Baddeley, M., Aijaz, A., Raza, U., Stanoev, A., Jin, Y., Schuß, M., Boano, C. A., & Oikonomou, G. (2021). 6TiSCH++ With Bluetooth 5 and Concurrent Transmissions. In *International Conference on Embedded Wireless Systems and Networks (EWSN 2021)* (pp. 25-30) https://doi.org/10.5555/3451271.3451274

6TiSCH++ with Bluetooth 5 and Concurrent Transmissions

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Abstract

Targeting dependable communications for industrial Internet of Things applications, IETF 6TiSCH provides mechanisms for efficient scheduling, routing, and forwarding of IPv6 traffic across low-power wireless mesh networks. Yet, despite an overwhelming body of literature covering autonomous, centralized, and distributed scheduling schemes for 6TiSCH, the design of an effective control solution remains an open challenge. Our paper fills this gap with a novel multi-PHY approach that eliminates much of the 6TiSCH routing and link-layer overhead. Specifically, we leverage the physical layer (PHY) switching capabilities of modern *single-radio, multi-protocol* wireless platforms to build on recent work highlighting the viability of CT-based flooding protocols across the Bluetooth 5 (BT 5) PHYs, demonstrating the feasibility of *single-radio* devices injecting a BT 5-based CT flood within a standard IEEE 802.15.4 TSCH slotframe. We present experimental evaluation and analytical modeling showing how our solution can exploit BT 5's high data-rate PHYs for rapid data dissemination, while the coded PHYs can provide reliable 6TiSCH association and synchronization even under external RF interference. We further discuss how the proposed technique can be used to address other open challenges within 6TiSCH.

1 Introduction

The Time Slotted Channel Hopping (TSCH) MAC layer option in the IEEE 802.15.4-2015 standard provides a mechanism to escape external RF interference, follow optimal transmission schedules, and improve network scalability and throughput by allowing co-located nodes to transmit on orthogonal channels. However, TSCH does not specify how a schedule should be built and maintained. IETF 6TiSCH [1] bridges this gap: by defining default functions for creating and disseminating a schedule, 6TiSCH is able to offer service guarantees to IPv6 routes across the mesh through efficient allocation of radio and network resources. Still, the design of an efficient mechanism for 6TiSCH control signaling remains an open challenge, and there exist relatively few examples of successful real-world deployments. Although wireless mesh networks have found application in smart metering [2], within industrial use-cases they are often merely employed as range extender for cellular systems [3]. While the efforts of 6TiSCH have been considerable, it is impossible to ignore the fact that maintaining mesh networks remains incredibly complex depending on the environment and application, while other wireless solutions tend to 'just work'. Indeed, the lack of means to efficiently disseminate centrally-computed control signaling poses a significant obstacle to the adoption of concepts such as Software Defined Networking (SDN), currently defined within the standard [1].

Subsequently, there has been considerable interest in two highly promising areas. Firstly, developing protocols based on Concurrent Transmissions (CT), where nodes synchronously transmit in-contention with their neighbors. Although conventional wisdom would suggest that contending transmissions will not be demodulated at the receiver, a number of physical layer (PHY) effects [4, 5] and considerable MAC layer redundancy ensure high probability of a correct reception. Multiple editions of the EWSN dependability competition [6] have also shown that CT-based flooding protocols outperform conventional approaches across a number of key performance metrics, even under external RF interference. Crucially, as they rapidly flood the network with high probability, CT protocols eliminate reliance on distributed control signaling and therefore address the routing and scheduling complexity seen in standard mesh solutions. Secondly, the advent of modern *single-radio, multi-protocol* wireless platforms has prompted recent interest in multi-PHY wireless solutions. In particular, the four PHYs available in BT 5 provide a suite of options for industrial low-power wireless use-cases, providing both high data-rate and long-range coded options within an already pervasive industry standard. Furthermore, for CT-based flooding protocols, recent research has highlighted the sensitivity of CT to the choice of underlying physical layer and network environment [7], establishing a strong argument for switching the PHY at runtime.

Our contributions. We propose 6TiSCH++ (6PP), a multi-PHY control solution for the IETF 6TiSCH low-power industrial wireless standard, in which we exploit recent advances in CT flooding protocols [8] alongside PHY switching capabilities of modern *single-radio, multi-protocol* wireless chipsets [9]. Our solution disseminates network configuration and synchronization information over the CT layer, and thus eliminates much of the routing and link-layer signaling overhead that hinders current 6TiSCH solutions. Crucially, 6PP demonstrates the feasibility of runtime switching between the BT 5 high data-rate and coded PHY options (as well as the classical IEEE 802.15.4 PHY) in a manner amenable to the standard. Fig. 1 demonstrates how 6PP still fits neatly within the standard 6TiSCH stack. We argue that CT-flooding over the high data-rate (1M and 2M) BT 5 PHYs addresses the challenge of how to provide rapid and reliable distribution of packets within a 6TiSCH network (for example, to provide firmware updates over the mesh), while switching to the BT 5 coded PHYs can provide robust network synchronization even under external RF interference.

Outline of this paper. After providing a primer on relevant aspects of 6TiSCH and CT, Sect. 2 relates 6PP to existing works. The rest of this paper is structured as follows.

- Sect. 3 outlines the design and technical aspects of 6PP.
- In Sect. 4 we validate our solution on the D-Cube testbed [10] and demonstrate how 6PP is capable of disseminating both 6TiSCH and RPL control signaling across the entire mesh with minimal latency.
- Sect. 5 provides simulation-based evaluation demonstrating how encapsulating a CT-based flood within the slotframe can significantly improve data dissemination latency and reliability within a 6TiSCH network.
- Finally, Sect. 6 gives directions and insights on how this work may be taken forward in future research as well as standardization activities, and concludes this paper.

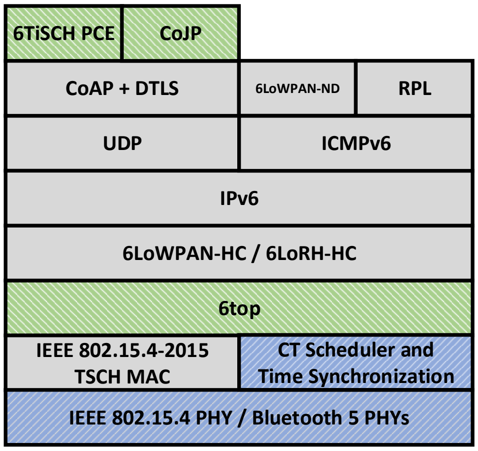

Figure 1: 6PP stack with respect to the 6TiSCH standard.

2 Background and Related Work

We provide a brief overview of key aspects in both 6TiSCH and CT that are relevant to this paper. For a detailed examination of 6TiSCH we direct the reader toward [1, 12], whereas for a survey of CT-based protocols and the underlying PHY phenomena underpinning CT we refer to [7, 8, 13, 14].

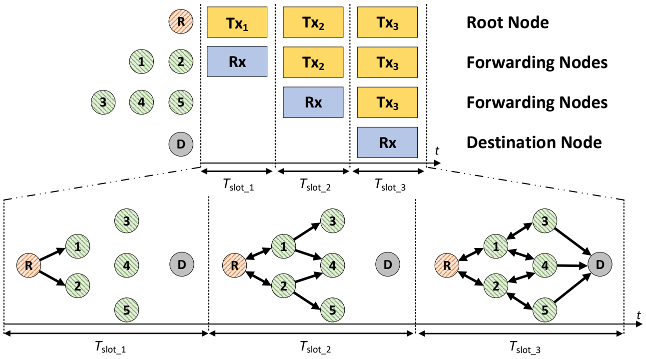

Figure 2: Time-triggered CT flood [11].

Centralized mesh control. 6TiSCH provides mechanisms for both *centralized* and *distributed* scheduling of the TSCH slotframe resources. Specifically, 6TiSCH differentiates between centrally allocated *hard* cells, and *soft* cells that are negotiated between neighboring nodes on a hop-by-hop basis across the underlying layer-3 topology. Yet, there are acute complexities in managing the signaling required to centrally provision networking and radio resources across a multi-hop mesh network. In addition to unreliable multi-hop links, the tree-like graphs formed by the commonly-employed RPL protocol [15] result in funneling effects that can cause severe delays and jitter near the root. Indeed, *downward* messaging, i.e., multi-hop messages *from* the root *to* nodes further down the tree, are an historic weakness in mesh networks [16].

Synchronization, bootstrapping, and routing. Within TSCH, synchronization is achieved through the inclusion of Information Elements (IEs) within Enhanced Beacons (EBs) and Keep Alive (KA) messages. Specifically, EBs are periodically sent by neighbors to synchronize joining nodes through the IE, as well as provide information on the configuration necessary to bootstrap and securely join the network. Once joined, IEs are again employed within KAs to maintain synchronization and compensate drift [12].

While RPL supports lightweight mechanisms for joining a tree-like graph for sending messages *upwards* towards the root, *downward* messaging involves a two-way handshake across multiple hops, with nodes declaring their existence through Destination Advertisement Object (DAO) messages, which are repeatedly sent to the root until the node receives an acknowledgment (DAO-ACK). As a network scales, DAOs sent by nodes further away are therefore subject to greater uncertainty, while poor links at bridging nodes can potentially occlude whole subsections of the network.

Crucially, the periodic nature of EBs and KAs means they represent a considerable portion of the overall 6TiSCH control messaging overhead, while the unreliable nature of RPL downward messaging can result in multiple DAO retransmissions to the root node in the event of missed DAO-ACKs – a significant issue in networks with unreliable links or high RF interference [16].

Concurrent Transmissions (CT). By *intentionally* scheduling nodes to transmit in-contention with their neighbors, CT-based protocols rapidly disseminate packets across a multi-hop mesh networks. Fig. 2 demonstrates how time-triggered

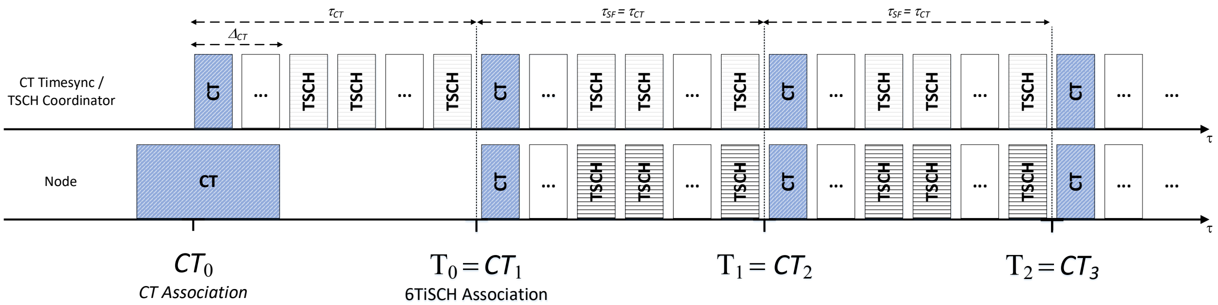

Figure 3: In 6TiSCH++, IEEE 802.15.4 EBs are flooded over BT 5-based CT to quickly synchronize and associate 6TiSCH.

back-to-back node transmissions [11] are initiated by the arrival of a correct reception from neighboring nodes. Packets are thus disseminated within theoretical minimal bounds on latency (as dictated by the data rate of the underlying PHY). However, while the majority of CT literature has been based on the 2.4 GHz IEEE 802.15.4 OQPSK-DSSS PHY [13], recent research has demonstrated CT over the BT 5 PHYs [8, 14]. With modern low-power wireless platforms supporting multiple PHY options on a single chip (such as the Nordic nRF52840 [9], which supports both the IEEE 802.15.4 OQPSK-DSSS and all four BT 5 PHYs), there is emerging interest in the development of CT protocols which leverage these multi-PHY features [7]. Furthermore, as these chipsets allow physical layer switching with *no additional radio overhead*, CT-based scheduling architectures [17, 18, 19] (which provide time-triggered scheduling services for a variety of CT-based protocols) are uniquely placed to offer multi-PHY scheduling solutions as they abstract the complexities of writing bare-metal CT-based protocols.

Related literature. While previous works have proposed integration with CT-based flooding protocols as a means for reliable and low-latency data dissemination within IEEE 802.15.4 TSCH networks [19, 20] there has been limited practical demonstration. Gomes et al. [21] have proposed IEEE 802.15.4 CT-based flooding within a TSCH slotframe as part of a solution submitted to the EWSN Dependability Competition [6]. However, this work did not target a 6TiSCH implementation (which would not have been possible on the legacy hardware [22] used in initial editions of the competition). More recently, and particularly relevant to this paper, Istomin et al. [23] have examined the use of CT to carry *downward* RPL traffic in asynchronous CSMA/CA IEEE 802.15.4 networks, while retaining routing-based transmission for *upward* traffic; thus successfully building on the strengths of both approaches. Aijaz et al. [24] similarly demonstrate the applicability of BT 5 CT as a mechanism for single-hop cooperative transmissions and multi-hop time-synchronization alongside a secondary optimized transmission schedule, drawing on similar reasoning to the arguments presented in this paper. However, this approach does not address the considerable challenges of 6TiSCH integration. Moreover, while Zimmerling et al. have previously proposed adaptive CT solutions based on application requirements [25], their efforts do not take into account recent works demonstrating the considerable impact of the underlying PHY on CT performance, and showing that the IEEE 802.15.4 PHY can be sub-optimal depending on network dynamics and RF environment [7, 14]. Finally, a recent survey [13] speculates on current research challenges, decoupling CT-protocols using dual-processor platforms, and future routes to standardization, thereby supporting the fundamental reasoning behind this work.

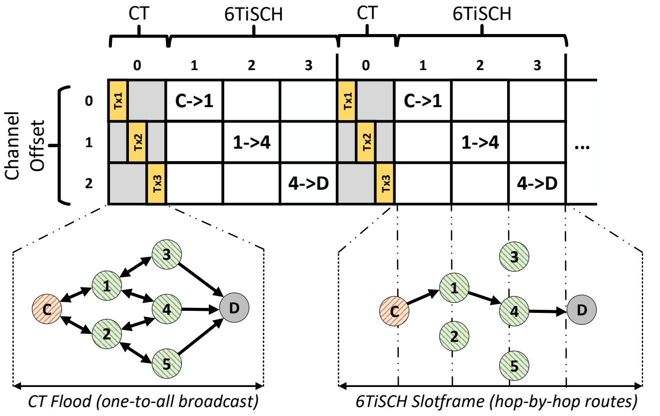

Figure 4: In 6PP, CT floods are interleaved within the slotframe.

To the best of our knowledge there has been no study proposing the use of BT 5 CT-based data dissemination in 6TiSCH networks, and ours is the first work to successfully demonstrate encapsulation of a CT flood within the IEEE 802.15.4 TSCH slotframe.

3 6TiSCH++: Concurrent MAC Scheduling

6TiSCH was primarily designed for low-power, low-rate communication over IEEE 802.15.4. As such, 6PP retains IEEE 802.15.4 for application traffic while addresses weaknesses in control dissemination through the introduction of CT-based flooding. However, recent literature has demonstrated that CT is particularly sensitive to the choice of PHY layer [7]. While this solution benefits from the obvious advantages of CT flooding, the multi-PHY approach advocated by 6PP allows the system to use the most appropriate PHY option for the current task at hand. For example, the BT 5 long-range 125K PHY option could be used to achieve reliable network association in harsh environments, while the BT 5 high data-rate 2M option could be used to rapidly deploy firmware updates[1]. 6PP is therefore designed around the careful and cooperative interleaving of periodic CT floods

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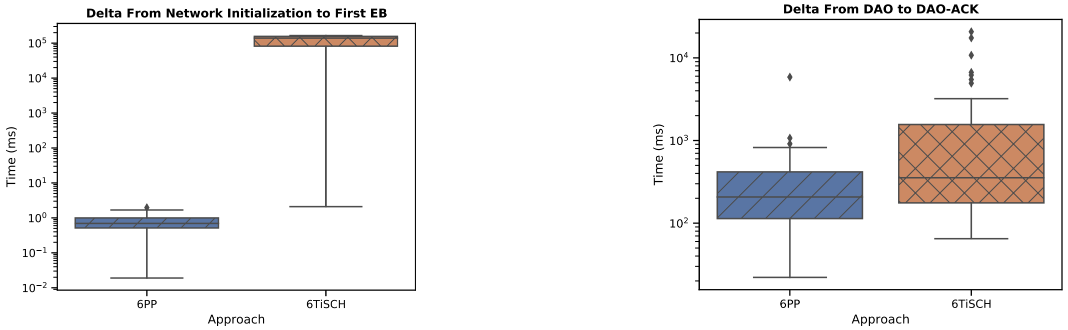
[1] Please note that, in principle, one could also just use IEEE 802.15.4 to carry out both CT and 6TiSCH communications, i.e, the use of BT 5 is not strictly required by 6PP to implement CT.



(a) Time taken for all D-Cube nodes to associate to the first EB.

(b) Timedelta from sending a DAO to receiving a DAO-ACK.

Figure 5: Time taken to (a) associate and (b) establish *downwards* routes on D-Cube (48 nodes over ≈10-hops).

Approach	**Reliability (%)**	**Mean Latency (ms)**
6PP (No Interf.)	100	250.60
6TiSCH (No Interf.)	100	403.96
6PP (With Interf.)	99.54	329.58
6TiSCH (With Interf.)	98.63	527.64

Table 1: Reliability and latency for 6PP and 6TiSCH in D-Cube's 20-node dense data dissemination scenario.

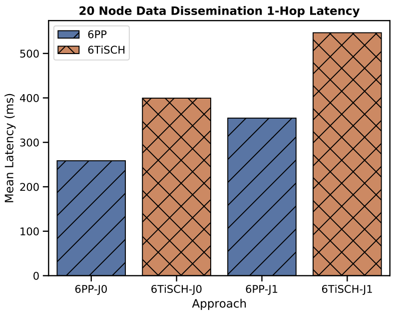


Figure 6: Mean latency from Table 1 – *without* (J0) and *with* (J1) external narrowband interference.

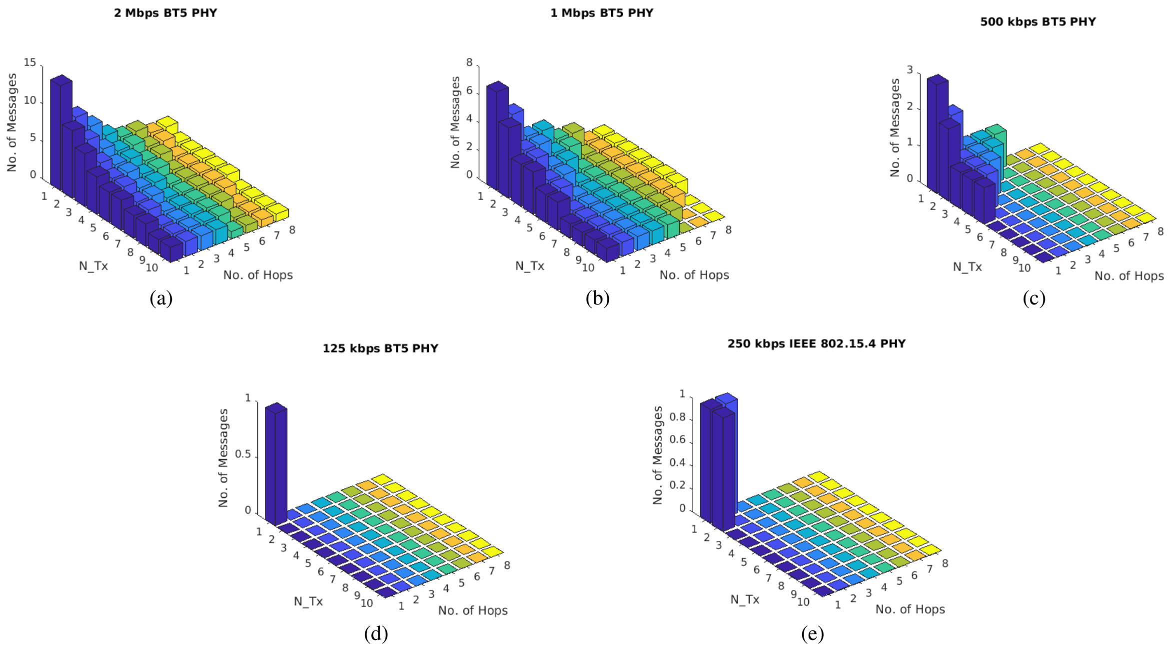
within a 6TiSCH slotframe – demonstrated in Figs. 3 and 4. The CT flooding layer is scheduled within dedicated 'free' slots of a slotframe, while remaining slots are delegated to the 6TiSCH scheduler. By separating the operation of both layers while maintaining synchronization, it is possible to switch both the MAC and physical layer in *real-time*, with only a 40μs radio ramp-up time as overhead [9]. Fig 4 shows a high-level example of this approach, while Sect. 5 later explores how the CT layer is able to perform many transmissions in the time it takes to complete a single 6TiSCH 10ms slot.

6PP employs a variation on the standard 6TiSCH minimal configuration [26]. 6TiSCH minimal bootstraps the network with a basic schedule that provides a single shared slot for all data, synchronization, and advertisement. This allows nodes to associate to the network, maintain synchronization, as well as transmit and receive data. In this manner, a slotframe size of 1 (i.e., back-to-back TSCH slots) would be equivalent to slotted CSMA, while increasing the slotframe size retains the single shared slot but leaving the remainder of the slotframe empty – saving energy. 6PP denotes a new CT designated link type at the start of the slotframe and reserves the number of equivalent 10 ms TSCH slots spanned by Δ_{CT}. However, rather than leaving the remainder of the slotframe free (as in 6TiSCH minimal), 6PP populates the rest of the slotframe with N shared slots. We stress however, that although 6TiSCH minimal is used to validate the fundamental approach of 6PP (in Sect. 4 we compare against a 6TiSCH minimal configuration with slotframe size 1), the 6PP CT slot reservation mechanism could be applied to any other (dynamic) 6TiSCH scheduler. In such a case, hard cells would be allocated upon joining the network to ensure that the 6PP slots are kept free for scheduled CT floods, and we propose this as a future research topic in Sect. 6.

Fig. 3 shows the association and bootstrapping process of 6PP. A single node is designated as *both* the CT timesync and the 6TiSCH coordinator. The joining and synchronization information contained within EB messages, usually sent on a hop by hop basis, is instead disseminated rapidly across the entire mesh through the CT flood. Once synchronized with the CT timesync, joining nodes set the reference time of the IEEE 802.15.4 TSCH timer from the reference time captured by the CT scheduler (CT_0), and set a CT flooding period equivalent to the duration of the pre-configured 6TiSCH slotframe duration such that $\tau_{CT} = \tau SF$. Successful CT association subsequently starts the TSCH association process, while disassociation from the CT network likewise disassociates the node from the TSCH network (and RPL DAG). Drift correction is performed every flooding period by compensating the TSCH reference time from the CT scheduler. In this manner, 6PP removes the need for KA messages, and further reduces the control signaling overhead within the mesh. Finally, building on a similar approach taken in [23], 6PP disseminates RPL DAO-ACK messages over CT floods. This allows 6PP to reliably and rapidly establish *downward* routes, which is a well-known challenge in wireless mesh networks [16]. In this manner, 6PP demonstrates the feasibility of associating and maintaining a 6TiSCH network through BT 5-based CT flooding, while further integration of the two layers is recommended as an area for further research.

4 Experimental Validation

Experiments were run on the D-Cube [10] testbed using the nRF52840 all nodes (layout 4) and dense (layout 3) dissemination scenarios alongside narrowband RF interference generation (jamming level 1). In this paper, 6PP uses a modified version of the Atomic-SDN CT scheduling architecture [19], which has recently been extended to support CT-



(a) (b) (c) (d) (e)

Figure 7: Number of distinct messages that can be transmitted within a 10ms TSCH slot for each nRF52840 PHY option.

based protocols over the four BT 5 PHYs [7] and incorporates recent nRF52840 support from Contiki-NG[2]. However, the 6PP approach could also be replicated on other CT scheduling architectures such as Baloo [18].

Association and destination advertisement. Fig. 5a shows the time taken for all nodes to to receive their first EB (i.e., the latency of network association). In 6PP, 6TiSCH's EB beaconing mechanism is replaced with centrally-broadcast EBs flooded over CT from the timesync/coordinator. As CT-based protocols intentionally contend and allow a message to be fully broadcast across the network with minimal latency, 6PP nodes are able to synchronize and associate with the network in a fraction of the time required in traditional 6TiSCH networks, and furthermore allows nodes to directly synchronize with a single timesource (as opposed to their neighbor). Fig. 5b shows the delta between a node sending a DAO to receiving a DAO-ACK from the coordinator. In this case, while DAO's are still sent *upwards* over the layer-3 RPL links, 6PP returns centrally computed DAO-ACKs as CT floods from the coordinator. By broadcasting DAO-ACKs in this fashion (as also demonstrated in [23]), it reliably establishes RPL *downward* routes more quickly than a hop-by-hop approach.

Reduction of control signaling. 6PP benefits from the network-wide reduction in control signaling. As EBs are sent over a CT flood, this becomes the default mechanism for synchronization, allowing 6PP to completely dispense with 6TiSCH's KA messaging and thus freeing up the 6TiSCH slotframe. In Table 1 we examine the performance of 6PP in D-Cube's dense data dissemination scenario. Furthermore, we employ JamLab-NG [27] to provide external narrowband radio interference. In this scenario, 64B messages are periodically generated at 5s intervals by the testbed and are disseminated from the coordinator to 20 nodes in a dense cluster. Even under the external interference conditions, both 6PP and 6TiSCH demonstrate high reliability due to channel hoping mechanisms over both the CT flood and the 6TiSCH slotframe (as previously shown in Fig. 4). However, Fig. 6 shows how the reduced control signaling in 6PP (in the form of eliminating EB and KA beaconing) results in application-level messages experiencing fewer collisions within the slotframe. This improves 6PP's end-to-end performance, resulting in a 42% reduction in latency without interference, and 37% under the external interference scenario.

5 Simulation-based Evaluation

To complement our experimental investigation we have conducted simulation-based evaluations of 6PP's latency. The multi-PHY capabilities of 6PP enable it to transmit multiple signaling/data messages within a single 6TiSCH timeslot. We assume that a CT-based flood carries a single signaling/data message from the controller to the entire multi-hop network. The number of distinct messages at a given PHY within a 6TiSCH slotframe can be calculated as:

$$N^{PHY}_{Messages} = \left\lfloor \frac{T_{SF}}{T^{PHY}_{slot} \times (N_{Tx} + N_H)} \right\rfloor, \tag{1}$$

where T_{SF} is the slotframe duration, T^{PHY}_{slot} is the slot duration for a CT, N_{Tx} is the number of times a message is transmitted after reception, and N_H is the (required) number of hops. Fig. 7 shows the number of distinct 64 byte messages (as per the D-Cube experimentation) that can be transmitted within a standard 6TiSCH slot duration of 10ms. The evaluation is based on a radio ramp-up of 40μs [9] and a CT protocol overhead of 6 bytes. The results indicate that the fast data transmission capabilities of the BT 5's uncoded physical layers provide an opportunity to reliably disseminate multiple messages over multiple hops when using CT (in comparison

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[2] https://github.com/contiki-ng/contiki-ng/pull/1310

to standard 6TiSCH), although this capability is somewhat limited at coded BT 5 and IEEE 802.15.4 physical layers. However, this analysis does not account for the long-range and reliability characteristics of these coded PHYs. As recent works have shown the sensitivity of CT performance to the underlying PHY, we recommend the adaptive selection of PHY at runtime as an area of interest for future research.

6 Discussion and Future Work

This paper has validated the novel approach taken by 6PP with initial promising results, and demonstrated the potential of multi-PHY CT flooding to support the IETF 6TiSCH standard. The synchronicity of CT allows messages to be sent in a deterministic manner that fits neatly into the 6TiSCH slotframe, and Sect. 4 showed how carrying EBs and DAO-ACKs over CT provides a low-latency mechanism for control signaling: freeing the slotframe for layer-3 messaging. Indeed, existing mechanisms in the IEEE 802.15.4-based 6TiSCH standard seem to be amenable to the inclusion of multi-PHY CT. For example, *hard cells* can be used to reserve immutable slots, allowing a global PHY schedule to be followed by all nodes. Unlike *soft cells*, these cannot be altered on an ad-hoc basis, which means that the multi-PHY CT operation can be neatly decoupled from 6TiSCH. Although an area with likely considerable hurdles to acceptance, this would help to support the SDN [28] concepts included within the standard. As demonstrated in Sect. 5, BT 5-based CT flooding (as opposed to IEEE 802.15.4 CT flooding) provides multiple options. While IEEE 802.15.4-based flooding would be a more universal approach, we believe adopting the multi-PHY capabilities of modern low-power wireless chipsets brings significant gains, and opens the possibility of switching the CT PHY at runtime in order to adapt to changing network conditions – such as provide fast data dissemination or increased reliability and range. Indeed, such an approach has been proposed in recent works that have expanded our understand of CT communications [8, 7] and is gaining considerable attention within the community. When utilizing the BT 5 high data-rate uncoded PHYs 6PP could also provide a means for rapidly distributing larger IPv6 packets such as those required in firmware updates – significantly reducing the time taken to update a network. In short, the gains that can be achieved with CT flooding protocols over the BT 5 PHY layers provides a strong argument for focusing future standardization efforts on interoperability between the two (CT and 6TiSCH). Finally, 6PP opens other intriguing directions for future research – particularly in mobility and synchronization. Firstly, by eschewing the need for topology control, CT protocols naturally lend themselves towards mobility scenarios. The addition of CT-based control mechanisms within the 6TiSCH slotframe could therefore support more dynamic scenarios than the current industrial IoT use-cases envisioned by the standard. Additionally, 6TiSCH currently requires generous guards to tolerate drifting [29]. This drift tolerance subsequently dictates the length of a TSCH timeslot, not only representing a minimum bound on latency but also incurring a cost on energy. As 6PP maintains highly accurate time synchronization through the CT scheduler, there is scope for reducing these guard times to provide even lower end-to-end latencies.

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