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A Novel Approach to Achieving End-to-End QoS for Avionic Applications

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Abstract: Future Internet of Things (IoT) applications, such as connected industry 4.0, become more challenging with the strict Quality of Service (QoS) requirements, including reliability and delay guarantees. Several mechanisms in the communication stack to match the expected QoS are already discussed and specified at different layers, with the goal to make the communication more reliable. They focus on the layer-specific enhancements. For example, Time-Slotted Channel Hopping (TSCH) is a link layer mechanism to avoid narrowband interference. On the network layer, several multi-path routing schemes are proposed to distribute the traffic load or to have backup paths with the purpose of making data transmissions more robust to link failures.

In addition to the layer-specific improvements, an integration of the cross-layer information can guarantee an end-to-end QoS for communication in dynamic environments. In this work we propose and evaluate a cross-layer framework for cell-disjoint routing, which eliminates overlapping resource scheduling in both time and frequency. It enables the end-to-end QoS for wireless sensor networks under the IPv6 Over the TSCH Mode of IEEE 802.15.4 (6TiSCH). The proposed framework, called 6TiSCH stack with cross-layer information exchange (6TiSCH-CLX), is validated on a selected set of aviation industry applications using both simulations and analytical model.

Keywords: End-to-end QoS, WAIC, TSCH, RPL, Cross-layer, Avionic, 6TiSCH, Wireless sensor networks, Delay minimization

1 Introduction

Modern aircraft uses different communication technologies and a large number of sensors and actuators for the purpose of improving the operations and simplifying the maintenance procedure. However, the current means of communication used for maintenance purposes, for example monitoring the temperature inside the cabin, are still based on wired connectivity. In 2015, the frequency band of 4200 to 4400 MHz was allocated for on-board wireless communication. The currently discussed standard is called Wireless Avionic Intra Communication (WAIC). Three typical scenarios which may utilize the WAIC standard are shown in Table 1. They have heterogeneous requirements w.r.t. number of nodes, delay, traffic prioritization and prevalence.

Table 1: QoS requirements for WAIC simulation scenarios

Name	Latency (upper bound)	Nodes	Priority	Periodicity
Seat status	1s	200	Average	aperiodic
Smoke alarm	1s	30	High	aperiodic
Cabin humidity monitoring	60s	20	Low	periodic

WAIC requires strict transmission power limits to satisfy the highly demanding radio protection criteria from [itu14]. While existing networks fail to meet the QoS requirements from Table 1, the approach presented in this work allows to adapt both routing paths and the link layer scheduling to support QoS demands of different applications. The proposed framework employs TSCH [tsc12], a Time Division Multiple Access (TDMA) channel access scheme in combination with the channel hopping, in the context of *IPv6 Over the TSCH Mode of IEEE 802.15.4* (6TiSCH) stack for wireless sensor networks. The *Routing Protocol for Low power and Lossy Networks* (RPL) protocol enables the routing. Its capability to adapt to a tree based hierarchy reflects the topology in WAIC scenarios. The contribution of this work is twofold: Firstly, the proposed framework, called *6TiSCH stack with cross-layer information exchange* (6TiSCH-CLX), is implemented and evaluated in the event-based OMNeT++ simulator with a full 6TiSCH stack and the Minimal Scheduling Function (MSF). The proposal provides RPL route selection and scheduling at the link layer, ensuring end-to-end QoS-aware communication by exchanging information across the protocol stack layers, in particular between the network layer, network sublayer and the link layer.

Secondly, a mathematical model is developed to analyze metrics such as the end-to-end delay and Packet Reception Probability (PRP). The model allows to quickly obtain expectation and boundary values by varying parameters such as number of hops and link error rate.

2 Cross-Layer Framework

The TSCH Medium Access Control (MAC) is designed to enable reliable communication in a scheduled manner. One *slotframe* in TSCH has a variable length and repeats periodically. Within a slotframe, one or more resources called *cells*, unique in both time and frequency domain, are assigned to each pair of nodes. The TSCH standard does not specify the schedule management, so an appropriate scheduling is required for good network performance. On the contrary, improper scheduling can degrade the network performance significantly, causing cell collisions and delays. To address these issues, we propose a novel cross-layer framework, leveraging RPL topology knowledge and a *6TiSCH Operation Sublayer* (6top) sublayer to construct a collision-free TSCH schedule, while also targeting the QoS in terms of end-to-end delay. Despite numerous proposed centralized [PAD$^+$12] and decentralized [DALW15] scheduling approaches, most of them focus on layer-specific improvements, rather than utilizing a hybrid, cross-layer strategy allowing for more flexibility and better control over the QoS.

Collision Handling: The proposed framework operates in two main phases, aiming to eliminate collisions and minimize end-to-end delay, respectively. In the first phase, cell coordinates for nodes are calculated using their MAC addresses, same as in the MSF. Further, the RPL sink assigns each branch a unique subset of frequency channel offsets for enabling collision-free communication, as highlighted in Figure 1. After phase I, the cells are still allocated randomly along a multi-hop path and a packet experiences considerable delays waiting for the next transmission opportunity, which can be set back to the next slotframe (see Figure 1).

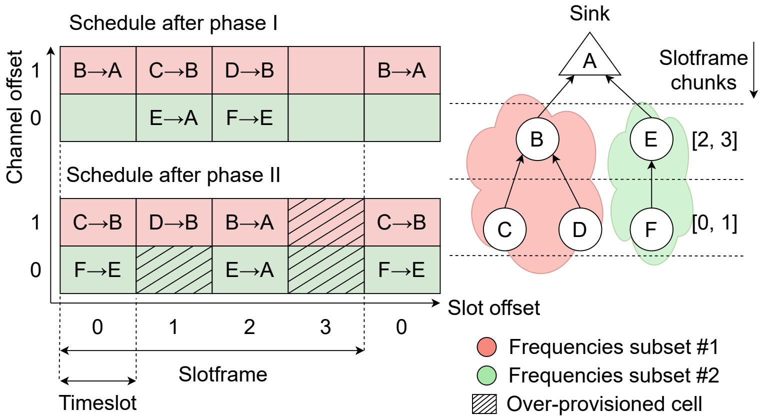

Figure 1: 6TiSCH-CLX scheduling example

End-to-end Delay Minimization: The second scheduling phase addresses the random allocation issue and ensures sink reachability from any leaf node within a single slotframe by actively utilizing the 6top sublayer alongside RPL topology information. The network is split into branches rooted at the sink. Each branch is assigned a unique subset of frequency channels and a full slotframe divided into ordered chunks based on the hop distance of the nodes (see Figure 1). Looking at the phase I random schedule, a packet generated at node C would always wait until the *next* slotframe to reach the sink, because the cell for link $C \to B$ occurs earlier in the slotframe than that of link $B \to A$. In other words, the slot offsets are in descending order for uplink direction. Therefore, in phase II, nodes relocate their cells to align with the chunks boundaries and achieve an ascending sequence of transmission cells — a daisy-chain — starting at the leaf node. Adaptability to traffic patterns is also ensured through cell over-provisioning.

3 Analytical & Simulation Results

To analyze the performance of the 6TiSCH-CLX framework, we develop a model of the network with the PRP and end-to-end packet delay as evaluation key metrics. To assess the impact of randomized cell scheduling the following two formulas can be used:

$$E[d_{qn}] = \sum_{i=2}^{h} i \binom{h-1}{i} \frac{1}{2^{h-1}}, \tag{1}$$

$$f_{PRP} = \left(1 - p_c^R\right)^D, \tag{2}$$

where $E[d_{qn}]$ is the expected queuing delay, caused by the descending sequence of transmission slot offsets along the path of h hops. Each pair of such links increases the queuing time by up to a whole slotframe, which is why the average number of such pairs in Equation 1 is counted based on the total number of hops h. f_{PRP} — PRP distribution based on an assumption, that a packet is delivered successfully if no link along the path of D hops experiences more than the maximum retransmission count R collisions.

To verify the advantages of the 6TiSCH-CLX framework, simulations based on the WAIC use cases from Table 1 are conducted in OMNeT++ with INET framework. Node layouts are shown in Figure 2 and 6TiSCH stack with MSF (6TiSCH-MSF) is used as a benchmark solution.

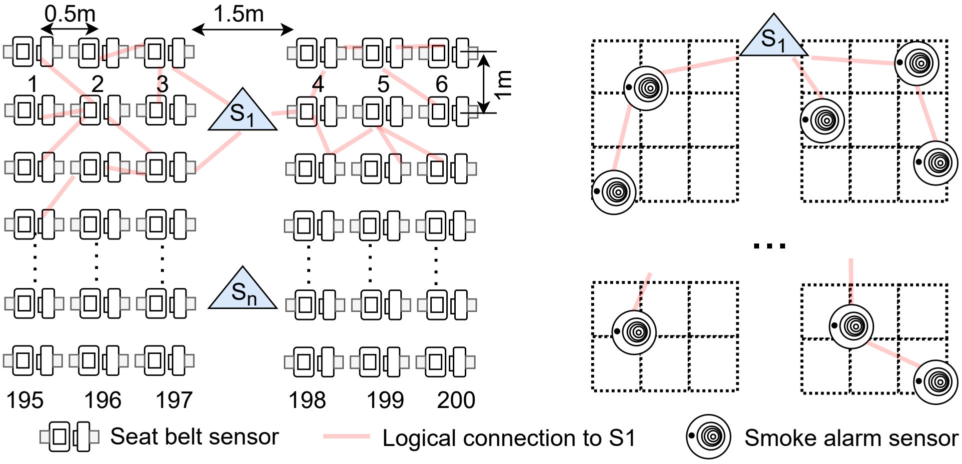

Figure 2: Layout of the simulation scenarios with n sinks in the large-scale seat belt status (left) and one sink in the small-scale smoke alarm and humidity monitoring scenario (right)

The end-to-end delay results for both small and large-scale scenarios are summarized in Figure 3. For the smoke / humidity sensors, the impact of the distance to the sink (hop count) on latency is shown, while for the seat belt sensors, the effect of multiple sinks is investigated additionally. Overall, 6TiSCH-CLX achieves up to a double reduction in latency compared to 6TiSCH-MSF. While 6TiSCH-MSF fails to meet the application requirement of a 1s delay for more than 1 hop away from the sink, 6TiSCH-CLX supports up to 4 hops, after which queuing delays are becoming prevalent. The latency incurred by 6TiSCH-MSF is close to its analytical expectation, with slight deviation caused by the same queuing delays.

The throughput and jitter in the seat belt scenario are visualized in Figure 4. With a single sink, 6TiSCH-CLX achieves slightly higher throughput and lower jitter than 6TiSCH-MSF, due to the lower and more consistent end-to-end delays for each packet.

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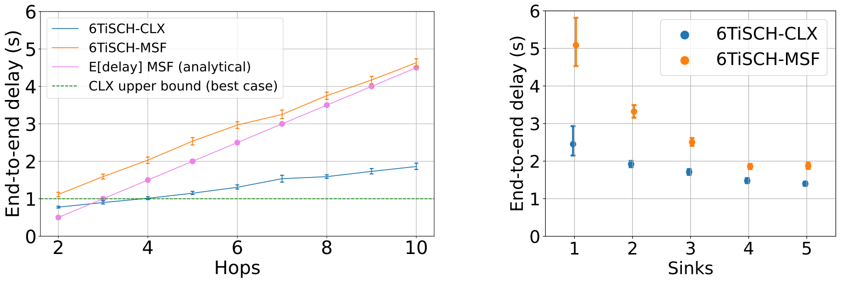

(a) Smoke / humidity sensors

(b) Seat belt status

Figure 3: End-to-end delay for small and large scale scenarios

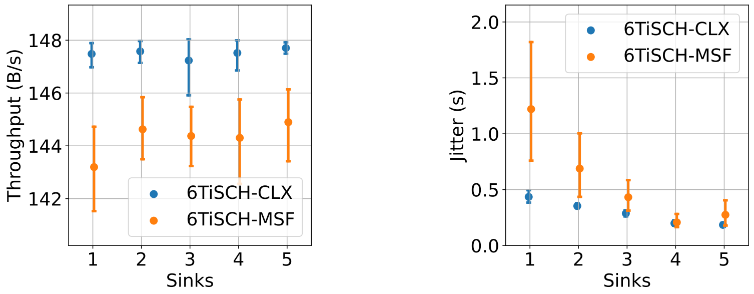

Figure 4: Throughput and jitter in the seat belt scenario

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