A Case for Ultra-wideband Concurrent Transmissions in Wireless Control

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***Abstract*—Wireless networked control systems (WNCS) are at the forefront of academic and industrial efforts, due to the high deployment flexibility and low cost offered by their untethered, multi-hop operation. However, they pose the unavoidable challenge of matching the reliability and latency of wired systems, exacerbated by energy efficiency constraints. Mainstream solutions, in industry and academia alike, largely rely on routing-based protocol stacks for IEEE 802.15.4 narrowband radios.**

We identify an *alternative to the status quo* in the unexplored synergy between *concurrent transmissions (CTX)* and *ultra-wideband (UWB)* radios. Low-power wireless stacks based on CTX are known to offer order-of-magnitude improvements w.r.t. mainstream ones in reliability, latency, and energy-efficiency—i.e., the key WNCS requirements above. UWB is very popular in localization applications but rarely considered in multi-hop networking despite its high data rate and resilience to interference, yielding a beneficial impact on the requirements above.

We elicit the potential of this synergy via a novel UWB stack based on a state-of-the-art CTX design. We *quantitatively* demonstrate its effectiveness in supporting different closed-loop control strategies in a realistic scenario via experiments in a 36-node, 6-hop cyber-physical testbed enabling direct comparison between the original narrowband system and our UWB one. Results show that the UWB stack achieves 10× higher reliability and 3× lower latency with half the energy consumption, pushing the envelope of low-power networking support for wireless control.

***Index Terms*—Ultra-wideband, wireless networked control systems, concurrent transmissions.**

I. Introduction

THE penetration of low-power wireless communications into our society has been steadily increasing over the past few decades. The worldwide spending on the Internet of Things (IoT) market has been recently forecast to hit 805 billion dollars, with a 10.6% increase over the previous year [1]. Initially, the ability of wireless technology to bridge the digital and physical worlds has enabled a wide range of powerful consumer applications [2], [3]; more recently, it has led to a paradigm shift in the industrial context, with the transition from wired to wireless control as its cornerstone [4].

Wireless networked control systems (WNCS) are the embodiment of low-power wireless technology in the industrial domain and a fundamental technological infrastructure to lead the Fourth Industrial Revolution [5], [6]. In WNCS, real-time fine-grained measurements acquired by sensor nodes attached to the physical plant are transmitted to one or more controllers, which in turn compute and distribute control commands to instruct actuators on how to timely interact with the physical system and modify its state. All communication to and from sensors, actuators, and controllers takes place over the wireless channel, entailing a bi-directional exchange of commands and feedback across the low-power wireless network. By eliminating the need for bulky and expensive wired infrastructures, WNCS are envisioned to transfigure and optimise production processes, abating installation and management costs while increasing the flexibility, versatility, and scalability of industrial sites.

WNCS: Challenges for networking. At the heart of this technological revolution lies the ability to enable *reliable, low-latency, and energy-efficient* wireless control, a complex task whose partial fulfillment has thus far limited WNCS adoption [7], [8]. From a networking standpoint, packet losses and delays must be front and center in protocol design, as the magnitude and stability of latency and the delivery guarantees offered by wired communications are not necessarily present with wireless ones. Moreover, to take full advantage of the scalability and flexibility WNCS offer, power cables should be avoided, placing energy efficiency in the limelight given the cost and complexity of replacing batteries. Finally, the concerns above should be satisfied over *multi-hop* wireless networks as WNCS often exceed the limited communication range of low-power wireless devices.

Concurrent transmissions (CTX) in WCNS. These concerns have been tackled for over two decades, fueling academic prototypes as well as industrial standards with commercial adoption like WirelessHART [9], ISA100.11.a [10], and 6TiSCH [11]. Nonetheless, these conventional, well-established approaches show ample margins of improvement.

In this paper, we focus on seizing the novel opportunities offered by *concurrent transmissions*, a recent multi-hop networking technique that has been shown to offer order-of-magnitude improvements in reliability, latency, and energy-efficiency w.r.t. conventional techniques both in general [12] and in the WNCS context, where these benefits have been applied to both periodic [13] and aperiodic [14]–[16] control strategies. In this respect, aperiodic paradigms like event-triggered [17], [18] and self-triggered [19], [20] control are paradigmatic examples of the challenges and synergies between wireless communication and control. By exploiting the wireless medium only when necessary, i.e., when dictated by physical system conditions, these state-of-the-art control strategies abate control traffic w.r.t. the time-triggered sampling and communication typical of classic periodic approaches, while retaining the desired control and system performance (§II-A). On the other hand, the aperiodicity of communication makes it challenging to rec-

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oncile the opposite requirements of minimizing energy costs by keeping the network as quiescent as possible, extending battery lifetime, while enabling a fast and reliable reaction whenever a relevant event occurs.

A case for UWB-based WNCS. The aforementioned efforts from academia and industry, and specifically CTX-based ones, focused primarily on IEEE 802.15.4 narrowband as the target low-power wireless radio. This choice clashes with the recent proliferation of physical layers, standards, and radio chips.

Among the many available alternatives, here we focus on ultra-wideband (UWB) radios. UWB is best known for its ranging and localization capabilities, currently unmatched in the IoT ecosystem [21]. Nevertheless, we argue that it offers a unique match to WNCS requirements as well, albeit still awaiting to be explored and practically demonstrated.

The data throughput of UWB, an order of magnitude higher than IEEE 802.15.4 narrowband, is well-suited for high-speed, high-rate, latency-sensitive applications, opening new research perspectives, e.g., for fast feedback control of large, multi-hop systems. Likewise, by operating outside the crowded 2.4 GHz ISM band, UWB signals enjoy a significantly less interfered spectrum w.r.t. narrowband, which intrinsically helps in increasing the reliability of UWB communication.

Still, somewhat surprisingly, the applicability and impact of UWB for wireless control is largely unexplored. Only a handful of works (e.g., [22]–[25]) explore the potential of UWB in industrial settings, via single-hop scenarios and in-field link-quality estimation campaigns, thus neglecting networking aspects (e.g., packet delays and losses, node coordination, and energy consumption) crucial to the multi-hop systems germane to WNCS applications. We explore related work along with the necessary background in §II.

Goal, methodology, and contributions. The goal of this paper is to *show quantitatively that the combination of state-of-the-art CTX techniques and UWB communications unlocks performance (reliability, latency, energy efficiency) currently precluded to mainstream technologies in WNCS*.

Our investigation is *system-driven* and relies on *i)* the complete re-implementation of a state-of-the-art CTX-based narrowband WNCS atop UWB, and *ii)* the comparison of its real-world performance vs. the original, via experiments carried out in a multi-hop cyber-physical testbed emulating a closed-loop control system. Clearly, by its nature, this investigation cannot be generalized. Still, what we lose in breadth we gain in depth, as we can analyze a real system on a real network, therefore informing researchers and practitioners of the opportunity at stake and hopefully inspire follow-up research.

Among the many existing narrowband WNCS, we focus on the recent Wireless Control Bus (WCB) [16] (§III). Apart from its unmatched reliability and ultra-low energy consumption, our choice is motivated by the fact that WCB supports two paradigmatic strategies of wireless control—periodic and event-triggered—via a single protocol stack. This versatility allows us to extend our findings to a broad class of wireless control problems, amplifying the scope and relevance of our study. As a secondary aspect, as we contributed to the design of WCB we have a deep understanding of its operation and implementation, that we leveraged to design, implement, and configure the UWB-based variant we hereafter call uWCB, and to ensure a fair comparison against the original.

uWCB targets the popular DW1000 UWB transceiver [26]. We seize the opportunities it offers (e.g., high data throughput and TX-RX scheduling precision) to enhance the uWCB performance (§IV) by re-implementing WCB from scratch. However, we rigorously preserve the original protocol logic and structure, as changing these aspects would unavoidably bias the comparison with the original WCB, undermining a key dimension of our work. Along the same lines, the choice of the control test case and experimental setup also plays a key role in a comparison; therefore, we employ the same water-irrigation system (WIS) use case and cyber-physical testbed adopted in evaluating the original WCB. To enable this goal, we extended the experimental facility in [16] to support UWB communication (§V), in the same 36-node, 6-hop network, now part of the CLOVES testbed [27]. To the best of our knowledge, this new cyber-physical experimental setup is the first where narrowband and UWB coexist, enabling the evaluation of WNCS tested under virtually identical environmental conditions, yet over different radios with radically different PHY layers.

We first investigate quantitatively the *communication performance* (§VI) by analyzing each protocol phase in isolation, drawing parallels between uWCB and its original narrowband counterpart and exploring the limits of the former. Next, we build on this knowledge to directly compare the overall *system performance* via hardware-in-the-loop testbed experiments (§VII) on the WIS use case. Results demonstrate the clear superiority of the UWB variant, which enables closed-loop control of a 10-sensor, 5-actuator network over 6 hops with a latency $<$64 ms, 3$\times$ faster than the original WCB, while achieving 10$\times$ higher, near-perfect reliability with half the energy consumption. In a nutshell, the original narrowband WCB already outperforms the state of the art; yet, uWCB significantly outperforms it in all three dimensions key to wireless control—reliability, latency, energy-efficiency.

Finally, we discuss (§VIII) the implications of these and other findings that, based on the superiority of the combination of CTX and UWB, enable novel opportunities for research on WNCS and its application in real-world systems, and offer brief concluding remarks (§IX).

II. BACKGROUND AND RELATED WORK

We summarize the necessary background on the main topics of this work—WNCS, CTX, and UWB radios—along with the related state of the art.

A. Wireless Networked Control Systems

WNCS are networks of sensors, actuators, and controllers governing a cyber-physical system by communicating exclusively over wireless links. Their adoption is increasing, as WNCS offer remarkable advantages over wired solutions in terms of versatility and scalability along with lower installation and maintenance costs [5], [28]. Nevertheless, WNCS also exacerbate the control requirements concerning low and stable latency and high reliability, easier to guarantee atop a wired infrastructure, and introduce novel ones about energy efficiency, crucial to fully seize the opportunities offered by untethered communication [8], [29].

From time-triggered to aperiodic control. In traditional time-triggered approaches, controllers rely on the periodic acquisition of sensor data and the consequent periodic dissemination of actuation commands. This fosters simple implementations and detailed analytical frameworks accurately predicting the system performance and guarantees. However, these benefits often come at the price of conservative sampling periods based on worst-case analysis of the closed-loop system dynamics. While this is not necessarily an issue in wired systems, it is detrimental in wireless ones where conservative designs yield to high communication overhead and therefore energy consumption.

To meet the new WNCS requirements, the control community has therefore begun to explore alternatives focusing on aperiodic sampling strategies [4] that *dynamically* adapt control operations to system conditions. This opens ample opportunities to remarkably reduce communication, hence energy demands, while preserving control performance and guarantees [19], although at the price of slightly more complex analytical frameworks.

Different flavors of aperiodic control exist [29], with self-triggered [19], [20] and event-triggered [17], [18] being the most representative. Hereafter, we focus on the latter as it is the one at the core of our quantitative evaluation.

Event-triggered control (ETC) determines control update times *on the fly* via a triggering condition depending on sensor data. If the condition holds—or, in ETC jargon, if an *event* is detected—sensor nodes transmit their latest measurements to the controller, which uses them to update control commands immediately distributed to actuators. Otherwise, unlike time-triggered approaches, *no communication takes place*. Intuitively, event detection implies that the system is deviating from the expected control performance; therefore, control actions, inducing communication, are needed to re-establish the desired system behavior.

Key to maximizing the benefits and practical adoption of ETC in WNCS is the possibility to *i)* design *distributed* triggering conditions [30] that can be checked by sensor nodes based only on their local knowledge, and *ii) evaluate periodically* these triggering conditions, known as periodic ETC (PETC) [31], [32]. Crucially, although PETC retains a periodic *local sampling*, typically negligible in terms of energy consumption, it relaxes the periodic *communication of sampled data*, occurring only if and when an event is actually detected. It is this decoupling of local sampling and distributed reporting, always occurring together in time-triggered approaches, that unlocks unprecedented reductions in communication overhead and therefore energy consumption.

An ample literature exists on event-triggering mechanisms and modeling frameworks for stability analysis, covered in recent surveys [18], [33]. Unfortunately, despite the solid theoretical foundation, their real-world adoption is still limited, hampered by the lack of dedicated network stacks [8] resolving the fundamental tension induced by ETC between minimizing communication overhead during steady-state periods and ensuring rapid, reliable reaction upon event detections.

This gap has been recently filled by WCB [16], our baseline (§III). WCB offers the first, full-fledged network stack tailored to multi-hop ETC, used in [16] to demonstrate and quantify experimentally in a real-world cyber-physical testbed the benefits that ETC enables over periodic control. At the core of the design and performance of WCB are concurrent transmissions, discussed next.

B. Concurrent Transmissions

A cornerstone of protocol design in wireless communications is the need to minimize packet collisions due to concurrent senders. When multiple channels are available, packets can be transmitted on different channels, retaining concurrency while avoiding collisions and increasing throughput. However, if the same channel must be used, transmissions must be staggered to avoid concurrency altogether. In direct contrast, CTX-based protocols [12] enforce nodes to transmit *concurrently* and on the *same* channel, enabling extremely fast, reliable, and energy-efficient multi-hop communications. This approach, surprising at a first sight, relies on two phenomena, non-destructive interference [34] and the capture effect [35], that let nodes decode a packet with high probability despite the superposition of multiple signals if specific constraints on the timing and relative signal power of the received packets are met. Many low-power wireless technologies, notably including IEEE 802.15.4 narrowband [36], BLE [37], LoRa [38], and UWB [39], have been shown to support CTX, albeit with different, technology-specific constraints.

Glossy and friends. Glossy [36] was among the first to concretely demonstrate the effectiveness of CTX. In Glossy, an *initiator* node begins a flood by broadcasting a packet. The rest of the network listens for the packet; upon its reception, each node retransmits it immediately and concurrently with others, yielding a CTX-based flood that rapidly propagates from the initiator's neighbors to the periphery of the network. After transmission, nodes switch the radio back to reception and repeat this RX-TX pattern up to N times—the so called Glossy redundancy factor—to further enhance reliability; then the flood completes and nodes can enter sleep mode. By enforcing and exploiting tightly synchronized transmissions, Glossy yields fast, reliable, and energy-efficient network-wide multi-hop data dissemination as well as time synchronization, both key components of WNCS systems. Moreover, CTX do *not* rely on MAC or routing layers, and therefore do not incur the related overhead in, e.g., idle listening or route maintenance.

Since the appearance of Glossy, a multitude of protocol stacks [12] have seized these peculiar characteristics of CTX to support traffic patterns other than pure network flooding. These systems confirmed that the benefits of Glossy and, more generally, CTX directly translate to higher-level protocols. Further, they demonstrated reliability, latency, and energy efficiency far beyond the one of conventional, routing-based systems, as clearly and quantitatively shown throughout the multi-year EWSN Dependability Competition [40] where all top protocols have routinely been CTX-based.

CTX for wireless control. These protocols show that CTX can cover nearly the entire gamut of application requirements, and wireless control is no exception.

The system in [13] leverages CTX to support fast feedback control with stability guarantees and mode changes, achieving update intervals of 20–50 ms over a 3-hop wireless networks when combined with a periodic controller. Ma et al. [15] present a holistic control architecture integrating CTX-based communication and self-triggered control (STC), an aperiodic control paradigm where, unlike ETC, nodes do not instantaneously react to event detection but decide ahead of time the next triggering instant [19], [20]. The solution is compared against rate adaptation, itself implemented atop CTX. The synergy of CTX and STC is also explored by Baumann et al. [14] to effectively reallocate the bandwidth freed up by STC over multi-hop wireless network with fast update rates. Instead, WCB [16] combines CTX and ETC, showcasing the potential of this synergy for fast, reliable, energy-efficient multi-hop wireless control; further, it supports also conventional time-triggered control, therefore reuniting both control options, and target applications, in a single network stack.

Still, all these works focused mainly on narrowband IEEE 802.15.4, arguably the main player in WNCS. In contrast, a key contribution of this paper is to explore *for the first time in the literature* the alternative offered by UWB in the WNCS context, by quantifying experimentally the benefits it enables once combined with CTX.

C. Ultra-wideband Radios

UWB is an established, leading technology in the IoT arena. Its popularity surged with the introduction of low-cost, energy-efficient transceivers like the DW1000 [41], and increased dramatically in recent years with the inclusion of UWB chips in smartphones and smartwatches [42], finally bringing this technology into the mainstream consumer domain.

UWB in a nutshell. Unlike conventional narrowband radios, UWB transceivers encode information into short pulses (≤ 2 ns) whose energy is spread across a wide spectrum channel (≥ 500 MHz). These unique physical layer features enable UWB radios to establish the time of arrival of a received frame with high precision and, consequently, measure distances and determine positions with accuracy unmatched by other radio frequency (RF) technologies—arguably the main factor in UWB current popularity.

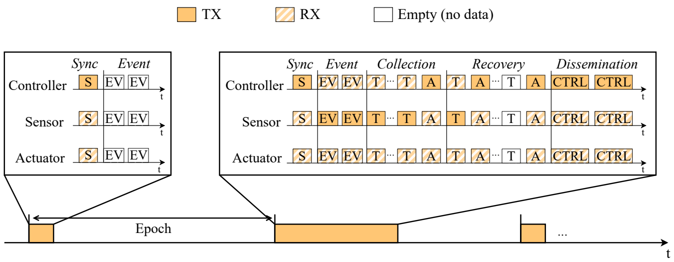
On the other hand, remarkable advantages are present also in the context of communication, where UWB enables fast and reliable packet exchanges. The IEEE 802.15.4 standard specifies a maximum data rate of 27 Mbps for the UWB PHY [43], with the popular DW1000 chip used in this work offering up to 6.8 Mbps. These are admittedly far from the data rates achieved by WiFi, that nonetheless incurs an energy consumption an order of magnitude higher than UWB. At the same time, the data rates of UWB are orders of magnitude higher than what supported by the narrowband PHY specified in the same standard, enabling UWB to abate packet on-air time while achieving a data throughput largely unprecedented for *low-power* wireless—an asset in latency-sensitive or high-rate applications. Likewise, the large bandwidth and low power spectral density of UWB signals translate to enhanced multipath immunity and limited co-existence issues with other RF technologies. Finally, UWB radios operate in the unlicensed bands between 3.1 and 10.6 GHz, i.e., above the notoriously crowded 2.4 GHz ISM band widely exploited by WiFi and other narrowband systems. This makes UWB transmissions significantly more reliable, especially in the noise-prone environments where WNCS are typically deployed, e.g., office buildings and industrial settings [23]. A threat to this state of affairs is the recent Wi-Fi 6E standard [44] enabling devices to operate in the 6 GHz frequency band overlapping with UWB channels 5–7. However, countermeasures exist [45] and several other UWB channels remain free from Wi-Fi interference.

UWB for wireless control: An open question. Despite these remarkable characteristics, the adoption of UWB technology for wireless communications is still limited and its exploitation for WNCS essentially absent. Research on this topic is mainly confined to the link quality assessment of UWB transmissions in industrial settings [23], [24] or single-hop control scenarios [22]; a far cry from real-world WNCS conditions and multi-hop deployments.

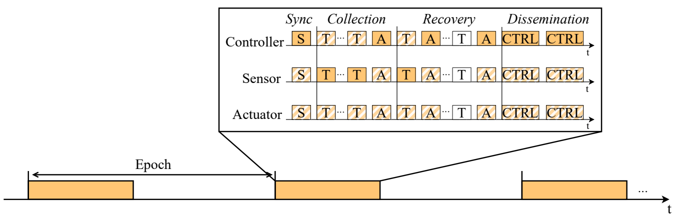
On the other hand, UWB radios have been shown to support CTX, enabling their exploitation with the unprecedented performance observed in narrowband—and more. The work in [39] laid the ground for these efforts by precisely eliciting, with micro-benchmark experiments in a dedicated setup, the conditions for successful CTX in UWB and the resulting tradeoffs, along with design guidelines. This enabled the exploration of the synergy of UWB and CTX in full-fledged systems, e.g., to coordinate UWB devices towards localization [46] and proximity detection [47], [48] as well as in protocol stacks offering multi-hop communication primitives targeting different traffic patterns and application demands [49]–[51]. In both contexts, UWB CTX-based systems have repeatedly proven their ability to ensure fast and reliable communications along with low energy consumption.

In this paper, we reconcile the two perspectives above, UWB networking and wireless control, by exploring if and how CTX-based techniques can be exploited to reposition UWB as a valid alternative to mainstream narrowband technologies in fulfilling the specific WNCS networking requirements. We achieve this goal by reimplementing the state-of-the-art WCB system [16], concisely described next. Towards this end, we took advantage of the peculiarities of UWB, while remaining true to the original high-level protocol design. The resulting artifact, called uWCB in this paper to distinguish it from the original WCB, is to the best of our knowledge *the first UWB system providing support for WNCS*. We extensively evaluate its performance against the one reported in [16] for its original narrowband counterpart by exploiting the same cyber-physical setup with real-world networking. This enables a direct comparison in the same conditions, showcasing concretely and quantitatively the potential of UWB for wireless control.

Next, we offer a concise description of the high-level design of WCB, retained in uWCB, followed in §IV by a discussion of the salient aspects of its implementation over UWB.



(a) Supporting event-triggered control: WCB-E.



(b) Supporting periodic control: WCB-P.

Figure 1: The Wireless Control Bus, WCB.

III. WCB: Wireless Control Bus

Wireless control poses challenging and conflicting networking requirements, further exacerbated by ETC. Minimizing the network overhead during steady-state—i.e., when control traffic is not present in ETC—is crucial to translate the efficient use of communication resources enabled by ETC into energy savings. Conversely, when an event is detected both the collection of readings from *all* sensors at the controller, required by distributed ETC schemes (§II-A), and the dissemination of new actuation commands should be timely and reliable, to retain control guarantees and performance. WCB exploits CTX to address these ETC challenges while also offering efficient support for conventional, time-triggered periodic control.

Protocol structure. WCB follows the common structure of CTX stacks, i.e., it divides time into epochs that repeat periodically. In WCB, periodicity is determined by the PETC sampling period (§II-A). Each epoch is composed by an initial active portion where communication occurs, followed by a typically much longer sleep portion where nodes turn off their radio to spare energy (Figure 1). The active portion is structured into the following phases, each containing non-overlapping time slots where distinct Glossy floods are executed: *Synchronization*, *Event*, *Collection*, *Recovery*, and *Dissemination*. The schedule of the active portion, and therefore its duration, is not defined a priori; to support ETC efficiently, WCB varies it at runtime according to system conditions.

The *Synchronization phase*, common to many CTX stacks, initiates the epoch. A Glossy flood from the controller is executed in a dedicated S slot and exploited to time-synchronize the network after a potentially long sleep period. Tight synchronization is key to CTX and provides a common time reference for control. After synchronizing, sensor nodes acquire new samples, check their triggering conditions and perform the *Event phase* as a series of floods in dedicated EV slots. This phase is crucial in WCB, efficiently solving the ETC dilemma between staying awake to retain control performance or promptly going to sleep to save energy. Sensor nodes at which the triggering condition hold (if any) signal the network to remain awake and participate in the subsequent collection by transmitting a small, identical event packet in every EV slot. If no node transmits this packet, the absence of packet reception in the Event phase implies the absence of event detection; no further action is required and the network can immediately re-enter sleep until the next epoch (Figure 1a, left). Otherwise, if an event packet is received, the schedule proceeds (Figure 1a, right) with the *Collection phase*, where all sensor nodes communicate their updated measurements to the controller, each initiating an isolated flood in a dedicated T slot. Collection ends with the controller acknowledging the received packets by flooding a cumulative ACK bitmap in a dedicate A slot. The following *Recovery phase* serves as a safety net to collect the missing packets. If all sensor readings have been ACKed, nodes can safely enter sleep. Otherwise, the network remains active and unacknowledged nodes concurrently initiate Glossy floods in the T slots in the attempt of communicating with the controller, which next acknowledges received packets in A slots. This TA sequence ends when all packets are acknowledged and the network safely enters sleep until the final dissemination or a predefined number R of TA slots have elapsed. Leveraging the collected readings, the controller generates commands for each actuator. Once aggregated in a single packet, these are flooded in one or more CTRL slots as part of the final *Dissemination phase* and immediately applied by actuators upon reception. After the last CTRL slot, all network nodes enter sleep until the start of the next epoch.

Supporting periodic control. WCB is designed to efficiently support ETC, yet it can be easily tailored to periodic control. Indeed, the latter can be seen as a degenerate case of ETC where the triggering condition *always* holds, i.e., sensor readings should be collected and new actuation commands disseminated in *all* epochs. This makes the distributed coordination provided by the Event phase superfluous, yielding the fixed, periodic schedule in Figure 1b. Whenever relevant to distinguish the two variants, we refer to the one supporting ETC as WCB-E and to the periodic one as WCB-P.

IV. uWCB: Exploiting UWB features in WCB

uWCB, our implementation of WCB over UWB, takes full advantage of the opportunities offered by the DW1000 chip to enhance its performance, as detailed next. Nevertheless, it also preserves the original protocol design (§III), enabling a fair comparison between the two variants (§VII).

Implementation details. We implement uWCB atop Time Slot Manager (TSM) [50], a publicly-available kernel designed to simplify and foster the development of time-slotted CTX protocol stacks in UWB. By leveraging the new capabilities of modern UWB chips, TSM ensures tight time synchronization and precise TX and RX scheduling, key functionalities that we extensively exploit to enhance the reliability, latency, and energy efficiency of uWCB and the Glossy communication primitive it relies on.

Specifically, instead of keeping the radio on for the entire flood duration, we reduce RX time and energy consumption in

Glossy by letting nodes listen for ≈32 µs (half the preamble duration plus a small guard time) at the beginning of every RX slot and immediately switch the radio to idle if no preamble symbol is detected within this period. Similarly, inspired by [39], we increase the flood reliability by slightly desynchronizing transmissions by inserting a small, random TX delay (up to ≈1 µs) on a per-slot basis. Indeed, we empirically verified that this improves reliability in UWB, especially when multiple nodes transmit different packets concurrently, as in the Recovery phase (§III).

Finally, for each uWCB protocol phase, we leverage the aggressive Glossy retransmission scheme proposed in [52] where, after a successful RX, all retransmissions occur in sequence. By reducing the number of RX slots to schedule, this variant slightly shortens the flood duration w.r.t. the original Glossy scheme [36] employed in WCB, at the price of a minor decrease in reliability. More importantly, this design choice is crucial to properly exploit UWB, where the energy cost of reception is almost twice than transmission.

Time synchronization. Another aspect worth commenting upon is time synchronization, crucial to any CTX-based approach and therefore also to uWCB and the original WCB. Nevertheless, although both systems rely on controller initiated Glossy floods—i.e., S, A, and CTRL—to synchronize, UWB is known to intrinsically provide higher network-wide time synchronization w.r.t. narrowband. For instance, the work in [49] reports an average time offset of only 26 ns over 4 hops in UWB, with a standard deviation of 3.89 ns—nearly *three orders of magnitude* lower w.r.t. the 2.5 μs reported in the original Glossy [36]. This provides a very accurate time synchronization *inside* a flood. Even *across* floods, i.e., in the active part of an epoch, the accumulated clock drift is small. For example, in our test case in §V, even considering a worst case frequency offset of ± 10 ppm between devices and no resynchronization during A and CTRL slots, the clock drift in uWCB remains <1.5 μs, i.e., comparable to the random TX delay mentioned above and therefore negligible in practice. As for the drift between two consecutive epochs, it essentially depends on their duration; if this reaches minutes or higher, the clock drift among nodes may become significant. However, accounting for these long epochs is an issue shared by all CTX-based approaches, and outside the scope of this paper. Moreover, we observe that *i)* techniques exist to address the problem, e.g., the recent one in [53], and *ii)* once again, the magnitude of the problem is significantly smaller when using UWB, due to the higher accuracy and stability of the clocks employed, as already noted.

Enhancing the EV phase. Reliable *and* energy-efficient network-wide reporting of event detection is what enables low-power wireless ETC systems to unleash their full potential.

In WCB-E, this is achieved by the EV phase, whose reliability and efficiency are improved by using local RX errors as an indicator that an event has been detected in the network.

In uWCB, we push this technique further, empowered by the rich and accurate information offered by the DW1000 chip. Specifically, upon an RX error, the receiver not only locally determines that an event is being reported in the EV phase, but also re-propagates an event packet as in the case of correct reception. This avoids interrupting the EV flood when packet collisions happen at nodes that, due their peculiar position, may be crucial to propagation. On the other hand, this technique is prone to false positives; a single one at a receiver can potentially trigger a network-wide false event detection.

We mitigate this aspect by *differentiating* among RX errors. Those *other than* the start-of-frame-delimiter (SFD) timeout (the UWB radio detects a preamble but not an SFD) and the physical header error (PHE, the SFD is correctly received but the physical header is not) always lead to an event propagation. Instead, for the SFD timeout and PHE errors, this occurs only if the received signal power exceeds a specific threshold. Indeed, we observed, in line with the literature [45], that these errors are the most affected by noise and can be incorrectly reported by the radio even in the absence of a packet. We show in our evaluation (§VII) that this selective use of RX errors to ensure progress of EV floods achieves near-perfect reliability. Before that, however, we need to discuss the experimental setup our evaluation is based upon.

V. Experimental setup

To evaluate the impact and practical applicability of using UWB communication for wireless control it is crucial to compare the performance of WCB and uWCB through real-world cyber-physical experiments performed in *exactly* the same network topology and control test case. However, to the best of our knowledge, there is no existing cyber-physical testbed that supports both UWB and narrowband radios. We overcome this limitation by extending the experimental framework in [16] to support UWB. We describe the key aspects characterizing our experimental setup, starting with the targeted application.

Control test case: A water irrigation system. In the control literature, water irrigation systems (WIS) are a canonical application example [54]–[57]. They are widely studied in the simplified, small-scale form of the double-tank regulation problem [20], [58] and typically characterized as a set of large-scale pools connected in series via controllable gates. The control problem is to dynamically regulate the gate openings to keep the water level in each pool close to its set point despite off-take disturbances. This enables an optimal utilization of each pool while avoiding loss of water due to spillover.

The test case we use is the same adopted to evaluate WCB, in line with our goal to compare it against uWCB as much as possible in the same conditions. Figure 2 offers a simplified view of the 5-pool system considered in §VII. Each pool is instrumented with two types of sensors, flow (F) and height (H), and one actuator (A). Actuators and flow sensors provide flow control and measurement capabilities to the gates. Height sensors, instead, measure the level of the water at the end of each pool, close to the next gate. Information from all sensors in every pool is collected at a centralized entity, the controller (C), which in turn computes and distributes control commands, one for each actuator. As WISs can span long distances, additional relay nodes (R) are typically exploited to interconnect sensors, actuators, and the controller in a single, large-scale, multi-hop wireless network.

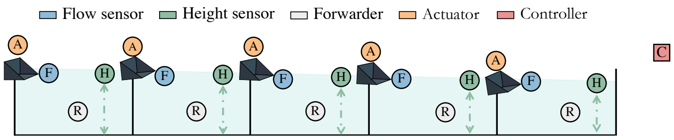


Figure 2: A simplified view of the 5-pool WIS test case (§VII).

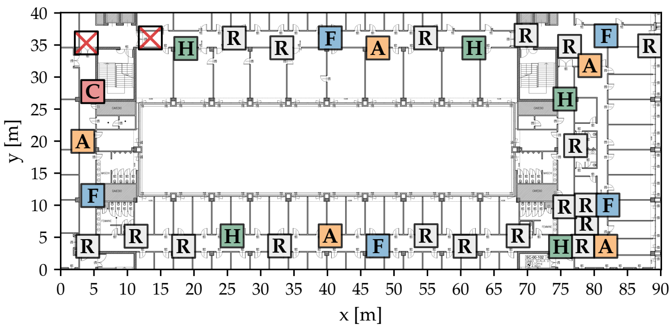


Figure 3: The testbed used in our experiments. The node placement and role in the emulated WIS is the same as in [16]. However, in this paper each node features both a narrowband (CC2538) and UWB (DW1000) radio. Colors follow the same convention of Figure 2. The crossed nodes are disabled to increase network diameter.

We refer interested readers to [16] for further details, including a formalization of the WIS model and of the centralized state-feedback controller used in our evaluation (§VII).

A WNCS testbed for narrowband and UWB. Our cyber-physical testbed offers a hardware-in-the-loop setup composed of two main components: *i)* a plant model, implemented in MATLAB/Simulink, emulating the physical system under study, and *ii)* a multi-hop wireless network with narrowband and UWB low-power wireless nodes where protocol stacks can be tested. The plant model, in our case the WIS, runs on a dedicated computer. Each wireless network node, instead, consists of two co-located platforms connected to the same Raspberry Pi (RPi): a Zolertia Firefly [59] and a Qorvo EVB1000 [60]. The former is equipped with a CC2538 2.4 GHz IEEE 802.15.4 narrowband radio, while the latter hosts a DW1000 UWB radio. To the best of our knowledge, this experimental testbed is *the first* enabling to test narrowband and UWB WNCS in virtually identical network conditions. Interactions between the plant model and the wireless nodes follow a predefined pattern: the plant model receives as input the actuators state changes from the network, and outputs sensor readings to be fed to the wireless devices. The RPis *i)* govern this information exchange, which occurs out-of-band via TCP/IP over Ethernet to avoid interfering with the operation of the wireless stack under investigation, and *ii)* enable automated, remote execution of experiments.

Control and network topology. We rely on CLOVES [27], a large-scale, publicly accessible narrowband and UWB testbed infrastructure deployed at the University of Trento (Italy). The testbed portion we use consists of 36 nodes installed on the ceiling of office corridors, covering an 83×33 m^2 area (Figure 3). This is the largest and most complex topology in [16], here complemented by the presence of UWB devices next to narrowband ones. We disabled the crossed nodes to prevent direct links—both narrowband and UWB—between the top and left corridors, yielding a 6-hop, mostly linear network topology. Figure 3 shows also the number and position of the control nodes enabling closed-loop control. The 10 sensors and 5 actuators are placed throughout the testbed; therefore, about half of the network nodes are actively involved in closing the control loop. These include also the controller, which is positioned at one network extreme, forcing all data flows to proceed along the same path and, likewise, all control messages to proceed in the opposite direction; a single node on the bottom left connects the controller with the rest of the network. Given the limited spatial and receiver diversity we induced, alongside the abundant signal reflections naturally caused by corridors, this topology is particularly challenging and therefore useful to investigate the reliability of low-power wireless control stacks.

Radio and TSM configuration. We configure uWCB to communicate on channel 4, with 64 MHz pulse repetition frequency (PRF) and the maximum TX power recommended by the manufacturers for this combination of settings [41]. To minimise latency while preserving energy consumption, we exploit the shortest UWB preamble symbol and highest data rate offered by the DW1000, i.e., ≈64 μs and 6.8 Mbps, respectively. The duration of TSM slots is set to 456 μs, enough to accommodate the reception of the largest uWCB data packet and its processing time. For WCB, we keep the same configuration exploited in [16].

VI. CHARACTERIZING uWCB

Before delving into the system performance of uWCB, we empirically study the reliability and latency of its protocol phases in isolation. In the process, we draw parallels with the narrowband counterpart, eliciting the main advantages provided by our UWB stack.

Methodology. For each uWCB slot type we perform dedicated micro-benchmark experiments. Each experiment consists of >65,000 Glossy floods (i.e., >2 million reception attempts across all nodes) with the same topology, initiating nodes, and packet sizes as in [16]. This enables us to directly compare the per-slot performance of uWCB against the original narrowband stack. The duration W_x of each uWCB slot, $x \in \{\mathsf{S}, \mathsf{T}, \mathsf{A}, \mathsf{CTRL}, \mathsf{EV}\}$, is determined analytically based on the network diameter H, the Glossy redundancy factor N_x, and the duration W_{TSM} of a TSM slot. To provide each node with N_x reception chances per flood, we set $W_x = (H + N_x) \times W_{TSM}$, where H=6 and W_{TSM}=456.4 μs (§V).

Dedicated, single-initiator slots. We begin by evaluating the performance of uWCB in slot types with a single flood initiator, i.e., all except EV. Table I compares WCB and uWCB in terms of *i)* mean packet delivery rate $\overline{PDR}$ for the *whole* network, and *ii)* slot size W, a proxy for the maximum flood duration.

Results showcase the reliability and latency improvements enabled by the UWB stack. When configured with the same

Table I: Reliability of WCB and uWCB configurations. W is expressed in ms. WCB results are taken from [16].

	WCB			uWCB					
Slot Type	N	W	$\overline{PDR}$	N	W	$\overline{PDR}$	N	W	$\overline{PDR}$
S	3	10	0.99993	3	4.11	1.0	1	3.19	0.99988
T	2	9	0.99914	2	3.65	0.99998	1	3.19	0.99960
A	3	11	0.99994	3	4.11	1.0	1	3.19	0.99986
CTRL	2	11	0.9998	2	3.65	0.99999	1	3.19	0.99988

Table II: Reliability of the EV phase in WCB and uWCB. WCB results are taken from [16] ($N = 2$, $W = 6$ ms). uWCB is configured with $N = 1$ and $W = 3.19$ ms.

	WCB		uWCB
U	$\overline{EDR}_{E=1}$	$\overline{EDR}_{E=2}$	$\overline{EDR}_{E=1}$
1	1.0	1.0	1.0
2	0.9994	0.999997	0.999999
3	0.9988	0.999993	1.0
5	0.9984	0.99998	1.0
7	0.997	0.9998	1.0
10	0.989	0.998	1.0

Glossy redundancy factor N_x adopted in WCB, uWCB offers *more than one order of magnitude higher reliability*. In practice, with uWCB only 48 T packets and 19 CTRL ones were lost out of the 2,222,880 expected, respectively. Arguably, UWB communications are less subject to external interference and less influenced by the number of nodes transmitting concurrently within the flood. As for latency, the beneficial impact of the higher UWB data rate becomes evident by comparing the maximum flood duration W_x. This parameter can be configured with a *duration 2 to 3 times shorter* than in WCB, which directly translates in a corresponding reduction in worst-case latency.

These results suggest that to achieve a reliability similar to WCB, a less redundant protocol configuration (i.e., smaller N_x) can be employed in uWCB, unlocking further advantages in latency and energy consumption. We verified this expectation empirically via dedicated experiments, whose results are summarized on the right side of Table I. Even when redundancy is brought to a minimum (N_x=1, i.e., nodes transmit packets only once per Glossy flood) uWCB ensures more than 3-nines reliability; this is close, and in some cases better, than narrowband while unlocking up to 3.45× latency improvements w.r.t. WCB. Notably, out of the few packet losses in uWCB, most occur at the same few nodes, likely affected by severe signal reflections. The majority of the network, instead, consistently experiences perfect reliability across experiments.

Multiple-initiator slot: EV. Table II compares the mean event detection reliability ($\overline{EDR}$) of WCB and uWCB, computed as the total number of event detection reports successfully received at all network nodes over the total amount expected. Each row refers to the number $U \in [1 \ldots 10]$ of concurrent event originators, i.e., the sensor nodes in our test case (§V).

Results demonstrate again the superiority of the UWB variant. In uWCB, a *single* EV flood with N_{EV}=1 is enough to guarantee perfect $\overline{EDR}$, independently from U. In practice, across all experiments only *1 event notification out of 6 millions* was lost. With the original narrowband WCB, a similar dependability cannot be reached even when doubling the number of EV slots scheduled per epoch (E=2) and increasing the amount of packet retransmissions per Glossy flood (N_{EV}=2). Specifically, reliability in WCB degrades as the number of concurrent event senders, and therefore contention, increases; with U=10, $\overline{EDR}$ falls below 3-nines, while uWCB still ensures perfect event reporting.

This remarkable reliability can be ascribed to two factors: *i)* the ability of uWCB to *select* the RX errors to be exploited for continuing the propagation of event packets (§IV), and *ii)* the intrinsic higher reliability of UWB communication (§II).

False positive event detections. On the other hand, relying on RX errors and propagating them may expose uWCB to false positives in event detection. For instance, the energy of noise present on the channel, e.g., due to other RF transmissions, can be mistaken by the DW1000 chip for a valid UWB signal [45], leading the radio to spontaneously trigger an RX error even in absence of an actual transmission. If this occurs during the EV phase, uWCB nodes incorrectly propagate an event packet that in turns triggers the data collection in vain (Figure 1), increasing the overall energy consumption. We verified empirically via dedicated experiments with all nodes synchronously scheduling 50 million *negative* EV floods (i.e., without *any* initiator) that the rate of false positives in uWCB is remarkably low: $<$ 0.00287%. Overall, these results demonstrate that the inner mechanics of EV floods in uWCB can be exploited in practice, bearing a negligible risk of false positives while ensuring very high reliability of event detection (Table II).

VII. WCB vs. uWCB: System performance

We now ascertain the applicability and performance of uWCB for wireless control by focusing on the WIS test case and carrying out an extensive experimental campaign in our dual-radio cyber-physical testbed (§V). We compare against the original WCB stack, which already yields state-of-the-art performance in reliability, latency, and energy consumption, and explore the efficacy of uWCB in supporting both periodic and event-triggered control via uWCB-P and uWCB-E, respectively (§III). Results are averaged over multiple hardware-in-the-loop testbed experiments, each emulating a full day (1440 epochs) of plant operation.

A. Protocol configurations

Table III summarises the WCB and uWCB configurations adopted hereafter. For the narrowband stack, we follow the same parameter choices in [16] but further enhance WCB latency and energy consumption by optimizing low-level protocol details, i.e., we reduced to a minimum the RX guards before the S phase and in between each WCB slot. For uWCB, we explore two configurations informed by the analysis in §VI: uWCB$_{N\geq1}$ and uWCB$_{N=1}$. The former replicates the original WCB configuration for all protocol phases except the Event one, in which a *single* EV flood per epoch is scheduled (E=1) with no retransmissions (N_{EV}=1), given the superior event

Table III: WCB and uWCB configurations in §VII. The values W_x are in ms. E and C indicate to the number of event and control slots scheduled per epoch, R represents the maximum number of TA pairs in the Recovery phase (§III).

	N_S	W_S	N_{EV}	W_{EV}	N_T	W_T	N_A	W_A	N_{CTRL}	W_{CTRL}	E	R	C
WCB	3	10	2	6	2	9	3	11	2	11	2	3	2
uWCB$_{N\geq1}$	3	4.11	1	3.19	2	3.65	3	4.11	2	3.65	1	3	2
uWCB$_{N=1}$	1	3.19	1	3.19	1	3.19	1	3.19	1	3.19	1	3	2

Table IV: WCB vs. uWCB in hardware-in-the-loop experiments: Reliability of the Event, Collection+Recovery, and Dissemination phases; fraction of epochs where the Recovery phase occurred; mean and min/max latency of the end-to-end control loop, from the beginning of the epoch to the receptions of the actuation commands.

		#Events	**Per-phase reliability [%]**				**End-to-end Latency [ms]**	
			Event	Collection+Recovery	Dissemination	Epochs with Recovery	Mean	Min/Max
WCB	Periodic	—	—	100	100	0.6	190.27	188.42/204.07
	ETC	151	100	100	100	0.1	203.18	201.29/215.88
uWCB$_{N\geq1}$	Periodic	—	—	100	100	0	70.32	69.40/71.70
	ETC	151	100	100	100	0	73.52	72.60/74.89
uWCB$_{N=1}$	Periodic	—	—	100	100	0.3	59.34	58.43/60.76
	ETC	152	100	100	100	0.05	62.53	61.62/63.90

detection reliability demonstrated by the UWB stack (Table II). Instead, in uWCB$_{N=1}$ we configure the underlying Glossy layer to minimize redundancy, and in turn latency and energy consumption, by setting N=1 for *all* protocol phases. A single event flood per epoch is scheduled (E=1) as in uWCB$_{N\geq1}$.

B. Network performance

The question whether uWCB can be exploited for wireless control hinges on its reliability and timeliness, whose analysis is the first target of our experimental campaign. Table IV directly compares the results for WCB and uWCB.

Reliability. uWCB ensures perfect event detection, sensor reading collection, and command dissemination, similarly to WCB. However, unlike WCB, it achieves zero packet losses even when the no-redundancy configuration (N=1) is employed. These results confirm at once the effectiveness of the overall WCB design, yielding perfect reliability regardless of PHY layer, radio chip, and type of controller adopted, alongside the higher reliability of the UWB stack. An effect of the latter is that the Recovery phase triggers significantly less often than in WCB, with clear benefits for energy consumption (§III). Remarkably, with uWCB$_{N=1}$ Recovery is triggered half of the times w.r.t. WCB and *never* with uWCB$_{N\geq1}$.

Actuation latency. The impact of the PHY layer becomes even more evident when analyzing the end-to-end latency of the two solutions, measured as the time elapsed between the beginning of an epoch and the delivery of the actuation commands. Both systems ensure remarkable, sub-second closed-loop control (Table IV). Nevertheless, the higher UWB data rate, along with the ability to precisely schedule the radio TX/RX (§IV), enable uWCB to drastically speed up protocol operation. Indeed, uWCB$_{N\geq1}$ delivers actuation commands 2.7× faster than WCB; further, the delta between the two increases with uWCB$_{N=1}$, 3.2× faster than the narrowband stack. Looking at these results from another perspective, in ∼200 ms, i.e., the time required by WCB to close the feedback loop, uWCB can support control systems with *5× more sensor nodes* or provide closed-loop control over a *3× larger* network. Moreover, not only the end-to-end closed-loop control latency is significantly reduced in absolute terms, but it is also *extremely stable* in uWCB; the minimum and maximum latency with uWCB are within ±1.2 ms of the mean (Table IV). These performance improvements clearly demonstrate the potential of UWB-based WNCS: by radically changing the existing trade-offs in terms of latency and scalability, UWB can dramatically expand the boundaries of applications and systems that can benefit from low-power wireless control. Finally, it should be noted that our baseline, the original WCB, already offers state-of-the-art performance currently unmatched by standard and mainstream routing-based solutions and, in many cases, even CTX-based ones. As a consequence, a direct comparison between uWCB and these solutions is likely to unveil even larger benefits.

C. Energy consumption

Reliability and timeliness are crucial to control performance, yet staple WNCS applications rely on battery-powered devices, adding energy efficiency to the requirements. This aspect is particularly relevant for UWB, whose use for communication is often dismissed due to the higher TX/RX energy costs w.r.t. narrowband. We determine quantitatively whether and to which extent this holds in practice by comparing the energy consumption of WCB and uWCB.

Methodology. We compare the two stacks in function of the time and energy spent by nodes with the radio in TX, RX, or idle mode within the active portion of an epoch (T_{active}). We inspect uWCB radio activity via the Radio State Monitor module [50], a reusable component designed to precisely estimate the time spent by the UWB radio in the various states during protocol operations. For WCB, instead, we *i)* exploit Energest [61] to trace the time T_{on} nodes remain in TX or RX within an epoch, and *ii)* compute the radio idle time as T_{idle}=T_{active}−T_{on}. Finally, we convert both radio timings into energy consumption (J_{on}, J_{idle}) by considering the reference voltages and nominal currents drained by the CC2538 [62] and DW1000 [41] transceivers in each radio state, as stated in the related datasheets [26], [62].

When the transceiver is neither in TX nor RX, it remains in the less expensive idle state, which is nonetheless significantly more energy-hungry than the sleep or deep sleep states. The only case in which nodes can enter these latter radio states during T_{active} is upon a successful Collection phase. In this situation, *all* measures have been received by the controller; no retransmission is required and the network as a whole can safely spend the entire Recovery phase in a sleep state, until the dissemination of actuation commands via CTRL floods occurs at the end of the epoch (§III). For the sake of simplicity, our analysis neglects the energy spent while in sleep, given that *i)* its contribution to energy expenditure is marginal in both systems, orders of magnitude lower than TX, RX, and idle states, and *ii)* the Recovery phase takes only a small fraction of the total protocol execution time.

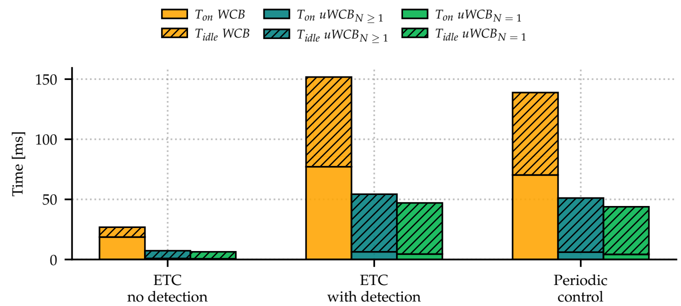
Per-epoch analysis. We first focus on individual epochs, which allows us to analyze separately the system dimensions affecting energy consumption.

Figure 4 offers an overview of the results, further summarized in Table V in terms of the overhead induced by WCB over the UWB variants. The significantly lower latency we already commented upon (§IV) translates into a similarly shorter T_{active}. Its duration in WCB is 3.2× longer (Table V, left) with periodic control and when an ETC event is triggered and control actions are taken; up to 4.2× when instead no ETC event is generated. Moreover, the fraction of time the two stacks spend in each radio state is also very different (Figure 4a). uWCB keeps nodes in idle state for up to >90% of the time; in contrast, in WCB this fraction of time (T_{idle}) is comparable to the time spent in TX/RX (T_{on}).

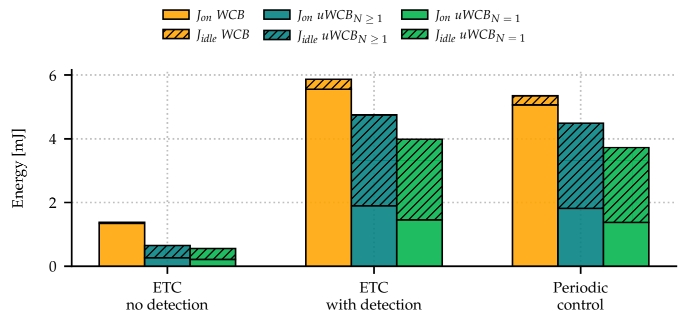
The more efficient radio utilization in uWCB hinges on two factors. The first one is the design of the TSM kernel that, by exploiting the ability of the DW1000 chip to schedule precisely the TX/RX times and automatically managing the time synchronization mechanisms necessary to CTX, ensures a fast switching of the radio from RX to idle when nothing is actually received (§IV). The second, and more relevant, is the significantly higher data rate of UWB w.r.t. narrowband, enabling uWCB to drastically reduce the time needed to transmit or receive a packet, compensating for the higher energy costs these operations incur in UWB.

The impact of the above on energy consumption is clearly visible in Figure 4b. Somewhat counterintuitively, given the significantly higher energy cost of TX/RX in UWB w.r.t. narrowband, *uWCB is consistently more energy-efficient than WCB*. Our results (Table V, right) show that WCB, when employed for periodic control, consumes 1.2× and 1.4× more energy than uWCB both with $N{\geq}1$ and its no-redundancy configuration with $N{=}1$, respectively; a similar performance is observed for ETC in epochs with event detection. In the absence of events, the common case in ETC, WCB requires up to 2.5× more energy.

Full-day WIS control traces. Yet, to truly ascertain the extent to which these significant energy savings hold in practice, we need to move away from the per-epoch perspective and analyze



(a) Duration of the active portion of the epoch: T_{active}



(b) Energy consumption

Figure 4: WCB vs. uWCB in hardware-in-the-loop experiments: Per-epoch radio active time (T_{on}, T_{idle}) and energy consumption (J_{on}, J_{idle}).

energy consumption across an entire control trace, in our case a full day of operation of the WIS test case (§V).

For periodic control, the overall consumption is readily determined by simply multiplying the average per-epoch consumption $J_{on}{+}J_{idle}$ (Figure 4b) by the number of epochs (1440); therefore, the observations we just distilled are still valid. Instead, the energy efficiency of ETC ultimately depends on the number of violations of triggering conditions leading to an event, which varies in function of the control problem at hand. In our WIS test case, the average number of event triggered over the full-day control trace is essentially the same (151–152) for the narrowband and UWB variants (Table IV). Nevertheless, in the specific mix of epochs with and without events offered by our test case, UWB *nearly halves the overall energy consumption* w.r.t. the original narrowband. Indeed, WCB-E consumes 1.7× more energy w.r.t. uWCB-E with $N{\geq}1$ and 2× with $N{=}1$, the most energy-efficient, no-redundancy configuration still achieving perfect reliability.

Generalizing to other control scenarios. Nevertheless, as mentioned, different control applications are likely to exhibit

Table V: WCB vs. uWCB in hardware-in-the-loop experiments: Per-epoch average duration of T_{active} and energy consumption.

	T_{active} **in WCB**			**Energy consumption in WCB**		
	ETC no detection	ETC with detection	Periodic	ETC no detection	ETC with detection	Periodic
uWCB$_{N\geq1}$	3.7×	2.8×	2.7×	2.1×	1.2×	1.2×
uWCB$_{N=1}$	4.2×	3.2×	3.2×	2.5×	1.5×	1.4×

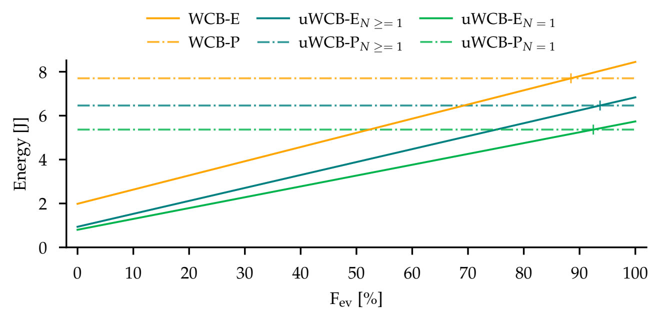


Figure 5: Generalizing the energy analysis to arbitrary control systems: Periodic vs. ETC and narrowband vs. UWB, as a function of the frequency of epochs with events. The small vertical lines highlight the break-even point of the two control strategies when implemented atop the same network stack.

a different frequency of event detection F_{ev}, i.e., the number of epochs with event detection over the total number of epochs, and therefore different energy consumption. To investigate the tradeoffs at stake we resort to modeling the energy costs J of the ETC network stacks in function of F_{ev}. This approach allows us to *i)* generalize our energy analysis to a broad spectrum of control problems, *ii)* investigate how the relative performance of ETC vs. periodic changes depending on whether a narrowband or UWB stack is used, and therefore *iii)* provide system designers with a simple yet powerful abstract tool for selecting the control strategy and radio technology best suited for the application at hand.

Luckily, in all WCB variants we considered, all nodes follow the same schedule and it is therefore easy to compute the network-wide consumption induced by ETC as

$$J = F_{ev} \times J_{ev} + (1 - F_{ev}) \times J_0$$

where J_{ev} and J_0 is the energy consumed in an epoch in presence and absence of an event, respectively, both easily derived from our evaluation (Figure 4b). We leverage this analytical model to concisely elicit (Figure 5) the tradeoffs at stake w.r.t. ETC vs. periodic control and narrowband vs. UWB as a function of the frequency of event triggering F_{ev}.

Figure 5 demonstrates that ETC solutions are preferable to periodic ones for a wide range of real-world control problems, independently of the radio technology adopted. ETC outperforms periodic control until F_{ev} approaches 90%, enabling significant energy gains especially at low event detection rates. Nevertheless, the break-even point is higher when UWB stacks are exploited ($F_{ev} \approx 88\%$ for WCB vs. $F_{ev} \geq 92\%$ for uWCB), again showcasing their superiority.

More generally, and key to the contribution of this work, Figure 5 clearly shows that:

i) for each variant, *the UWB implementation is always more energy-efficient than the narrowband one*, and

ii) *UWB-based ETC is always preferable to periodic control over narrowband*; conversely, UWB-based periodic control (uWCB, N=1) already outperforms ETC over narrowband (WCB-E) at $F_{ev} \approx 50\%$.

In other words, the use of UWB significantly affects, in a positive way, both the theoretical and system tradeoffs between event-triggered and periodic control.

VIII. Discussion and Outlook

We now discuss the implications of salient features unlocked by the synergy of UWB and CTX in the context of wireless control, against and beyond the state of the art.

Cooperative vs. concurrent transmissions. Cooperative transmissions have also been proposed for wireless control (e.g., [63], [64]). In a nutshell, these approaches mitigate the impact of packet loss by exploiting a cooperative packet retransmission from a properly identified set of neighbors.

Interestingly, the recent GALLOP system mixes cooperative and CTX: the TDMA schedule GALLOP builds to support closed-loop control is time-synchronized via network-wide Glossy floods, and cooperative retransmissions occur "simultaneously" [64]. However, the latter are performed *i)* only when a missing packet is detected, and *ii)* only by a designated set of neighbors. In contrast, CTX-based stacks rely on network-wide floods for *both* the original packet *and* retransmissions, if any. In a sense, packet loss in CTX systems is intrinsically mitigated by the spatio-temporal diversity built into CTX floods, without a need to identify the nodes in charge of it. Instead, GALLOP and similar cooperative approaches must explicitly select these nodes and schedule their transmissions, incurring significant complexity and overhead w.r.t. CTX. Further, reliability is also significantly inferior in GALLOP; in the testbed evaluation, the highest PDR achieved is 99.95%, using frequency hopping in a 10-node star topology with only one node at 2 hops from the controller. In comparison, uWCB achieves 100% reliability on a 36-node, 6-hop network and using a single frequency channel.

More scalable, reliable, efficient WNCS communications. Existing wireless control approaches, including the above, typically build and maintain a network topology tailored to the nodes participating in control (i.e., sensors, actuators, controller). In contrast, CTX-based stacks in general and uWCB in particular do not maintain *any* topology (§II-B) and each communication is network-wide, reaching each of the relevant nodes independent of their placement and number. An extreme scenario where *every* node participates in control can be supported without any modification to uWCB.

Further, our UWB stack ensures order-of-magnitude higher reliability, as UWB signals are less affected by co-located RF systems. Crucially, it also enables the use of less redundant protocol configurations w.r.t. WCB, its narrowband counterpart, with tangible benefits not only in energy efficiency but also latency, without detriment to reliability. Together, these features enable a more efficient use of the shared communication medium, accommodating many more nodes at once, and ultimately pushing the system scale that can be tackled by WNCS at large, beyond what is currently possible with narrowband network stacks.

In this respect, our recent work on the FLICK network primitive [51] can yield further improvements. In a nutshell, FLICK enables network nodes to take global binary decisions with near-perfect reliability and, in comparison to Glossy floods, is 10× faster and 4.4× more energy-efficient. In uWCB, this finds application in the distributed decision in the EV phase, specifically improving the common case of epochs without events. Exploring quantitatively the impact of this optimization is part of our research agenda.

Fast feedback control via UWB CTX. uWCB delivers control commands more than 3× faster than its narrowband counterpart, ensuring ultra-reliable closed-loop control over a 6-hop network in $<$64 ms with only a very small latency jitter of ±1.2 ms. Its timeliness is comparable to the one achieved, in a much smaller 3-hop network setup, by state-of-the-art narrowband systems [13], [65] expressly targeting fast feedback control. Nevertheless, unlike uWCB, these systems aim at minimizing end-to-end latency to meet tight deadlines even at the expense of reliability, as controllers can tolerate the occasional packet loss thanks to the short sampling interval. The same compromise could be seized in uWCB by exploiting its baseline near-perfect reliability to remove the Recovery phase; in our setup, this would yield an end-to-end latency of only ≈40ms, a 40% reduction w.r.t. the above state-of-the-art works.

UWB-based and energy-efficient: An oxymoron no more. Our empirical evaluation shows that the higher energy cost of UWB radio operation, often regarded as the main barrier to the adoption of this technology for communication and control purposes, does not necessarily translate into a higher energy consumption of the overall system. Conversely, when communications are wisely orchestrated by the networking stack, UWB can ensure energy consumption *even lower than* staple narrowband solutions, as showcased by uWCB.

Further, recent years have seen an ever-increasing trend towards energy-efficient UWB platforms. Examples are the newer DW3000 chip from Qorvo [66] and the SR1000 chip from SPARK [67] that reduce, if not reverse, the energy gap between narrowband and UWB radios. Harvesting these hardware-level improvements in already energy-efficient communication stacks like uWCB can further expand the landscape of control systems that can benefit from UWB technology, potentially inspiring new applications hitherto unexplored.

IX. Conclusions

Our work aims to investigate the unexplored potential of the synergy between UWB and CTX for wireless control. We accomplish this by presenting uWCB, to the best of our knowledge the first UWB-based WNCS capable of supporting both event-triggered and periodic control. We evaluate its real-world performance via cyber-physical experiments carried out in a large-scale, multi-hop narrowband and UWB testbed that we designed as a secondary contribution. The outcome is very positive. uWCB achieves better reliability, latency, and energy efficiency w.r.t. IEEE 802.15.4 narrowband, the de-facto reference technology for wireless control, opening up intriguing research and application opportunities.

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