Less is More: Towards low-latency Communication trough Cross-technology Communication

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ABSTRACT

Supporting time-sensitive (TS) communication in a radio spectrum shared with broadband (BB) data is challenging, especially in the unlicensed spectrum. A traditional Multi-Technology Access Point (MTAP) equipped with two different radio interfaces, which is serving both TS and BB data, suffers from Head-of-Line blocking phenomenon that severely degrades its latency performance. This paper targets this problem by utilizing the possibilities of Cross-Technology Communication (CTC) which enables direct communication between otherwise incompatible radio technologies by means of waveform emulation. Therefore, we convert a normal AP into a virtual MTAP (vMTAP) where just a single radio interface is sufficient to provide native support for the wireless technology used for BB transmission while the radio technology to be used for TS communication is just emulated through CTC. In the event of the arrival of a time critical data packet to be transmitted, we do not have to preempt any ongoing BB data transmission of the vMTAP but, instead, we embed the CTC emulated TS data frame directly into the not yet transmitted payload of the ongoing BB transmission. Our approach represents some kind of virtualization with the second radio interface being fully emulated in software, hence reducing the overall hardware cost and power consumption. Moreover, while being fully transparent to the client stations it offers a superior performance to state-of-the-art MTAP solutions with preemption because the overhead of channel access can be avoided entirely in most cases.

KEYWORDS

Wireless Communication, Time-sensitive, Cross-technology

ACM Reference Format:
Anatolij Zubow, Piotr Gawłowicz, Falko Dressler. 2022. Less is More: Towards low-latency Communication trough Cross-technology Communication. In *17th ACM Workshop on Mobility in the Evolving Internet Architecture (MobiArch'22), October 21, 2022, Sydney, NSW, Australia.* ACM, New York, NY, USA, 6 pages. https://doi.org/10.1145/3556548.3559628

The authors acknowledge the financial support by the Federal Ministry of Education and Research (BMBF, Germany) in the programme of "Souverän. Digital. Vernetzt." Joint project 6G-RIC, project identification no. 16KISK030.

MobiArch'22, October 21, 2022, Sydney, NSW, Australia

ACM ISBN 978-1-4503-9518-2/22/10…$15.00
https://doi.org/10.1145/3556548.3559628

1 INTRODUCTION

Novel applications like industrial IoT [14], gaming, remote control, etc. require time-sensitive (TS) data communication. Although progress was made in the design of new wireless protocols (e.g., 802.11ax) optimized for delivery of low-latency data they are suffering in environments where the radio spectrum is being shared with other types of traffic like broadband (BB) data (e.g., video streaming). This is made even more difficult when different radio technologies are simultaneously used within the same radio spectrum. Here a Multi-Technology Access Point (MTAP) equipped with two interfaces of two different radio technologies which is serving BB data on one and TS data on the other interface is suffering from the Head-of-Line (HOL) blocking problem that severely degrades its latency performance. A known solution to this problem is the preemption of an ongoing BB data transmission in the event of the arrival of TS data.

This paper presents an approach that utilizes the possibilities of Cross-Technology Communication (CTC) in order to create a virtual MTAP (vMTAP) and to eliminate the HOL problem. With CTC it is possible to directly communicate between otherwise incompatible radio technologies by means of waveform emulation, e.g., CTC between WiFi and LoRa [6] or WiFi and Bluetooth (BT) [9]. With `CTCforLowLat` our vMTAP is equipped with only a single radio interface providing native support for the wireless technology used for BB transmission while the radio technology to be used for TS communication is only emulated through CTC. The gain results from improved channel access as the same medium access control is used by both radio technologies, i.e., native and CTC emulated transmissions. In the event of the arrival of a TS data packet we do not have to physically preempt any ongoing BB data transmission of the MTAP but instead we embed the CTC emulated TS data frame into the not yet transmitted payload of an ongoing BB transmission which represents some type of virtual preemption. Our approach offers a superior performance to state-of-the-art solutions as the overhead of channel access can be avoided in most cases. Moreover, it is more cost-efficient as in contrast to classical MTAPs it requires only a single RF interface at the AP side.

Contributions: We show for the first time that the degrees of freedom provided by CTC can be utilized for optimizing the downlink (DL) transmissions of a vMTAP with respect to channel access delay of TS data transmissions performed on a radio technology different from the one used for BB data when both sharing the same radio spectrum. `CTCforLowLat` represents a generic concept of using CTC for embedding TS traffic into BB traffic. We also discuss how the uplink (UL) can be realized in such a configuration. As a proof of concept and as a demonstration of the feasibility of CTC-based frame embedding we consider `CTCforLowLat` for the

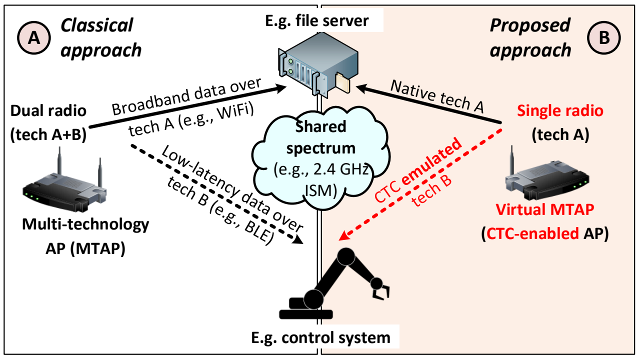

Figure 1: Scenario with BB and TS data delivered over different radio technologies: (a) classical vs. (b) proposed approach.

specific case of a vMTAP using native WiFi and emulated LoRa technology for BB and TS communication respectively.

2 PROBLEM STATEMENT

The envisioned scenario with a MTAP delivering both BB and TS data using two different radio technologies, *A* and *B*, in the DL is shown in Fig. 1A. According to the classical approach the MTAP is equipped with two dedicated radio interfaces, one for each type of traffic, i.e., one optimized for delivery of BB and another for TS data.[1] As we assume that both radio technologies are sharing the same radio spectrum, e.g. 2.4 GHz ISM band, co-existence between the two technologies has to be assured, i.e., orthogonalization of channel access in time (e.g., CSMA) or frequency domain (usage of different channels within the spectrum band). However, the first approach suffers from the HOL blocking problem, i.e., a long running BB transmission might block the channel access for a small but TS high-priority packet requiring low-latency. Such a situation can arise in two ways. First, the MTAP itself is responsible for the blockage by sending out a long BB packet on one radio interface which might block the transmission of a TS packet on the other radio as the same or overlapping radio channels are being used. Known solutions to this problem are: *i)* using the possibility of preemption of frame transmissions (i.e., termination of an ongoing BB data transmission) or *ii)* the usage of two non-overlapping radio channels for the two technologies within the radio spectrum. Second, the blockage happens on the radio channel itself where a third wireless node is transmitting a long BB packet on the same or overlapping channel. A solution to this problem is the usage of full-duplex radios which would make it possible to interrupt such transmission from another node.

This paper focuses on the first case where the MTAP itself is responsible for the blockage. Moreover, we assume that due to insufficient or crowded spectrum an orthogonalization of the two radio technologies in the frequency domain is not feasible. This is a valid assumption when using the crowded 2.4 GHz ISM band [2].

[1] Note, some chips are incorporating multiple radio technologies, e.g. WiFi and BT, in order to share components like antennas. However, to the best of our knowledge techniques like frame preemption are not implemented.

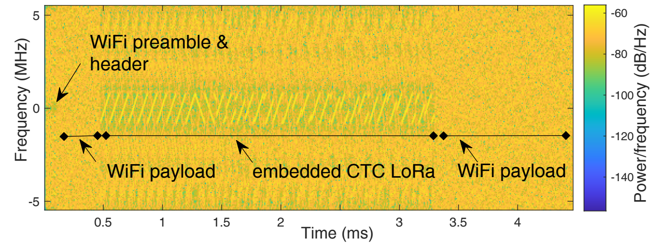

Figure 2: Example spectrum of CTCforLowLat frame for the case of 802.11b (11 Mbps) and LoRa (SF7, 1.6 MHz).

3 PROPOSED APPROACH

3.1 `CTCforLowLat` in a Nutshell

Fig. 1B illustrates our proposed approach of a vMTAP. Our key idea is to utilize the degrees of freedom provided by CTC. Specifically, `CTCforLowLat` uses only a single radio interface for native communication on technology (tech.) *A* (BB data) while the second radio tech. *B* which is used for TS data transmission is only emulated through CTC. Our approach represents some kind of virtualization with the second radio interface being emulated in software.

Having a single radio interface together with CTC solves the HOL blocking problem as follows. On the arrival of a high priority TS data packet a possibly ongoing native BB data transmission is not physically interrupted. Instead the not yet transmitted part of the frame payload is changed on-the-fly to a bit sequence representing the waveform of the CTC emulated TS packet for tech. *B*. Specifically, the carefully selected bit sequence will generate a waveform of tech. *B* after being traversing the TX chain of a device adhering to the tech. *A*. Note that the due to limitations of the signal-emulation-based CTC, the wavefom will only approximate the one of foreign technology. However, as shown in [6, 9, 11] the signal distortions are small, and a legacy device can decode it with only small performance (e.g., BER) degradation. Also note, that for the duration of the emulated frame the bits of the BB data packet are corrupted. Thus, through CTC-based frame embedding the transmission of the TS packet can start immediately since there is no need to wait for the end of the long-running BB transmission. Moreover, the channel access overhead (e.g., carrier sensing, interframe space (IFS) and backoff (BO)) for tech. *B* can be fully avoided. Note, whenever a TS packet arrives when there is no ongoing BB transmission a dummy BB packet is created with the purpose of transmitting the CTC emulated and embedded packet.

As an example, consider `CTCforLowLat` for the specific case of WiFi and LoRa technologies used for BB and TS communication, respectively. Fig. 2 shows the corresponding radio spectrum of an 802.11b frame (tech. *A*) with embedded CTC emulated LoRa frame (tech. *B*) using Complementary Code Keying (CCK)-based emulation [6].

3.2 Detailed Specification

Fig. 3 shows the protocol stack of `CTCforLowLat`. The two applications, BB and TS, have their own native communication stacks up to the higher MAC layer (i.e., the non-time sensitive part of the MAC layer). The two lower layers, i.e., lower MAC and physical layer,

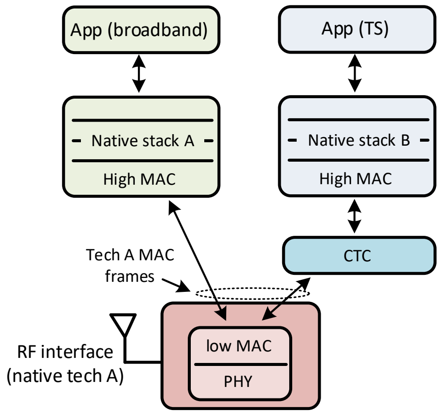

Figure 3: Protocol stack of CTCforLowLat with low MAC and PHY layer of tech. *A* being shared.

are provided by tech. *A* and are shared with tech. *B*. Moreover, we see the additional CTC block sitting between the high MAC of tech. *B* and the shared lower MAC. It is responsible for conversion of the MAC frames of tech. *B* into MAC frames of tech. *A* so that they can be transmitted by the two lower layers of tech. *A*. Such translation process is based on the approximation of the native waveform of tech. *B* with the modulation schemes available in tech. *A* (e.g., CCK) and reversing of the TX chain to get the proper payload bits for the frame to be transmitted on tech. *A*.[2] The shared lower MAC must be able to accept new packets from the higher layers even when being in transmitting state. This is required in order to be able to handle the arrival of TS packets at any time as they have to be embedded within the payload of an ongoing BB transmission.

Immediate channel access.
Fig. 4 compares the DL channel access of a MTAP using the two classical approaches with `CTCforLowLat`. Here we assume that both radio technologies *A* and *B* use CSMA/CA for channel access with radio tech. *B* using parameters giving it a strict prioritization over packets from tech. *A*. Moreover, for reasons of illustration we assume no competition from other wireless stations on that channel. Here in the middle of an ongoing BB data transmission (on tech. *A*) a high priority TS data packet is delivered by the application layer for transmission. For all three cases we are interested in the channel access delay of that TS packet.

The first case which is the classical approach without preemption (baseline) offers the highest waiting time (both average and worst-case) which is determined mostly by the size of the blocking BB data packet whose transmission cannot get interrupted. Moreover, after its completion a full channel access (CMSA/CA) for the TS data on tech. *B* composed of carrier sensing, IFSs and BO procedure need to be performed which further increases the latency.

The second case offers a much lower latency and also less jitter due to the possibility of interruption (preemption) of the ongoing BB transmission (tech. *A*). Still some latency is introduced due to the required full channel contention using tech. *B*, i.e., carrier sensing, IFS and BO procedure. Note, in order to assure a strict prioritization the IFS plus maximum initial BO size of tech. *B* must be smaller than the IFS of tech. *B*, i.e., AIFS_B + CWMIN_B < AIFS_A. Note, that in absence of competition from other wireless nodes with such a configuration the delay of the TS data is fully determined by AIFS_B and CWMIN_B with the latter being responsible for the jitter.

The third case representing our `CTCforLowLat` approach offers on average the smallest channel access delay. On the arrival of a high priority TS data packet the ongoing BB data transmission is not physically interrupted. Instead the not yet transmitted part of the frame's payload is modified on-the-fly to the bit sequence representing the CTC emulated TS packet for tech. *B*. The amount of time required for this operation is the only source of delay as no channel contention for tech. *B* is needed as the channel is still being used by the node that won the last channel access contention. Care must be taken if the TS frame arrives almost at the end of the BB transmission and there is not enough transmission duration left to accommodate the emulated frame. In such a case the point in time for the transmission is delayed and the TS frame is transmitted as a separate frame in the subsequent transmission. Unfortunately the delay is increased due to additional channel contention with parameters for tech. *B* and overhead due to required transmission of the physical layer preamble and header on technology. This corresponds to an CTC approach with preemption instead of embedding.

Modifying frame payload being in transmission.
The proposed frame embedding scheme could be implemented using a transmit (TX) ringbuffer data structure inside the shared radio interface (Fig. 5). On the arrival of an emulated high-priority frame the TX ringbuffer content will be overwritten immediately after the current TX pointer of the ongoing frame transmission. Such an approach requires the possibility to change the content of the frame payload being in transmission. Note, that such a frame manipulation can be reliably detected by the BB receiver (tech. *A*) by verifying the Frame Check Sequence (FCS) and dropping incorrect frames.

The embedding of an emulated frame destroys the actual native BB frame resulting in wastage of resources due to necessary retransmissions. If the TS packets are sent at a high rate, this results in a severe throughput degradation of the underlying BB transmission. In `CTCforLowLat` we address this problem by utilizing the possibilities of frame aggregation of modern MAC layers like the A-MPDU aggregation in 802.11n. The idea is to transmit multiple small subframes each wrapped in an 802.11n MAC header and hence protected with its own FCS. Only the subframes overlapping with the embedded emulated frame need to be retransmitted as the other subframes are unaffected and contain valid content. In the 802.11n protocol a mechanism called selective block acknowledgment is used which allows to retransmit only the subframes in error.

What about the uplink?
The support of UL transmissions is based on the generalization of the signal hitchhiking technique which was proposed by Liu et al. [13] for the specific case of CTC from LoRa towards WiFi. It works as follows. When a WiFi station is receiving a WiFi packet from an WiFi AP, a LoRa device transmits simultaneously, leading to intentional collisions with the WiFi packet in the air. This way,

[2] A detailed description of this translation process is omitted for reasons of space. The interested reader is recommended to refer to [6, 11].

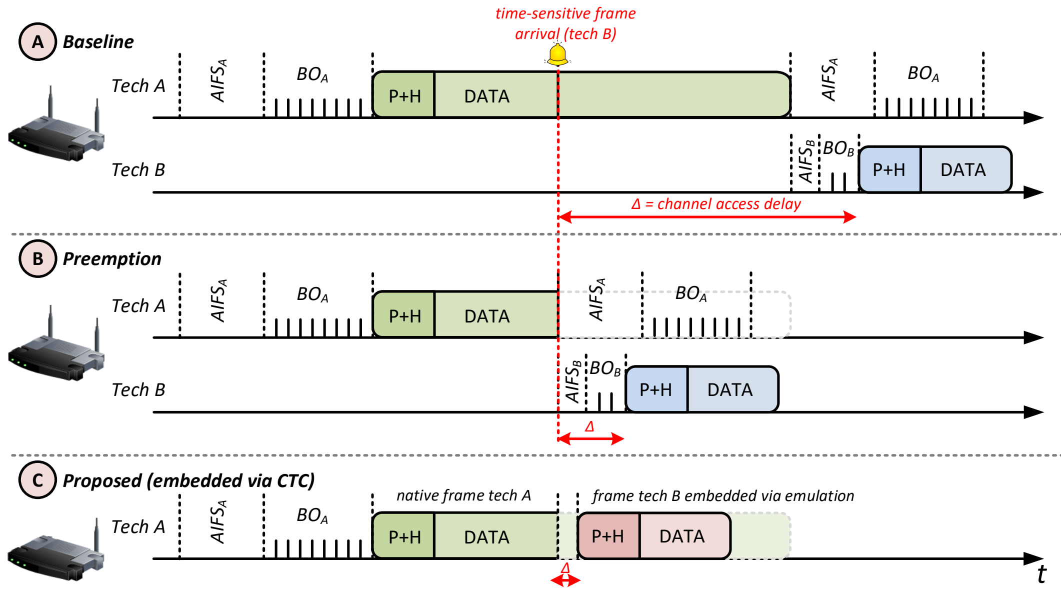

Figure 4: DL channel access of baseline without and with preemption compared to proposed approach using emulated frame embedding.

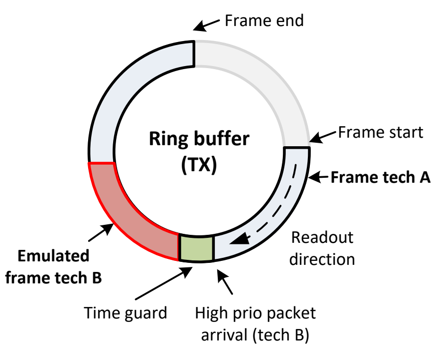

Figure 5: Implementation of `CTCforLowLat` using TX ring-buffer structure which is modified on arrival of TS frame.

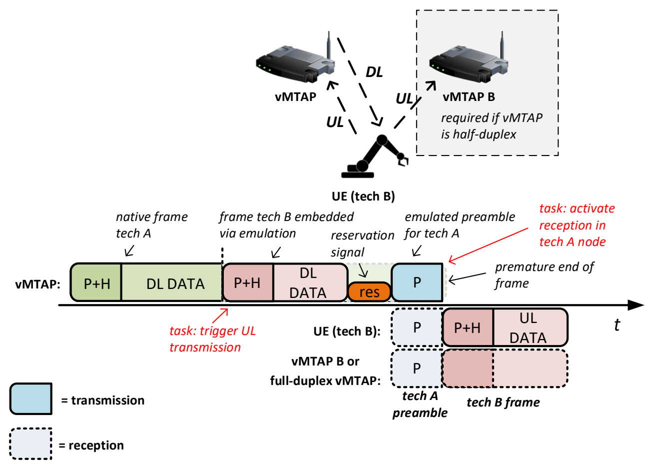

Figure 6: Operation of `CTCforLowLat` in UL utilizes signal hitchhiking technique.

the LoRa packet hitchhikes on the WiFi packet and enters the WiFi radio, where it can be decoded through waveform reconstruction and subsequent LoRa decoding. Note, that the signal hitchhiking technique is not bound to CTC from LoRa to WiFi and can be generalized in order support additional pairs of technologies, e.g. CTC from BT-LE to WiFi or ZigBee to WiFi. Therefore, `CTCforLowLat` utilizes this technique in order to support UL transmissions (Fig. 6). Our key idea is to emulate two frames within a single DL radio transmission:

(1) Emulated DL frame (tech. *B*) to trigger UL transmission (e.g., trigger frame or data followed by ACK),
(2) Emulated tech. *A* preamble to activate the RX chain of the tech. *A* device (here vMTAP).

The second step, i.e., emulation of tech. *A* preamble, is required in order to receive the tech. *B* frame hitchhiking with tech. *A*, e.g. LoRa signal hitchhiking on top of WiFi. The actual decoding process of the tech. *B* UL frame is as follows. First, the whole frame is decoded using the native radio interface for tech. *A*. The decoded payload bits are afterwards used to reconstruct the waveform from which the frame of tech. *B* can be decoded fully in software. Note, that such an operation requires tight synchronization which is assured by `CTCforLowLat`. Moreover, the received power level of both the tech. *A* preamble and the tech. *B* frame should be similar as otherwise the dynamic range of the receiver device maybe incorrectly scaled, and the tech. *B* transmission will be not detected. This can be achieved by some calibration process. In `CTCforLowLat` the reception of the UL frame takes place either by another co-located vMTAP (vMTAP B in Fig. 6) or directly by the vMTAP itself in case it supports full-duplex operation. In the former case the received UL frame needs to be forwarded over some backhaul to the original vMTAP.

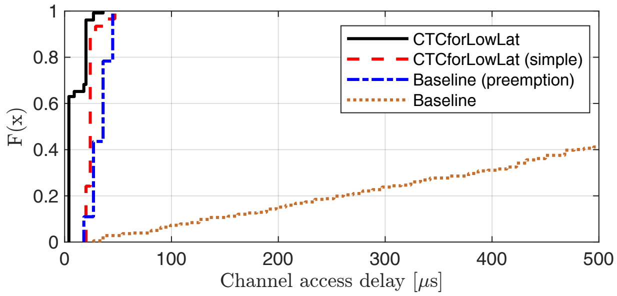

Figure 7: Channel access delay of DL LoRa.

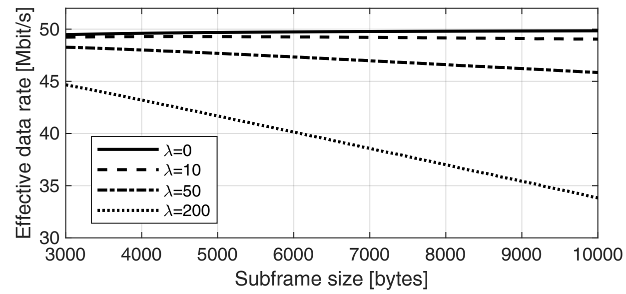

Figure 8: Impact of TS arrival rate on BB data rate.

4 PERFORMANCE EVALUATION

4.1 Methodology

We consider `CTCforLowLat` for the specific case of a vMTAP equipped with a single 802.11b WiFi radio and CTC emulated LoRa used for BB and TS communication respectively (Fig. 1). The scenario consists of a single vMTAP and two user devices. Both WiFi and LoRa are operating in same spectrum using overlapping channels. For LoRa we assume a CSMA/CA based channel access with strict prioritization over WiFi as ALOHA would be not suitable. Finally, we assume high SNR for both links resulting in no packet loss. We compare the following approaches:

(1) `CTCforLowLat` - our proposed approach,
(2) `CTCforLowLat (simple)` - a simplified version of (1) with preemption instead of frame embedding,
(3) `Baseline (preemption)` - classical approach with two radio interfaces and preemption,
(4) `Baseline` - same as (3) but without preemption.

As performance metrics we identified the channel access delay for the transmission of the TS data as well as the effective data rate of the BB communication.

4.2 Results

The channel access delay of the four approaches for the transmission of the TS data is shown in Fig. 7. `CTCforLowLat` offers the best performance and is even superior to `Baseline (preemption)`. This is because the overhead of channel access composed of carrier sensing, interframe spacing and BO procedure can be fully avoided in most of the times due to the frame embedding. This is the main reason why `CTCforLowLat` outperforms `CTCforLowLat (simple)` as the latter needs to perform a full channel access before the transmission of each CTC emulated frame. Note, that `Baseline` offers the worst performance as the channel access delay directly depends on the length of the BB packet which was set to 1 ms in our analysis. The data rate of the BB transmission depends on the activity of the TS application. The higher the activity, the lower the effective data rate of the BB communication due to congestion and possible interruptions when preemption is being used. This is the case with `Baseline (preemption)` and also our `CTCforLowLat` approach where subframes of the BB frames being overlapped with the embedded emulated TS frame are corrupted and therefore need to be retransmitted. In contrast the influence on `Baseline` is negligible as BB frames in transmission are not interrupted.

In the following we study the impact of the subframe size on `CTCforLowLat` using the subsequent additional simulation parameters. For WiFi a constant data rate of 50 Mbit/s and a 32 Bytes overhead per subframe was used. For LoRa we created the smallest possible frame using SF5, 1.6 MHz bandwidth and 1 Byte payload resulting in an airtime of 0.5 ms. Fig. 8 shows the impact of arrival rate λ of LoRa packets modeled as Poisson process on the effective data rate of WiFi data. The minimum subframe size for WiFi was set to fit a single LoRa frame. We see that with increasing λ and subframe size the effective data rate of WiFi drops. With $\lambda = 200$ and a subframe size of 10 kBytes the WiFi rate drops by a third. We also see that for smaller λ there is an optimal subframe size, e.g., for a $\lambda = 10$ the optimal subframe size is ≈ 4400 Bytes. For higher λ the optimal subframe size shrinks as the probability of loosing a subframe due to embedded LoRa frame grows. In summary, having knowledge about λ and the size of TS packets allows `CTCforLowLat` to select the optimal subframe size for BB communication.

5 DISCUSSION

As our approach relies on CTC emulation techniques for operation, it bears all the disadvantages of CTC. First, the increased spectrum usage if a narrowband technology is being emulated using a wideband technology, that could be otherwise used for multiple narrowband transmission. Second, the performance degradation of the emulated technology due to signal emulation imperfections resulting in drop in SNR or increased BER/PER. Moreover, as it share the lower part of the medium access control layer it is subject to the channel access restrictions of tech. A, i.e., usage of same carrier sensing parameters like energy detection threshold. Finally, there are inherent limitations of CTC as wideband technologies cannot be emulated with the help of narrowband technologies, or only with a few exceptions.

The frame embedding scheme used in `CTCforLowLat` has the advantage that the embedded frames are better protected against cross-technology interference in case a virtual channel reservation is used by the BB transmission. Take our specific instance of WiFi and LoRa. Here the channel for the embedded LoRa frames is implicitly reserved by the WiFi transmission (by setting the NAV) so that any other WiFi station would defer from channel access for the duration of the LoRa frame helping to eliminate possible inter-technology hidden terminal problems. This exclusion zone can be further increased when enabling the RTS/CTS handshake to take place before the actual WiFi unicast transmission as the channel is also reserved for more distant WiFi nodes via the CTS. Finally, `CTCforLowLat` inherits the advantages of CTC like the possibility of simultaneous emulation of multiple narrowband technologies (e.g., multiple LoRa/ZigBee channels) within a single BB frame (e.g., WiFi) which can be used to improve the reliability of the emulated radio technology.

We evaluated `CTCforLowLat` for the specific case of native WiFi with emulated LoRa. As can be seen from next section, other combinations are possible, e.g. WiFi and BT LE.

6 RELATED WORK

Cross-technology Communication: The signal emulation technique was introduced in a pioneering CTC scheme called WEBee [11], which enabled a WiFi device to transmit a ZigBee waveform by proper selection of its frame payload bits. It operated with the native data rates of ZigBee but suffered from a high packet error rate due to the inherent distortions of the emulated signal. TwinBee [4], LongBee [12], and WIDE [8] further improve the quality of signal emulation and hence the reliability of WEBee. Then, the signal emulation enabled CTC between WiFi and BT [9], WiFi and LTE [5, 7]. Since these schemes rely on the OFDM modulator of 802.11n WiFi, they cannot perfectly emulate foreign waveform during the OFDM cyclic prefix, which constitutes up-to 20% of each symbol time. In [6] we showed that the CCK-based modulator of 802.11b WiFi can be used as a PWM generator, that can generate a valid LoRa waveform. Li *et al.* [10] showed that with CCK-based signal leaves some unique signatures when it flows into the BLE receiver. The authors proposed a technique called symbol transition mapping to convey data between WiFi and BLE. An good overview on CTC schemes for IoT is given by Chen et al. [3].

Low-latency Communication: Next generation WiFi (802.11be) aims to include time-sensitive networking (TSN) capabilities to support low latency and ultra reliability in license-exempt spectrum bands, enabling many new Internet of Things scenarios. The IEEE 802.1Qbu TSN standard, defines frame preemption as a way to interrupt an ongoing operation of a low-priority (preemptable) queue if a TS (preempting) queue is selected for transmission. Such technique is required for devices transmitting multiple traffic flows as placing the TS traffic in the highest priority queue may not be sufficient to mitigate the residual delay caused by large ongoing low-priority transmissions, which may include many aggregated packets and last up to the maximum physical protocol data unit duration (i.e., 5 ms) [1]. The feasibility of TSN over wireless in general and the 802.1Qbu-based frame preemption is particular is being under study by TGbe. Note, that 802.11be targets devices having a single radio which is different from our assumption of having a MTAP with two different radio interfaces each optimized for a different type of traffic.

7 CONCLUSION

We discussed the feasibility of utilizing CTC techniques to counter the HOL blocking problem that severely degrades the latency performance of a classical wireless MTAP serving both broadband and time-sensitive data over two different radio technologies but sharing the same radio spectrum. The key idea of `CTCforLowLat` is to create a virtual MTAP where the radio technology used for the transmission of TS data is being emulated through CTC. Our software-based approach offers a superior performance to state-of-the-art MTAP solutions with two dedicated radio interfaces and preemption because the overhead of channel access can be avoided in most of the times. Moreover, it is more cost-efficient as it requires only a normal AP with a single radio which outweighs the slight increased in complexity.

As future work we plan to prototype `CTCforLowLat` using the instance of WiFi and LoRa/BT-LE/ZigBee by either using commodity hardware or Software-defined Radio (SDR) technology which would allow us to validate our approach under real channel and network conditions.

REFERENCES

[1] Toni Adame, Marc Carrascosa-Zamacois, and Boris Bellalta. 2021. Time-Sensitive Networking in IEEE 802.11be: On the Way to Low-Latency WiFi 7. *Sensors* 21, 15 (7 2021), 4954. https://doi.org/10.3390/s21154954

[2] Sanjit Biswas, John Bicket, Edmund Wong, Raluca Musaloiu-E, Apurv Bhartia, and Dan Aguayo. 2015. Large-scale Measurements of Wireless Network Behavior. In *ACM SIGCOMM 2015*. Association for Computing Machinery (ACM), London, United Kingdom, 153–165. https://doi.org/10.1145/2829988.2787489

[3] Ying Chen, Ming Li, Pengpeng Chen, and Shixiong Xia. 2019. Survey of cross-technology communication for IoT heterogeneous devices. *IET Communications* 13, 12 (July 2019), 1709–1720. https://doi.org/10.1049/iet-com.2018.6069

[4] Yongrui Chen, Zhijun Li, and Tian He. 2018. TwinBee: Reliable Physical-Layer Cross-Technology Communication with Symbol-Level Coding. In *IEEE Conference on Computer Communications (INFOCOM 2018)*. IEEE, Honolulu, HI, 153–161. https://doi.org/10.1109/INFOCOM.2018.8485816

[5] Piotr Gawłowicz, Anatolij Zubow, Suzan Bayhan, and Adam Wolisz. 2020. Punched Cards over the Air: Cross-Technology Communication Between LTE-U/LAA and WiFi. In *IEEE International Symposium on a World of Wireless, Mobile and Multimedia Networks (WoWMoM 2020)*. IEEE, Virtual Conference. https://doi.org/10.1109/WoWMoM49955.2020.00058

[6] Piotr Gawłowicz, Anatolij Zubow, and Falko Dressler. 2022. Wi-Lo: Emulation of LoRa using Commodity 802.11b WiFi Devices. In *IEEE International Conference on Communications (ICC 2022)*. IEEE, Seoul, South Korea.

[7] Piotr Gawłowicz, Anatolij Zubow, and Adam Wolisz. 2018. Enabling Cross-technology Communication between LTE Unlicensed and WiFi. In *IEEE Conference on Computer Communications (INFOCOM 2018)*. IEEE, Honolulu, HI. https://doi.org/10.1109/INFOCOM.2018.8485984

[8] Xiuzhen Guo, Yuan He, Jia Zhang, and Haotian Jiang. 2019. WIDE: Physical-level CTC via Digital Emulation. In *ACM/IEEE International Conference on Information Processing in Sensor Networks (IPSN 2019)*. ACM, Montreal, Canada, 49–60. https://doi.org/10.1145/3302506.3310388

[9] Wenchao Jiang, Zhimeng Yin, Ruofeng Liu, Zhijun Li, Song Min Kim, and Tian He. 2017. BlueBee: A 10,000x Faster Cross-Technology Communication via PHY Emulation. In *ACM Conference on Embedded Network Sensor Systems (SenSys 2017)*. ACM, Delft, Netherlands. https://doi.org/10.1145/3131672.3131678

[10] Lingang Li, Yongrui Chen, and Zhijun Li. 2021. WiBle: Physical-Layer Cross-Technology Communication with Symbol Transition Mapping. In *IEEE International Conference on Sensing, Communication and Networking (SECON 2021)*. IEEE, Virtual Conference. https://doi.org/10.1109/secon52354.2021.9491581

[11] Zhijun Li and Tian He. 2017. WEBee: Physical-Layer Cross-Technology Communication via Emulation. In *ACM International Conference on Mobile Computing and Networking (MobiCom 2017)*. ACM, Snowbird, UT, 2–14. https://doi.org/10.1145/3117811.3117816

[12] Zhijun Li and Tian He. 2018. LongBee: Enabling Long-Range Cross-Technology Communication. In *IEEE Conference on Computer Communications (INFOCOM 2018)*. IEEE, Honolulu, HI, 162–170. https://doi.org/10.1109/INFOCOM.2018.8485938

[13] Ruofeng Liu, Zhimeng Yin, Wenchao Jiang, and Tian He. 2020. XFi: Cross-technology IoT Data Collection via Commodity WiFi. In *28th IEEE International Conference on Network Protocols (ICNP 2020)*. Institute of Electrical and Electronics Engineers (IEEE), Madrid, Spain. https://doi.org/10.1109/icnp49622.2020.9259363

[14] Amina Seferagić, Jeroen Famaey, Eli De Poorter, and Jeroen Hoebeke. 2020. Survey on Wireless Technology Trade-Offs for the Industrial Internet of Things. *Sensors* 20, 2 (Jan. 2020), 488. https://doi.org/10.3390/s20020488