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Initial Design of a Generalization of the 6TiSCH Standard to Support Multiple PHY Layers

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Résumé : Ce rapport contient des résultats préliminaires d'une étude pour utiliser plusieurs couches physiques dans un même réseau 6TiSCH. Il s'agit d'une première étape dans le but de publier nos travaux complets, sous le titre (en anglais) "Generalized 6TiSCH for an Agile Multi-PHY Wireless Networking". Ce rapport détaille l'architecture évaluée, et présente les performance de l'approche, en comparaison avec un réseau qui n'utilise qu'une seule couche physique.

Mots-clés : Internet des Objects Industriel, Reseautage Agile, 6TiSCH, OpenWSN.

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Initial Design of a Generalization of the 6TiSCH Standard to Support Multiple PHY Layers

Abstract: This report introduces early results from an experiment to integrate multiple radios in the same 6TiSCH network. It provides an initial step towards the publication of an article tentatively titled "Generalized 6TiSCH for an Agile Multi-PHY Wireless Networking". The work discussed the architecture of the proposed solution, and presents its performance compared to single-PHY networks.

Key-words: Industrial IoT, Agile Networking, 6TiSCH, OpenWSN.

1 Introduction

Applications for industrial wireless connectivity span diverse use cases such as : environmental monitoring [1], smart building [2,3], precision agriculture [4], automated meter reading [5], indoor localization [6], micro-robot connectivity [7], smart grid management [8] and predictive maintenance [9]. They vary in their quality-of-service demands. Some require long range connectivity, while in others, saving battery life is most important.

This diversity in requirements means that different approaches are possible. Short-range radios generally lead to improved battery lifetime and can offer satisfying coverage for some applications involving few nodes within a building-floor [2, 3], a peach orchard [4, 6], or a few single-chip micro-motes [7]. Long-range radios can offer the necessary coverage for deployment spanning multiple km^2 such as a large factory [9] or a power grid [8], at an acceptable trade-off with battery lifetime [10].

The Internet Engineering Task Force (IETF) is organized in Working Groups, some of which standardize IoT protocols. One of these Working Groups works on a group of standards for Industrial IoT cases that demand high reliability : the IPv6 over the Time Slotted Channel Hopping mode of IEEE802.15.4e (6TiSCH) Working Group. At the Medium Access Control (MAC) layer, 6TiSCH uses IEEE802.15.4e in TSCH mode, which is also at the root of industrial wireless protocols such as ISA100.11a and WirelessHART. At the PHY layer, 6TiSCH only supports a single PHY for the entire network. Currently, the chosen PHY for the standard stack is IEEE802.15.4 at 2.4 GHz.

This report is an initial design for generalizing 6TiSCH to support a multi-PHY approach ; we call this "g6TiSCH". In g6TiSCH, nodes dynamically switch between using a low bit-rate and high bit-rate PHY, based on the link quality to each neighbor. We implement g6TiSCH in OpenWSN, the reference open-source implementation of 6TiSCH [11]. In this implementation, we use three PHYs : FSK 868 MHz option 1 at 50 kbps (offering the lowest bit-rate), OFDM 868 MHz option 1 MCS 3 at 800 kbps (offering the highest bit-rate), and O-QPSK 2.4 GHz at 250 kbps as an intermediate option. We experimentally compare the performance of g6TiSCH against the performance of the 6TiSCH architecture with each PHY individually.

2 Testing Setup

To examine the performance of the g6TiSCH architecture, we use the OpenTestbed [12] for experimental evaluation. The OpenTestbed is deployed indoors in an office building at the Inria research center in Paris (floorplan in Fig. 1). The OpenTestbed is composed of 36 OpenMote B boards (shown in Fig. 2). The OpenMote B is a low-power wireless platform that features both a CC2538 SoC (a micro-controller and O-QPSK 2.4 GHz radio) and an AT86RF215 (an FSK 868 MHz and OFDM 868 MHz radio) [13].

The network is run three times with each PHY individually. It is then run a fourth time with the generalized multi-PHY architecture.

3 Experiment Results

This section details the findings from this experimentation.

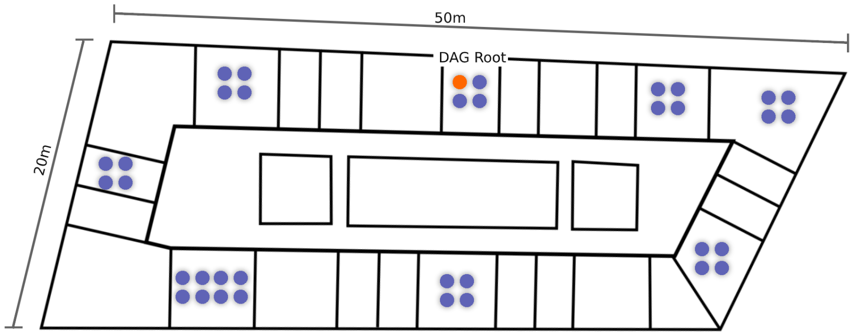

FIGURE 1 – Locations of the 36 motes of the OpenTestbed across an office floor at Inria-Paris. Borrowed from [12].

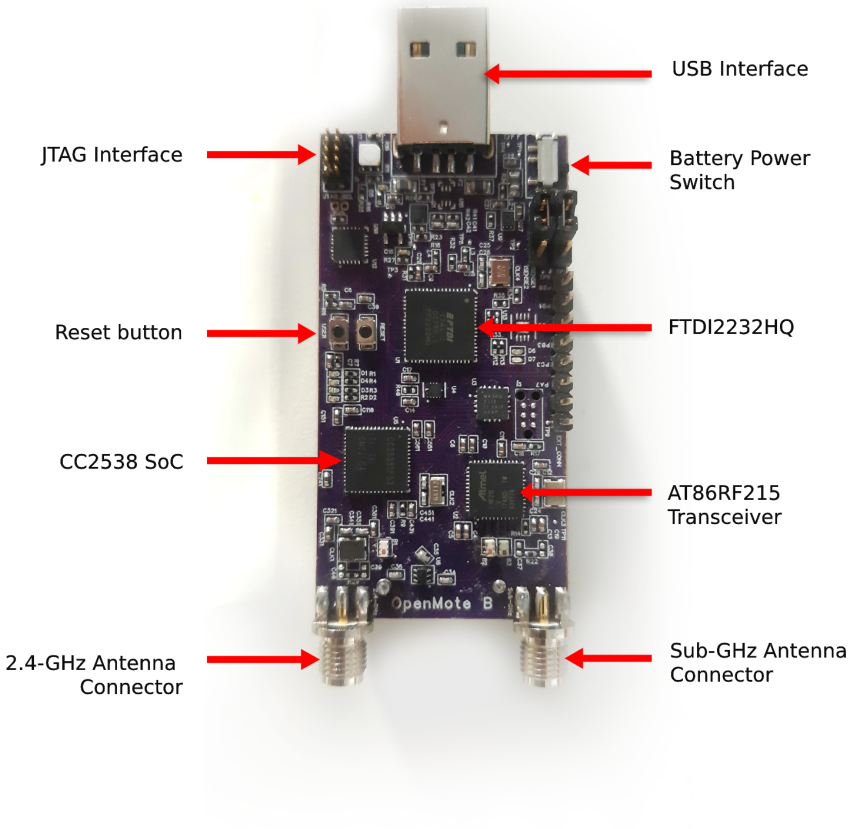

FIGURE 2 – The OpenMote B board with multi-PHY support

FIGURE 3 – The OpenTestbox used for experimental evaluation in the Open Testbed. Borrowed from [12].

3.1 Network Formation

We plot in Fig. 4 the cumulative density of the time-to-first-data-packet from each of the 36 motes in the network. For g6TiSCH, the formation time is in the same order of magnitude as FSK 868 MHz and O-QPSK 2.4 GHz networks in spite of the larger number of available links. This is because the g6TiSCH network dynamically improves its selected PHYs ; its formation time remains within the same efficiency. This can be observed in Fig. 5, which shows the number of PHYs selected for routing as the g6TiSCH network is forming. Multi-PHY neighbor discovery enables the network to combine the advantages of each PHY. Therefore, this leads to robust network formation.

3.2 End-to-end Latency

Fig. 6 is a time-domain plot of the end-to-end latency in the network. The cumulative density of all the packets, during steady state, is shown in Fig. 7. The g6TiSCH architecture exhibits a latency improved over that of each single-PHY network.

3.3 End-to-end reliability

Table 1 shows a statistical summary for the PDR for all motes in the last 30 min for each network. We note that the FSK 868 MHz network outperforms O-QPSK 2.4 GHz, which is consistent with the previous observation in [14].

Packet loss can occur from packets being dropped because of buffer overflow. Fig. 8 shows the maximum buffer size captured in the network. Both g6TiSCH and FSK 868 MHz show lower memory footprint than O-QPSK 2.4 GHz and OFDM 868 MHz, 30 min into the experiment.

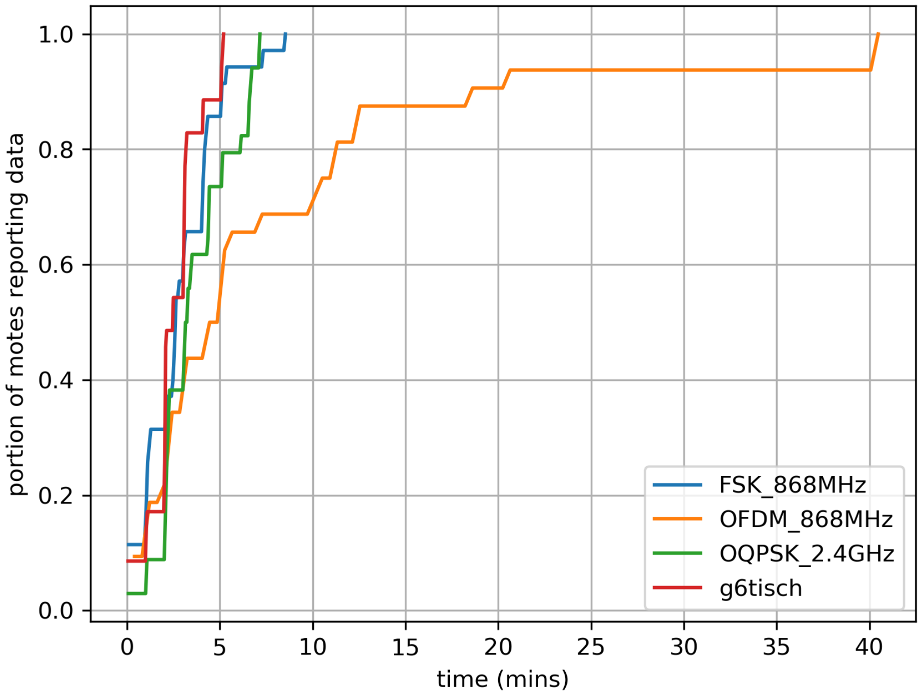

FIGURE 4 – Dynamic selection among multiple radios allows keeping the network formation time within the same order of magnitude as FSK 868 MHz network.

TABLE 1 – End-to-end Packet Delivery Ratio (PDR) statistics over all motes in the network, computed over the last 30 mn of the experiments.

	Min	**Average**	**Median**	**Max**	**StDev**
FSK 868 MHz	100.0%	100.0%	100.0%	100.0%	0.0%
OFDM 868 MHz	100.0%	100.0%	100.0%	100.0%	0.0%
O-QPSK 2.4 GHz	96.7%	99.7%	100.0%	100.0%	0.96%
g6TiSCH	100.0%	100.0%	100.0%	100.0%	0.0%

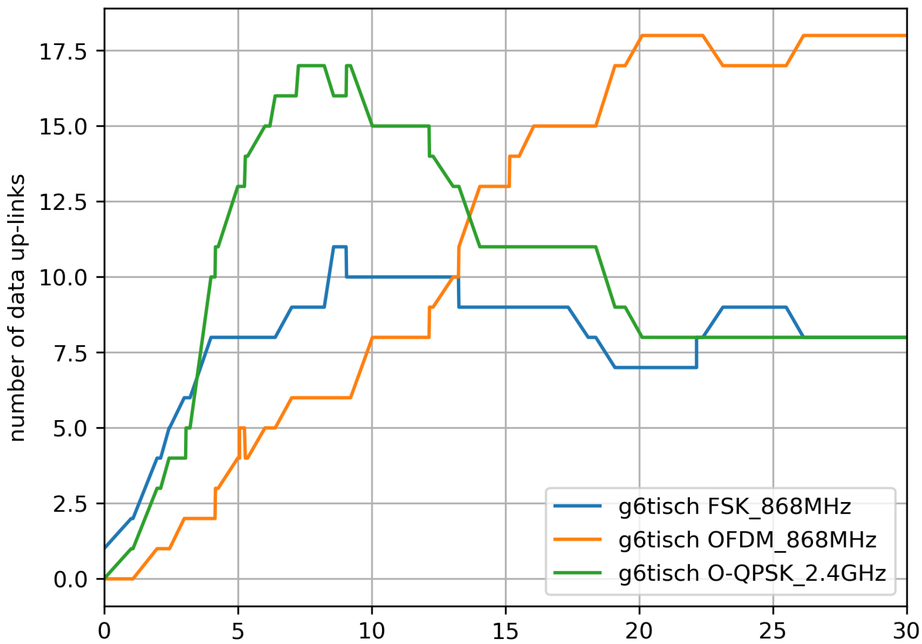

FIGURE 5 – As the g6TiSCH data collection tree is forming, it routes up-link traffic over diverse PHYs.

3.4 Battery lifetime

Fig. 9 shows the evolution of the transmit duty cycle in the network over the duration of the experiment. g6TiSCH shows an overall lower radio duty cycle than FSK by nearly 30%.

It is interesting to see the benefit g6TiSCH brings to RPL as it dynamically switches to parents with faster bit-rates when possible. The impact can be seen in Fig. 10 as we observe that the duty cycle of FSK 868 MHz and O-QPSK 2.4 GHz keeps decreasing over time, along with a slight increase in OFDM 868 MHz duty cycle. This is because the g6TiSCh objective function switches to parents with faster bit-rates as the topology converges.

Fig. 11 shows the expected battery lifetime at steady state for g6TiSCH compared to each single-PHY network. FSK 868 MHz has the shortest lifetime (compared to O-QPSK 2.4 GHz and OFDM 868 MHz), which was expected as it has the lowest bit-rate.

g6TiSCH demonstrates generally better lifetime than the FSK 868 MHz network thanks to the overall lower duty cycle.

4 Conclusions

This report presents an initial design of a generalized 6TiSCH architecture for multi-PHY wireless networking. This approach adds agility to the protocol stack : nodes use multiple physical layers within the same network, and adapt their links depending on their conditions. Compared to a single-PHY solution, experiments of g6TiSCH show faster network formation and lower latency, while maintaining wire-like end-to-end reliability. This is achieved by dynamically switching to faster bit-rates when possible, while maintaining latency and reliability performance.

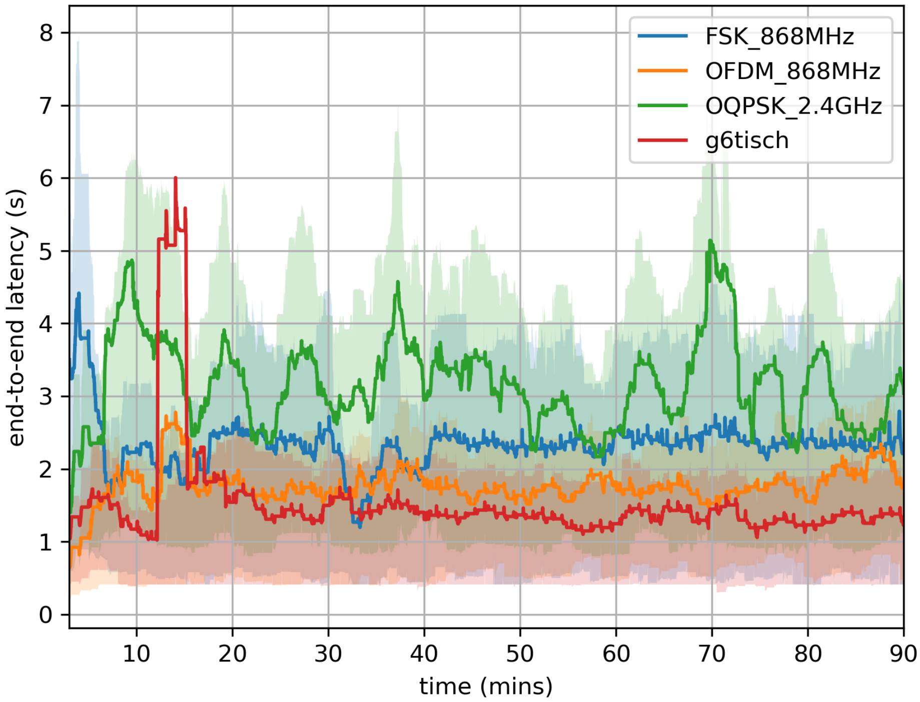

FIGURE 6 – Using multiple radios at the same time yields lower end-to-end latency than using a single radio.

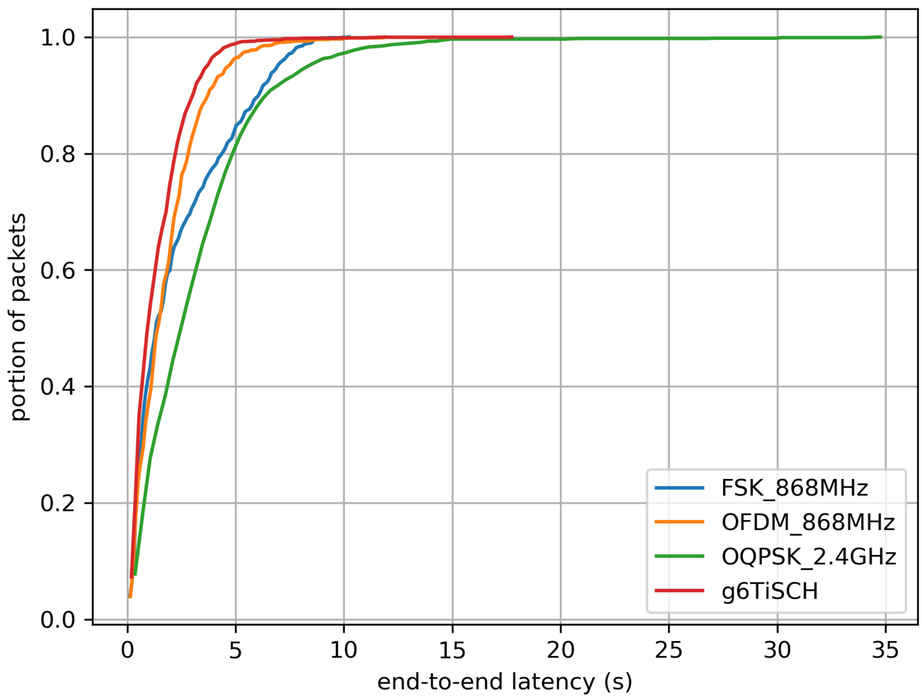

FIGURE 7 – Cumulative Density Function of end-to-end latency, at steady state.

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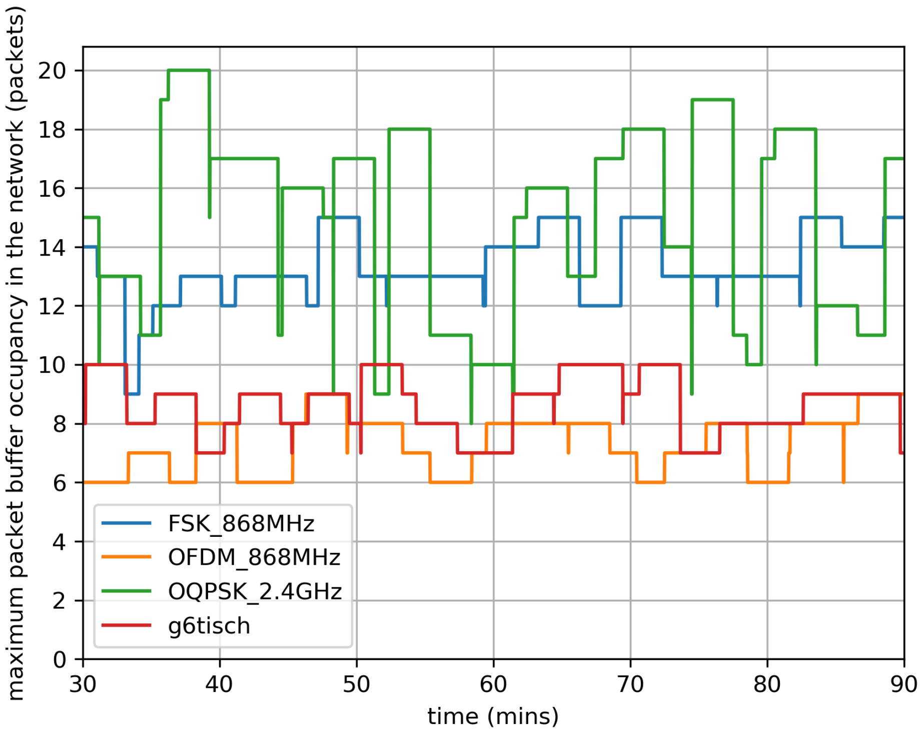

FIGURE 8 – Improved overall link quality in g6TiSCH leads to efficient buffer usage due to fewer re-transmissions and forwarding. The buffer can hold up to 15 data packets (and 5 reserved entries). Packet buffer is efficiently used and packets are not dropped because of buffer overflow.

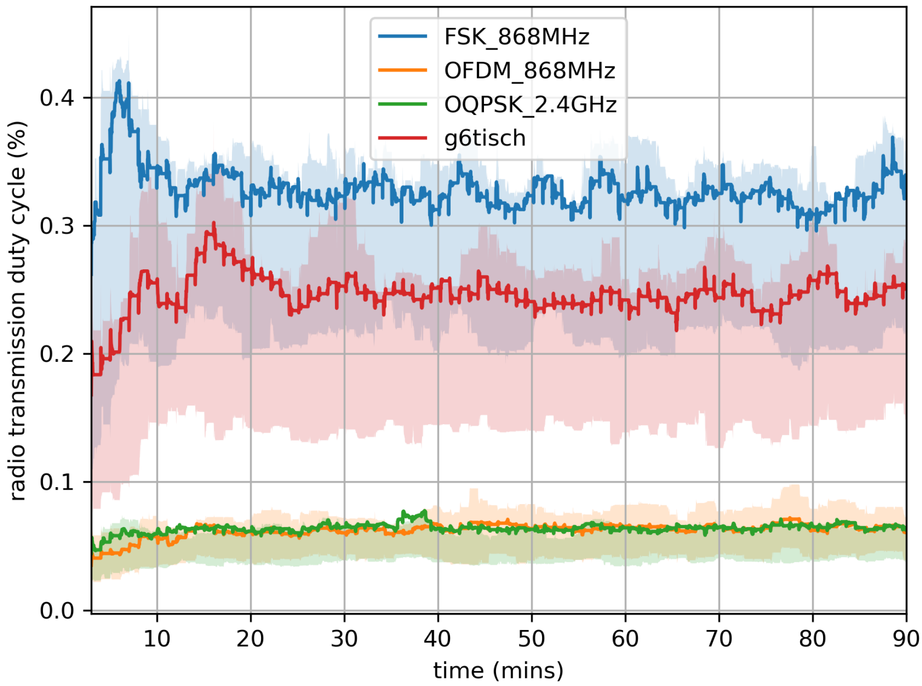

Figure 9 – Diversity of radios allows overall lower radio duty cycle compared to a pure long range FSK 868 MHz network.

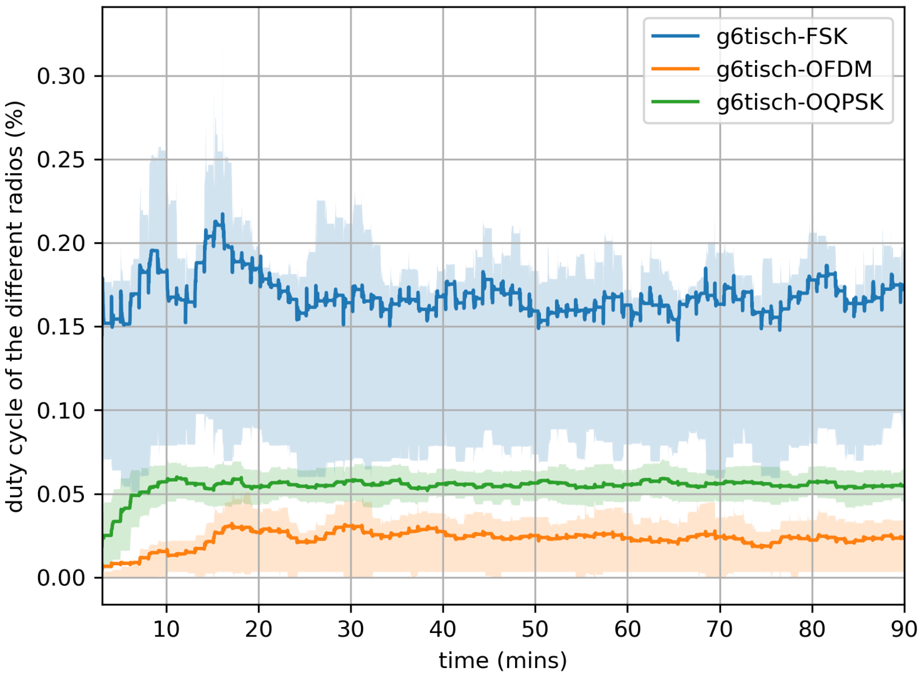

FIGURE 10 – Over time, the objective function favors the use of OFDM 868 MHz over FSK 868 MHz and O-QPSK 2.4 GHz, saving on the transmission radio duty cycle.

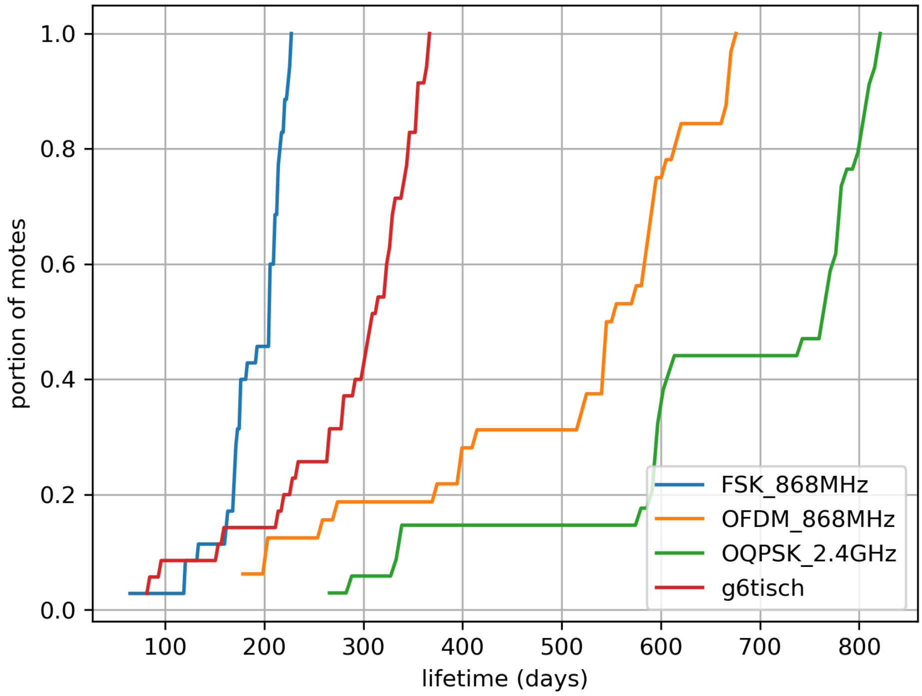

FIGURE 11 – CDF of battery lifetime in the network demonstrates the g6TiSCH improving the energy footprint of the network compared to a pure long range FSK 868 MHz network.

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