: We use the Nordic Semiconductor nRF52840 Dongle [26] as our hardware platform, as it is cost-effective and supported by Contiki-NG. To reflect its hardware characteristics in simulation, we aim to capture RSSI and PDR values under both normal and interfering conditions, as well as its energy consumption. First, to model wireless communication, we use the log-normal path loss model, which relates received signal strength to distance and is well suited for indoor and dense urban environments where multipath and shadowing effects dominate. The path loss in decibels is defined as [22]:

$$PL(d) = PL(d_0) + 10\,\gamma\,\log_{10}\left(\frac{d}{d_0}\right) + X_\sigma,$$

where d is the distance, $PL(d_0)$ the path loss measured at a reference distance d_0, and X_σ a normally distributed random variable with zero mean that models shadowing effects. The parameters γ and σ are estimated from empirical measurements. Hence, we record RSSI and PDR values at varying distances and transmit power levels. In addition to measuring RSSI and PDR under ideal conditions, we also characterize interference behavior in our communication model. Specifically, we experimentally determine RSSI thresholds beyond which transmissions from other nodes cause collisions or become negligible. These thresholds can then be applied in the k-hop interference model described in Section IV-A3.

Finally, we measure the energy consumption of the nRF52840 using the Power Profiler Kit II [27], both under load and in sleep mode. Together, the communication and energy models help bridge the gap between abstract optimization formulations and practical deployment.

2) Contiki-NG Extensions for DetNet: We plan to integrate our proposed mechanisms into the 6TiSCH stack. The most widely used implementation today is provided by the Contiki-NG operating system [3]. However, Contiki-NG currently focuses on distributed resource allocation for best-effort traffic and does not yet implement the Track concept defined in RFC 9030 [2]. Hence, we propose two extensions.

First, we extend the routing layer. RFC 9030 advocates the use of Generalized Multiprotocol Label Switching (GMPLS), an extension of MPLS. In TDMA-based networks such as IEEE 802.15.4 TSCH, a GMPLS label can represent a specific timeslot and channel offset, enabling deterministic forwarding and resource reservation along Tracks. However, GMPLS support is currently missing in Contiki-NG.

Second, we revise the buffering and queuing mechanisms. At present, Contiki-NG maintains a First-In-First-Out (FIFO) queue per neighbor, without prioritization between deterministic and best-effort traffic or among different deterministic flows. Moreover, no dedicated mechanisms exist to handle retransmissions or replications during buffering. To address these limitations, we plan to investigate flow-based buffering in combination with sorted priority queues, thereby enabling deterministic packet scheduling.

V. CONCLUSION

This paper outlined a research roadmap to advance 6TiSCH towards deterministic networking, structured around three main objectives. First, we highlighted the potential of cross-layer, multi-objective optimization to jointly address routing, scheduling, and channel assignment. Second, we discussed reliability and robustness, focusing on retransmissions, replications, and the novel use of falsification by optimization. Third, we emphasized real-world validation through radio model calibration on nRF52840 hardware and targeted extensions to Contiki NG, including Tracks, GMPLS-based routing, and improved buffering and queuing. These contributions aim to bridge the gap between theoretical models and practical implementations of deterministic networking in IEEE 802.15.4, and to provide a platform for future research towards dependable, low-power DetNet solutions.

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