The Impact of the Physical Layer on the Performance of Concurrent Transmissions

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Abstract—The popularity of concurrent transmissions (CT) has soared after recent studies have shown their feasibility on the four physical layers specified by BLE 5, hence providing an alternative to the use of IEEE 802.15.4 for the design of reliable and efficient low-power wireless protocols. However, to date, the extent to which physical layer properties affect the performance of CT has not yet been investigated in detail. This paper fills this gap and provides the first extensive study on the impact of the physical layer on CT-based solutions using IEEE 802.15.4 and BLE 5. We first highlight through simulation how the impact of errors induced by de-synchronization and beating on the performance of CT highly depends on the choice of the underlying physical layer. We then confirm these observations experimentally on real hardware through an analysis of the bit error distribution across received packets, unveiling possible techniques to effectively handle these errors. We further study the performance of CT-based flooding protocols in the presence of radio interference on a large-scale, and derive important insights on how the used physical layer affects their dependability.

I. INTRODUCTION

A recent breakthrough in the low-power wireless community has been the development of communication protocols based on Concurrent Transmissions (CT). CT-based solutions intentionally let multiple relaying nodes forward packets by simultaneously broadcasting them on the same carrier frequency. Thanks to the capture effect [1] and to non-destructive interference [2], nodes overhearing these concurrent transmissions have a high probability to receive at least one transmission correctly, which enables the creation of reliable and efficient cyber-physical systems and Internet of Things (IoT) applications [3]. The key benefit of CT is the ability to exploit sender diversity to realize simple flooding and synchronization services across large-scale multi-hop wireless networks [4], as well as improving wireless performance in single-hop systems [4]. Relaying nodes in a mesh network utilizing CT-based protocols do not need to explicitly avoid collisions using conventional techniques such as carrier sensing, and can avoid the overhead of routing and link-based communication [3].

A large body of work has proposed CT-based data collection [5, 6, 7] and dissemination [8, 9] protocols that can achieve unprecedented gains in terms of reliability, end-to-end latency, and energy efficiency. These protocols can outperform existing solutions even in the presence of harsh radio interference [10, 11, 12, 13], as shown by four editions of the EWSN dependability competition [14]. However, the vast majority of CT-based protocols have only been implemented and verified experimentally using off-the-shelf platforms based on 2.4 GHz IEEE 802.15.4 radios, e.g., the very popular but rather outdated TelosB mote [15]. These solutions employ a physical layer (PHY) based on Orthogonal Quadrature Phase Shift Keying (OQPSK) and Direct Sequence Spread Spectrum (DSSS), as specified by the IEEE 802.15.4 standard [16], where DSSS provides the coding robustness needed by CT to be sufficiently reliable [17].

CT and the impact of different PHYs. An experimental study by Al Nahas et al. [18] has shown the feasibility of CT also when using Bluetooth Low Energy (BLE). Their preliminary results show that reliable and efficient CT-based flooding is possible on BLE-based mesh networks, but highlight that the performance largely depends on the employed PHY, as confirmed by the measurements reported in Schaper’s MSc thesis [19]. Indeed, the most recent version of Bluetooth Low Energy (BLE 5) supports four PHYs that largely differ in terms of data rate and robustness [20]: 2M (2 Mbps), which doubles the nominal throughput of the original 1M PHY (1 Mbps), and two coded PHYs with coding rates of 1/2 and 1/8 respectively (i.e., the 500K and 125K PHYs).

These preliminary observations are important in light of the increasing number of commodity IoT platforms that embed low-power radios supporting multiple wireless standards and PHYs, as they hint that developers need to carefully select the physical layer used for CT-based communication. Notable examples of such off-the-shelf platforms are the TI CC2652R [21] and the Nordic Semiconductors nRF52840 [22], which support, among others, the 2.4 GHz IEEE 802.15.4 OQPSK-DSSS PHY as well as the four PHYs specified by BLE 5 on the same chip. However, to date, the extent to which physical layer properties affect CT-based solutions employing IEEE 802.15.4 and BLE 5 has not yet been investigated in detail. Firstly, there is no experimental study systematically analyzing how physical layer effects such as beating induced by relative carrier frequency

1Beating is a pulsating interference pattern between two or more signals at slightly different frequencies, as described in Sect. [4].
Shedding light on these aspects is important to (i) provide a better understanding on the role of the physical layer on the reliability and efficiency of CT, as well as to (ii) empower developers to use the physical layer as a means to fine-tune the performance of CT-based protocols at runtime.

Our contributions. This paper addresses this gap and provides the first in-depth experimental study on the impact of the PHY on CT-based solutions employing IEEE 802.15.4 and BLE 5.

We first simulate the performance of CT for the different BLE 5 PHYs, highlighting the role of beating under different interference scenarios. We then set up an extensive experimental campaign to confirm these simulation results and to systematically study the performance of CT across all the IEEE 802.15.4 and BLE 5 PHYs supported by the nRF52840 platform. To this end, we use the D-Cube public testbed \[24, 25\], recently enhanced with 50 nRF52840-DK devices, to observe both beating frequencies and de-synchronization effects on real hardware through an analysis of the error distribution across received packets. Our experiments demonstrate that the impact of errors induced by de-synchronization and beating on CT performance is highly dependent on the choice of the underlying PHY, on the relative carrier frequency offset between transmitting devices, and on the number of concurrent transmitters. Specifically, we observe that: (i) high data rate PHYs experience wider beating and can mitigate its impact through repetition; (ii) if the power delta between signals is insufficient, then the BLE 5 convolutional coding is no longer effective to sustain reliable CT; (iii) the pattern mapper used in the 125K PHY allows it to effectively handle narrow beating.

We further use D-Cube to perform the first experimental study on the performance of different CT-based flooding protocols as a function of the underlying PHY in the presence of RF interference on a large scale. To this end, we make use of D-Cube’s JamLab-NG functionality \[26\] to generate artificial Wi-Fi interference and stress-test the performance of CT-based protocols such as Glossy \[4\] and robust flooding (RoF) \[10\] under no, mild, and strong interference. Our results allow us to derive important insights on which PHYs are effective to help CT-based protocols in mitigating the impact of interference.

Fig. 1: Beating due to relative oscillator frequency inaccuracies between devices. Signals combine to produce periods of constructive and destructive interference (CI and DI).

offset \[2\], and de-synchronization due to clock drift \[23\] affect the reliability of the received signal in the presence of multiple concurrent transmitters. Furthermore, there is no experimental work trying to verify whether the robustness of CT-based flooding protocols to radio interference holds true when using different PHYs (or studying whether the performance of CT in harsh RF environments differs depending on the used PHY).

Such insights include: (i) the superiority of IEEE 802.15.4 and BLE 5 500K PHY under strong interference, (ii) the fact that the BLE 125KPHY should not be used in conjunction with long payload lengths under interference, as well as (iii) the need to dynamically change PHY at runtime to provide the best trade-off between reliability, latency, and energy efficiency.

After providing some background knowledge on CT in Sect. II, this paper makes the following specific contributions:

- We simulate the performance of CT for all BLE 5 PHYs, highlighting the role of beating (Sect. III).
- We are the first to experimentally observe beating frequencies and de-synchronization effects on real hardware and wireless channel for different PHYs through an analysis of the bit error distribution across received packets (Sect. IV).
- We evaluate the performance of CT-based flooding protocols under radio interference, and provide insights on how the employed PHYs affect dependability (Sect. V).

We then describe related work in Sect. VI to highlight how our insights align with existing literature, and conclude our paper in Sect. VII along with a discussion on future work.

II. Concurrent transmissions in low-power wireless networks

CT is the concept by which several nodes transmit the data they want to share at the same time. The physical layer of low-power IoT devices is typically based on different variations of binary frequency-shift keying (BFSK) modulation, as specified in both BLE 5 and IEEE 802.15.4. Early works such as Glossy \[4\] showed that, when using frequency-based modulations, if nodes are sufficiently synchronized, then transmissions of the same data will align and the packet will be correctly received with cooperative gain. Meanwhile, later works have shown that transmissions of different data greatly benefit from capture effect due to energy diversity between transmitters. CT therefore constitute a robust technique to deploy simple, diverse, and latency-optimal mesh networks. Nevertheless, recent literature has shown that CT introduce two types of errors that degrade the communication performance:

1) Synchronization errors. Concurrent transmitters are not perfectly synchronized, which introduces intersymbol interference when different bits overlap on the air. To minimize this effect, packet transmissions must be triggered within a time interval ideally lower than half the symbol period \[23\].

- OQPSK with half-sine pulse shaping is equivalent to Minimum-Shift Keying (MSK) and can be demodulated as a frequency modulation \[27\].

Fig. 2: Beating manifests in many forms depending on the relative frequencies between devices and their channel gains. Strong beating attenuates a signal toward zero in a beating ‘valley’.

1QPSK with half-sine pulse shaping is equivalent to Minimum-Shift Keying (MSK) and can be demodulated as a frequency modulation.
2) **Beating Effect.** When CT overlap on the air, the resulting waveform has a beating amplitude due to alternating periods of constructive and destructive interference (beating). As shown in Fig. 1 with two concurrent transmitters, the waveform’s envelope has a sinusoidal shape, while featuring more complex forms when more than two transmissions overlap [28]. While potentially introducing a certain degree of energy gain during peaks, beating greatly increases the chances of bit errors during low-energy periods (valleys) and has generally a negative net effect.

Notably, beating will impact dense topologies when there is no dominant transmission and will consequently be affected by deep fading. On the other hand, its impact is reduced when different transmissions are received with enough energy diversity and the capture effect kicks in. In Fig. 2 we categorize beating as **wide and strong**, **wide and weak**, **narrow and strong**, or **narrow and weak**. Beating will be randomly narrow or wide depending on the relative carrier frequency offset between transmitters, while it will manifest as strong or weak depending on the relative difference in received signal energy.

### III. IMPACT OF PHYSICAL LAYER ON CT PERFORMANCE: ANALYSIS AND SIMULATION

While synchronization errors can be greatly reduced by properly designing the CT network protocol and its retransmission strategy, **beating cannot be avoided.** Beating always appears when signals from non-coherent transmitters overlap in the air, due to their different carrier frequency offset (CFO). Moreover, the temporal period of the beating is different for each set of concurrent transmitters and randomly depends on their oscillator inaccuracies. The unpredictable temporal length of the beating largely affects the error rate, since the beating periods can be very narrow (and several peaks and valleys can appear within a packet transmission), or very wide (and a packet can be completely shadowed within a valley).

To better analyze the impact that different PHYs have on the performance of CT under beating, we simulate the different communication systems using MATLAB to obtain the average Packet Error Rate (PER) vs. Signal-to-Noise Ratio (SNR) for two CT recovered with a non-coherent BFSK receiver, as in [29]. We assume constant additive white Gaussian noise and no synchronization errors. We repeat this for the different BLE 5 coded (500K and 125K) and uncoded (1M and 2M) PHYs, for different oscillator inaccuracies (which result in either wide or narrow beating) and power deltas. Both coded PHYs are based on the 1M PHY, adding a convolutional code of rate 1/2 and are received with a hard-decision Viterbi decoder [30]. In addition, the 125K PHY adds a Manchester pattern mapper of four elements per coded bit.

We define the Relative Frequency Offset (RFO) – which determines the beating frequency – as the difference between the CFO of each individual transmitter, and the power delta $\Delta P$ as the power ratio with which both CT are received.

The SNR is defined relative to the strongest transmission (assuming $P_{R1} > P_{R2}$) and $N$ being the noise power:

$$RFO(\Delta) = |CFO1 - CFO2| = 1/T_{\text{Beating}},$$

$$\Delta P(dB) = 10\log_{10}(P_{R1}/P_{R2}),$$

$$SNR(dB) = 10\log_{10}(P_{R1}/N).$$

The BLE standard requires the CFO to be within $\pm150kHz$ [31], which results in RFOs lower than 300kHz. Therefore, the RFO is always lower than the (coded or uncoded) symbol frequency (i.e., 2MHz in BLE 5 2M and 1MHz for the other three PHYs).

The results of our simulation are presented in Fig. 3. Based on these results, we derive the following observations:

1) **Impact of beating.** We first compare the results obtained with two concurrent transmitters (2 CT) with those obtained with a single transmitter (no beating). With low-noise (SNR $>15$ dB), beating negatively affects packet reception and increases the PER. Only when operating in high-noise conditions (SNR $<10$ dB), 2 CT experience a PER lower than that of a single transmitter, due to the positive net effect of constructive interference intervals. CT are hence an optimal mechanism in harsh environments with high noise, in which packet loss is high. Otherwise, the effect of destructive interference dominates and the PER increases.

2) **Wide ($T_{\text{Beating}} > T_{\text{Packet}}$) and strong ($\Delta P \approx 0 dB$) beating, Fig. 3a.** In this case, $T_{\text{Packet}}$, which denotes the over-the-air time of a packet is the key factor dictating the PER. Indeed, the probability that the transmission spans a destructive interference interval is lower as the time the packet spends on the air decreases. Hence, when subjected to a same fixed $T_{\text{Beating}}$, uncoded PHYs (BLE 5 1M and 2M) perform better than coded ones (125K and 500K), since the former benefit from faster transmissions. With wide energy valleys, convolutional codes are ineffective: as a result, BLE 5 125K is the worst performing PHY, since it features the longest packet durations.

3) **Narrow ($T_{\text{Beating}} < T_{\text{Packet}}$) and strong ($\Delta P \approx 0 dB$) beating, Fig. 3c.** In this configuration, the packet transmission always spans one or more destructive valleys. The BLE 5 2M PHY benefits from having the shortest packet duration, outperforming the 1M PHY. The convolutional encoder used in the BLE 5 500K and 125K PHYs is ineffective against beating, since it is optimal for discretely distributed one bit errors, but not to correct the burst errors that typically occur with beating. Nevertheless, the BLE 5 125K PHY features a good performance in narrow beating conditions when noise is very low (SNR $>20$ dB), experiencing a waterfall-like PER decrease, whereas BLE 5 500K does not experience such a decrease until SNR $>30$ dB, performing worse than uncoded PHYs in the mid-to-low noise range.

4) **Very low noise (SNR $>25$ dB) and strong beating ($\Delta P \approx 0 dB$), Fig. 3a and Fig. 3c.** Under these conditions, the most promising PHYs are BLE 5 2M, when fast

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3 When using BLE 5 125K PHY’s Manchester Pattern Mapper, a ‘0’ is translated into ‘0011’, whereas a ‘1’ is translated to ‘1100’ [31], [32].

4 $T_{\text{Packet}}$ is computed as $T_{\text{Packet}} = B \times (1/DR)$, with $DR$ being the data rate of the chosen PHY and $B$ being the length of the packet in bits.
(a) Wide and strong beating (2 CT, RFO=500Hz, $\Delta P=0\text{dB}$)

(b) Wide and weak beating (2 CT, RFO=500Hz, $\Delta P=1\text{dB}$)

(c) Narrow and strong beating (2 CT, RFO=10kHz, $\Delta P=0\text{dB}$)

(d) Narrow and weak beating (2 CT, RFO=10kHz, $\Delta P=1\text{dB}$)

Fig. 3: Simulation results showing the PER when sending 30-byte packets with two concurrent transmitters and with a single transmitter (no beating). Differences in beating periods (wide or narrow) and power deltas have a significant impact on how beating affects performance, which explains why different node pairs (with different RFOs) may experience very different PERs.

In real-world networks, all four scenarios depicted in Fig. 3 may simultaneously appear in different sections of a multi-hop network, depending on the practically unpredictable CFOs and power level relationships between the concurrent transmitters. Even for a given link, conditions may change over time, since temperature alters the CFO and surrounding interference or multipath propagation cause dynamic fluctuations in the power deltas. It is hence desirable that an optimal PHY tailored to handle CT features robust behavior in all four scenarios, since controlling operating conditions within a wireless network is challenging.

Observations for beating mitigation. Based on these simulation results, we infer that beating can be mitigated by boosting energy diversity with proper node placement and techniques to dynamically control the transmission power. Nonetheless,
this would affect the main advantages of using CT-based protocols: scalability and simplicity. When using lower data rates, which ultimately results in narrower beating periods relative to the packet period, it is more likely that packets will not completely fade: here, coding and Forward Error Correction (FEC) techniques can be exploited to introduce sufficient diversity to recover the errors introduced during the valleys by using the information received during the peaks. This is the case for IEEE 802.15.4, which uses Direct-Sequence Spread Spectrum (DSSS), and for the BLE coded PHYs (500K and 125K), which feature FEC. However, the convolutional encoder used in BLE coded PHYs is not effective in low-noise conditions, and the main gain in this region comes from the addition of the Manchester pattern mapper in BLE5 125K. An exception is the case of networks operating in very noisy environments, in which the coded PHYs (especially BLE 5 500K) may be able to trigger successful packet receptions where classical (routing-based) schemes and coded PHYs may fail. Contrarily, higher data rates experience relatively wider beating periods, since the packet duration is shorter. In this scenario, whole packets may be blocked by wide valleys, which completely precludes any correction attempt. Similarly, the packet may randomly experience a wide peak, and be properly received. With high data rates, as in BLE uncoded PHYs (1M and 2M), the strategy should hence be different. Instead of trying to correct the errors, it would be more effective to repeat the packet several times, practically trying to randomly trigger a transmission spanning an energy peak.

Next, we confirm our simulation results on real hardware using over-the-air experiments. As we expect physical layer properties to cause a fluctuating error probability across received packets, we directly observe beating by mapping the distribution of bit errors across a packet.

IV. CT PERFORMANCE OVER DIFFERENT PHYs: EXPERIMENTAL EVALUATION OF BIT ERROR DISTRIBUTION

Previous CT literature has attributed gains seen at the receiver to so-called Constructive Interference (CI) [3]. More recent works [2], [23], in addition to this paper’s analysis in Sect. III, have proposed that, contrary to this assertion, instances of few concurrent transmitters will result in beating (observed as periodic peaks and valleys across a waveform) due to innate CFO inaccuracies between devices (defined as RFO in the previous section). Rather than a CI gain, beating causes periods of both constructive and destructive interference across the packet, leading to errors during beating valleys, while beating peaks will benefit from a receiver gain. This has recently been demonstrated experimentally by observing the raw in-phase and quadrature (IQ) samples observed when connecting a small number of CT devices to a Software Defined Radio (SDR) using coaxial cables [28]. Although these efforts help to better explain some of the processes underpinning CT-based communication, it is hard to directly witness and evaluate how the occurrence of fundamental physical layer properties affect CT performance. To date, there has been no over-the-air testbed experiment able to demonstrate how PHY effects, such as RFO-induced beating and de-synchronization due to clock drift, directly affect the signal observed by a receiving node.

To address this gap, we present a set of experiments that evaluate physical layer effects on a 1-hop network of nodes communicating wirelessly by means of CT. Given that PHY properties cause the error probability to flux across the received packet (as shown in Sect. III), we observe beating by mapping the distribution of bit errors across a packet when considering a large transmission sample. Specifically, we study the CT performance across the multiple available PHYs supported by the nRF52840 devices in D-Cube. We observe both beating frequencies and de-synchronization effects through analysis of the received error distribution, and demonstrate that their impact on CT performance is highly dependent on the choice of the underlying PHY, on the RFO between transmitting devices, and on the number of concurrent transmitters. All experiments in this section use the Atomic-SDN CT stack [33], [34] developed for the EWSN 2019 Dependability Competition [35].

A. Experimental Setup

The D-Cube testbed was configured to provide a single-hop scenario for up to 12 concurrently-transmitting nodes and a single fixed receiving node. Fig. 4 demonstrates this setup and shows how the network is able to synchronize all transmitting nodes whilst limiting packet receptions at the receiver to only those that are a sum of signals from multiple concurrent transmitters. Node R ignores the first transmission from the CT initiator I in Ts1, while allowing concurrent nodes to receive and synchronize to I. In Ts2 all concurrent nodes synchronously transmit, including the initiator, and are observed at R. Node I was configured to periodically generate and transmit a pseudo-random payload every 250 ms, which was logged before each transmission in Ts1, alongside an 8-byte CT header. When using IEEE 802.15.4, this was a 119B payload (due to the 127B maximum transmission unit limitation), while a payload of 200B was used for the BLE 5 PHY. At the receiving node R, the byte arrays of all correctly received and incorrectly received packets were logged in Ts2.

\*Atomic-SDN employs a back-to-back CT approach similar to the Robust Flooding (RoF) protocol evaluated in Sect.\*.

\*Although 200B is not the full maximum transmission unit of BLE 5, it allows sufficient time to capture wider beating effects while reasonably limiting transmission time when using the BLE 5 125K PHY.
As discussed in Sect. III, the higher data rate PHYs (BLE 5 2M, 1M) experience fewer beating valleys. While these uncoded PHYs are unable to recover errors if they fall within a valley, the repetition commonly employed in CT protocols (TX_N = 4) provides sufficient gain to survive beating. This is consistent with the findings previously shown through simulation in Fig. 3c (narrow and strong beating), where it is likely that this pair experiences very low noise (SNR > 25 dB). As discussed in Sect. III, the higher data rate PHYs (BLE 5 2M and 1M) experience fewer beating valleys. While these uncoded PHYs are unable to recover errors if they fall within a valley, the repetition commonly employed in CT protocols (TX_N = 4) allows the observation (by omission) of packets for which there was an energy minimum during a preamble’s reception, resulting in the radio discarding the packet.

This setup was run across the IEEE 802.15.4 and all the BLE 5 PHYs for 2, 3, 4, 6, 8, 10, and 12 concurrently transmitters at -8 dBm, where we define CT density as CT2, CT3, ... CT12 respectively. Each experiment was run for ≈18K transmitted packets, representing over 100 total hours of experimental data.

### B. Results

#### Beating effect on different PHYs

Fig. 5 shows the bit error distribution for a single CT2 pair across all supported BLE 5 PHYs on the nRF52840. This specific pair experiences significant beating, with valleys observed as bit error peaks and clearly visible across all PHYs (with exception of the coded 125K). The sinusoidal waveform generated by this bit error distribution displays a constant beating period relative to the data rate for each PHY. These results are expanded further in Fig. 7, which shows how the PRR and PER are closely linked to the way in which beating manifests across the various PHYs, and supports the findings previously shown through simulation in Fig. 3c (narrow and strong beating), where it is likely that this pair experiences very low noise (SNR > 25 dB).

As discussed in Sect. III, the higher data rate PHYs (BLE 5 2M and 1M) experience fewer beating valleys. While these uncoded PHYs are unable to recover errors if they fall within a valley, the repetition commonly employed in CT protocols (TX_N = 4) in these experiments) means it is likely that a retransmission will successfully fall between valleys and allow a successful reception of the preamble. This can be observed in the higher error rate for the 1M PHY, which experiences additional beating valleys as opposed to 2M. Furthermore, while it would be natural to assume that the redundancy employed in coded PHYs helps them to better recover from beating errors, our results show that the BLE 5 convolutional coding is unable to cope with significant beating (as seen from the high PER in the BLE 5 500K results shown in Fig. 7). The same applies to the DSSS employed in IEEE 802.15.4, although it helps in recovering errors (despite the higher number of beating valleys caused by the lower data rate). On the other hand, the addition of the Manchester pattern mapper in the BLE 5 125K PHY provides sufficient gain to survive beating.

#### Increasing CT density

The effect of increasing CT density is explored in Fig. 6. Experiments were run across all PHYs for a single transmitter (no CT), as well as increasing CT density from CT2 to CT12. Plots represent an average of multiple experiments run with randomly selected CT forwarders per experiment, while the same pseudo-random forwarding set remains consistent across each PHY. This averaging eliminates bias due to narrow and strong beating experienced by CT2 pairs such as Figs. 3e and 3f. Reliability drops significantly at CT3 due to the high data rate of the BLE 5 2M PHY, which requires a significant difference in received power between signals to experience the capture effect. This is consistent
While the start of a preamble can randomly coincide with a beating valley or peak, these results are relative to received packets (i.e., those for which the preamble was successfully detected) and hence have bias towards a certain initial phase relationship. This bias is further increased by calibration the receiver performs during the reception of the preamble. As the packet is being received, the beating changes the signal properties and this calibration is no longer optimal; before periodically returning to the optimal operation point with a frequency equal to the beating frequency. It is worth noting that this explains why beating is visible through an error distribution analysis, and that with no bias (i.e., no preamble) it would present as a flat error distribution.

High data rate PHYs benefit from packet repetition. As shown by Fig. 5 packet transmissions in high data rate PHYs span fewer beating valleys (potentially zero if the packet period is shorter than the beating period). Since the position of peaks and valleys is random, after several repetitions, i.e., with a higher TX_{N}, it is likely that a packet will not experience a valley during the preamble and will be correctly received. Note that TX_{N} is a core component of many CT-based protocols.

Beating frequencies are device-specific. As shown by Fig. 8 beating frequencies depend on the RFO between device pairs, and one cannot directly extrapolate results from a specific pair.

Preambles are sensitive to beating. While the start of a preamble can randomly coincide with a beating valley or peak, these results are relative to received packets (i.e., those for which the preamble was successfully detected) and hence have bias towards a certain initial phase relationship. This bias is further increased by calibration the receiver performs during the reception of the preamble. As the packet is being received, the beating changes the signal properties and this calibration is no longer optimal; before periodically returning to the optimal operation point with a frequency equal to the beating frequency. It is worth noting that this explains why beating is visible through an error distribution analysis, and that with no bias (i.e., no preamble) it would present as a flat error distribution.

Low data rate PHYs benefit from the coding gain. Fig. 7 shows a significant difference in reliability between the BLE 5 500K and 125K PHYs. Indeed, BLE 5 500K exhibits the worst performance of any of the PHYs compared in this section. It is likely that the convolutional coding employed by BLE 5 is sensitive to beating errors, while the gain seen using the 125K PHY stems from the additional pattern mapper redundancy over the payload (as mentioned in Sect. III). Similarly, while not achieving the same gains of BLE 5 125K PHY, the DSSS used in IEEE 802.15.4 halves the PER in comparison to the BLE 5 500K PHY. It is worth noting that results in this section do not consider significant external noise or interference, which may particularly penalize the very long packets of the BLE 5 125K PHY, as seen in the following section, and the use of the 500K PHY may again constitute an effective trade-off in harsh environments, particularly to survive intermittent jamming.

V. CT PERFORMANCE OVER DIFFERENT PHYs: EXPERIMENTAL EVALUATION WITH RF INTERFERENCE

This section presents an experimental study on the impact of different physical layers on CT-based protocols in the presence of RF interference. Specifically, we evaluate three CT-based flooding protocols on a large multi-hop network: Glossy, Robust Flooding (RoF), and Robust Flooding Single Channel (RoF (SC)), whose operations are depicted in Fig. 9.

Early CT literature adopted the flooding approach popularized in Glossy, which triggers transmissions after successful receptions, thereby alternating Rx and Tx slots at each hop. However, not only does the original Glossy approach operate on a single channel, meaning it is susceptible to RF
interference at that frequency, but this reception-triggered Rx-Tx technique means that Rx failures will result in a missed transmission opportunity \[10, 36\]. That is, using this technique, it is difficult to resume a CT flood if it is interrupted by interference. An alternative approach was taken by the authors of \[10, 37\], introducing back-to-back CT transmission slots (i.e., Rx-Tx-Tx) alongside robust frequency diversity through per-slot channel hopping. In this Robust Flooding (RoF) approach, the first transmission of a node is still triggered by correct reception, but further transmissions are time-triggered, with nodes synchronously hopping frequency at each slot. Specifically, at each slot, a node in RoF chooses a channel to from a successful reception channel list to receive.

We compare these two approaches (Glossy and RoF) as they are commonly used as primitives to construct more complex CT-based protocols, and are hence representative of wider CT literature. Furthermore, we introduce a variant of RoF – the RoF Single Channel (RoF (SC)) – to observe how this protocol performs w.r.t the single-channel environment used by Glossy.

A. Experimental Setup

We evaluate each protocol (Glossy, RoF, and RoF (SC)) by computing three key dependability metrics: end-to-end reliability, latency, and energy consumption – all metrics measured in hardware by the D-Cube testbed. We consider three scenarios characterized by the absence or presence of interference, denoted as no, mild, and strong interference.

D-Cube’s controllable RF interference is generated by its observer nodes (Raspberry Pi 3) using JamLab-NG \[28\]. Mild interference (aka level 2 in D-Cube) uses a power of 30 mW, generating interference for \(\approx 5\) ms every 13 ms period. Strong interference (aka level 3 in D-Cube) emulates the transmissions of multiple Wi-Fi devices across all the 2.4 GHz band. Each Raspberry Pi 3 node chooses a different channel, generating interference with a power of 200 mW for \(\approx 8\) ms every 13 ms.

Each protocol (Glossy, RoF, and RoF (SC)) is run on D-Cube’s data dissemination scenarios, i.e., those sending data from a single source to multiple destinations over a multi-hop network. To emulate event-based scenarios, we configure D-Cube to generate aperiodic messages with short (8B) payload for an alarm scenario and long (64B) payload for a condition monitoring scenario. Other experimental parameters are set as follows. We set the maximum number of transmission attempts per node during a flooding period (defined as \(TX_N\) and set to three in the example shown in Fig. 9) to 6 for all protocols and fix the flooding periodicity to 200 ms. In Glossy and RoF (SC) the radio frequency is set to 2.480 GHz (i.e., channel 39 in BLE and channel 26 in IEEE 802.15.4), while RoF hops between 3 different channels (2.4025 GHz, 2.425 GHz, and 2.480 GHz). Finally, we set the transmission power to 0 dBm, which leads to a network diameter between 6 and 10 hops depending on the employed D-Cube layout.

All the results shown in this section utilize publicly available implementations of Glossy and RoF which we subsequently ported to the nRF52840-DK platform supported by D-Cube.

B. Results

Reliability. Prior to the introduction of external interference sources, Fig. \[10\] shows that, as data rate increases, the evaluated PHY layers struggle to maintain reliability. RoF exhibits the highest reliability out of the three evaluated protocols, while its single channel alternative, RoF (SC), decreases rapidly at higher data rates in comparison to Glossy. Since the time-triggered back-to-back transmission approach of RoF and RoF(SC) does not allow nodes to resynchronize at every Rx slot (as in Glossy), nodes can be subject to synchronization errors due to drift. The high data rate PHYs are particularly sensitive to such errors: BLE 5 2M is only able to tolerate CT synchronization errors of up to 0.25 \(\mu\)s \[13\]. In general, longer transmission times result in a greater chance of encountering interference and corrupting the packet. This is reflected in the reliability difference between D-Cube’s long (64B) and short (8B) payloads under all three interference scenarios. This is additionally seen in the reliability of BLE 5 125K, where longer transmission times mean the PHY struggles to escape interference and results in surprisingly poor reliability across all three protocols. We also observe that the back-to-back repetition of packets in RoF and RoF (SC) improves reliability over Glossy under mild and strong interference. Furthermore, as expected, the frequency diversity introduced through RoF’s channel hopping mechanism has a significant impact on the performance of all PHYs, except for the BLE 5 2M PHY. This is likely due to the higher data rate of this physical layer. As the interference generated by JamLab-NG is periodic across multiple channels, if all RoF hopping channels are occupied for the duration of that interference, then the flood will fail. However, the longer transmission time of the PHYs using a lower data rate practically increases the chance that one of the repeated transmissions is successful, hence allowing a node to escape interference.

\[8\]https://github.com/ETHZ-TEC/Baloo/tree/2.0 - 212dcde

\[9\]https://github.com/ETHZ-TEC/robust-flooding - a0f3f38a
Latency. The end-to-end latency of CT-based flooding protocols is inherently linked to their reliability. Indeed, the brute-force repetition inherent in CT-based flooding protocols means that packets may successfully be received on poor channels, but much later in the flood. Fig. 10b supports this, and we observe significant latency jumps as the amount of interference increases. As D-Cube latency is only computed based on received messages, it is conceivable that low latencies can be achieved even when reliability is poor. This is particularly apparent in mild interference, where we observe in Fig. 10b that the BLE5 uncoded PHYs exhibit low latency despite poor reliability. In general, coded PHYs (i.e., BLE5 125K, BLE5 500K, and IEEE 802.15.4) have better performance with respect to latency. It is notable that under no and mild interference in RoF (SC), BLE5 500K latency increases in comparison to other PHYs and the other two protocols (Glossy and RoF). This is likely due to a combination of the lower data rate in comparison to the uncoded PHYs, alongside lower reliability due to its sensitivity to beating (as demonstrated in Sect. III and IV). Finally, Fig. 10b shows that, for shorter packets, the BLE5 125K PHY enjoys low latency similar to the other PHYs. This is likely due to its improved receiver sensitivity, which provides longer transmission ranges (and, hence, the ability to span the network in fewer hops).

Energy. Similar to latency, the energy consumption of all nodes in the network is intrinsically linked to the overall reliability. Unsuccessful reception means the radio needs to remain on for a longer time. As shown in Fig. 10c, although in principle higher data rate PHYs should have a lower energy consumption, this relationship with reliability means that for short payloads BLE5 1M and 2M are less energy efficient than the coded PHYs. However, the underlying PHY rate is still a fundamental factor in the node’s energy consumption. For long payloads, indeed, the lower data rates supported by the coded PHYs mean the radio can take a considerable time to transmit a packet, and incur greater energy consumption over the uncoded PHYs.

C. Key Observations

With respect to these results, we make a number of key observations on the network-wide performance of CT-based flooding protocols under interference as a function of the employed PHY.

At a network level, high data rate PHYs struggle even under no interference. Without the redundancy gains of coded PHYs, high data rate PHYs are sensitive to both desynchronization and beating, particularly at greater CT density. Even with the added benefit of frequency diversity, RoF still cannot achieve high reliability when using the BLE5 2M PHY. The BLE5 125K PHY is not necessarily the answer. Although performing well when there is no interference, BLE5 125K suffers from poor performance as soon as interference kicks in and packet size increases, taking a relatively large hit with respect to latency and reliability in comparison to the other PHYs.

BLE5 500K and IEEE 802.15.4 perform well under interference. Under interference BLE5 500K achieves higher reliability and similar or lower latency compared to other BLE5 PHYs, while performing worse than the other coded PHYs when there is no interference. This is consistent with the findings in Sect. III which showed that 500K will outperform other PHYs when there is a significant received power delta, which is likely to occur in high noise conditions. Furthermore, IEEE 802.15.4, on which much of the CT literature is based,
demonstrates similar high reliability under interference while benefiting from the increased data rate. If the level of network interference is unknown, CT protocols benefit from transmission on either the BLE.5 500K or IEEE 802.15.4 PHYs.

**RoF’s time-triggered transmission and channel hopping produce significant gains.** It is clear from Fig. 10 that the combination of back-to-back time triggered transmissions and channel hopping employed in RoF provides significant gains under all interference scenarios. However, results from RoF (SC) show that, without frequency diversity, there is a chance that at higher data rates, the interference duration may be longer than the flooding period. As a blunt instrument, TX.N could therefore be increased to take advantage of greater temporal redundancy and improve protocol reliability under interference.

VI. RELATED WORK

We discuss next related work and highlight how the contributions presented in Sect. III – V advance the state-of-the-art. **CT on different PHYs.** After the influential work by Ferrari et al. [4] published in 2011, a large number of researchers has started to study CT and develop CT-based protocols [1], [3], [5], [6], [7], [8]. While most of the early works targeted exclusively IEEE 802.15.4 devices using the 2.4 GHz band, in the last years, a few studies have shown the feasibility of CT on other physical layers supported by IEEE 802.15.4, such as the UWB PHY [40], [41], [42], as well as sub-GHz short-range [43], [44] and long-range technologies [45], [46].

A number of works have recently focused on studying the feasibility of CT on BLE [18], [19], [28], [47]. Specifically, Al Nahas et al. [18] verified the feasibility of a CT-based flooding protocol, named BlueFlood, on the different BLE 5 PHYs experimentally, and also reported its performance on IEEE 802.15.4 [28]. Schaper [19] studied the conditions to make CT successful in these PHYs in an anechoic chamber.

Different from these studies, our current work does not aim to prove the feasibility of CT on different radio technologies or PHYs, but instead to provide an in-depth characterization of the role of the physical layer on the reliability and efficiency of CT-based solutions employing IEEE 802.15.4 and BLE 5. To the best of our knowledge, we are the first to do this in a systematic manner by demonstrating experimentally the impact of errors induced by de-synchronization and beating distortion in CT-based protocols as a function of the employed PHY.

**CT performance under interference.** Several works have shown that CT-based data collection and dissemination protocols can outperform conventional routing-based solutions in terms of reliability, end-to-end, and energy consumption even in the presence of harsh radio interference [10], [11], [12], [13], as also highlighted in the context of the EWSN dependability competition series [14], [24], [25]. To sustain a dependable performance under interference, CT-based solutions have been enriched, among others, with mechanisms such as local opportunistic retransmissions [4], [48], [49], channel-hopping [10], [11], [50], [51], network coding [8], [9], [53], [54], [55], noise detection [11], [12], stretched preambles [13], data freezing [12], as well as an improved understanding of the network state [56], [57], [58].

However, most of these protocols have been implemented and evaluated with IEEE 802.15.4 technology only. In this paper, we are the first to study the performance of CT-based data collection protocols on a large scale under interference as a function of the employed PHY. We did this by evaluating the dependability of CT-based protocols on a large scale using modern multi-radio platforms supporting several PHYs, and by analyzing the impact of other factors such as the length of the transmitted messages and the harshness of the interference. **Impact of beating effect on CT.** A few studies have tried to underpin the foundations of concurrent transmissions on a signal level. Ferrari et al. [4] have simulated CT signals with Matlab and explained how accurately packets should be aligned in order to design reliable protocols. Other works [59], [60], [61] have analyzed CT signals theoretically and argued that it is difficult to generate ideal constructive interference, due to the timing errors caused by radio propagation and clock drift.

Liao et al. have been the first to argue that there exists a beating effect caused by innate CFO between device oscillators [1]. Specifically, in [2], the resultant signals are generated by Matlab and a TelosB node was used to observe how the DSSS modulation in IEEE 802.15.4 saves CT signals from the beating effect. More recent studies have demonstrated these beating effects generate periods of both constructive and destructive interference by observing the raw IQ samples of devices connected to an SDR using coaxial cables [28].

In this paper, to the best of our knowledge, we are the first to demonstrate how physical layer effects such as CFO-induced beating, and de-synchronization from hardware clock drift, directly affect the signal observed by a receiving node using over-the-air testbed experiments.

VII. CONCLUSIONS AND FUTURE WORK

To date, a significant volume of work has shown that CT-based protocols have an important role to play in providing robust and low-latency communication in mesh networks. Particularly in high interference environments, CT is a valuable tool allowing designers of low-power wireless protocols to mitigate the impact of harsh RF conditions. This paper provides the first systematic experimental evaluation into the role of IEEE 802.15.4 and BLE 5 PHY layers on CT performance, with important insights into how the choice of the physical layer can exacerbate or reduce errors due to beating, de-synchronization, and external radio interference.

Specifically, we find that the coding used by the BLE.5 500K PHY is effective against interference in sparse networks, but ineffective against beating, whereas the BLE.5 125K PHY is effective against beating, but long transmission times may mean that packets fail under intermittent interference conditions as modeled in D-Cube. Furthermore, we show that the BLE.5 1M and 2M high data-rate PHYs are not particularly robust against interference, but that repetition and short packet on-air times can improve the overall performance against beating. We conclude that the BLE.5 500K or IEEE 802.15.4 PHYs should
be used for long packets when operating in harsh wireless conditions, whereas the BLE 5 125K PHY should be used for short packets and when the interference is not high or the number of CT is high enough to increase the SNR (dense networks). On the other hand, in low-noise environments with few CT, the use of the BLE 5 2M PHY reduces errors due to beating, while supporting far higher data-rates. As the number of CT increases, however, BLE 5 125K provides significant gains over other PHYs.

While these findings are important to the design of CT protocols, there are a number of key areas that require additional research and further clarification. Crucially, greater understanding is needed around how beating errors affect a protocol’s scalability on a network level. While Sect. IV presents results on the impact of CT density, real-world RF conditions and deployments make it difficult to know the amount of concurrent transmissions received at each node. Furthermore, CFO is particularly sensitive to temperature. The relative frequency offset may therefore change over time, resulting in changes to the beating frequency. Finally, this paper has highlighted the effectiveness of coding in improving CT reliability. Techniques such as interleaving, i.e., bit shuffling, (which improves the robustness of forward error correction with respect to burst errors) and bit voting are missing in the analyzed physical layers, and would be a very effective addition to increase the reliability of CT.

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