Experimental Study of UWB Connectivity in Industrial Environments

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***Abstract*—Experimental results on the connectivity of IEEE 802.15.4-2011 ultra-wideband (UWB) devices are presented in two industrial scenarios: a large-size aircraft assembly hangar and a medium-size production hall. These measurements are the first ones reported for off-the-shelf UWB devices in such setting and shed light on the potential of UWB to support emerging industrial applications. By comparing the packet loss rate to well-established ZigBee devices, we show that UWB can largely reduce the need of relay nodes, contributing to a lower end-to-end latency. We argue that this, together with inherent features that are not easy to replicate by other physical layers, position UWB as a promising industrial communications technology.**

***Index Terms*—Experimental assessment, IEEE 802.15.4-2011, Industrial sensor networks, UWB, Industry 4.0.**

I. Introduction

The introduction of wireless systems in industrial environments promises a rapid and cost-effective reconfiguration of machines and associated sensors. The requirements for such industrial communications are, however, very diverse [1]. Some applications require high throughput; others depend on low latency and ultra-high reliability. A key question is thus: Which wireless technology is best suited for industrial settings? ZigBee, WirelessHART, ISA 100.11.a (IEEE 802.15.4), and WiFi (IEEE 802.11) are technologies of widespread use in industry, and low-power Bluetooth also received attention recently. None of them, however, offers a comprehensive solution to the broad scope of industrial use cases. The transceiver consumption of ZigBee and Bluetooth is suitable for operation on battery plus harvested energy (see [2], [3]), but both fail to support high data rates, such as those required for vibration monitoring or video-based surveillance. Although Bluetooth specifies 1 Mbit/s, its effective application rate falls to the ZigBee range, just slightly above 200 kbit/s, due to the high overhead associated to the short packets used. WiFi provides a high data rate, but its drawback is the high power consumption [4]. The lack of alternatives capable of achieving a good balance between these conflicting rate and energy goals currently hinders developments.

Ultra-wideband (UWB) technology targets a broad range of applications from medicine over body area networks to homeland security (see [5], [6]). The current UWB standard IEEE 802.15.4-2011 [7] contemplates rates up to 27 Mbit/s with compliance to existing systems (e.g., WirelessHART is based on the same specification). Using transceivers with a typical current consumption of 35 to 118 mA [8], a rate-energy balance that meets the industry's requirements set is possible. Interestingly, UWB is these days mostly used for *localization* (see [9]–[11]) and has not yet consolidated its use as an option for *communications*. We conjecture that its flexibility and key added features (see [1], [5]) can create a solid basis for an industrial wireless (sensor and actuator) network.

This paper contributes to the positioning of UWB as an industrial communications technology by presenting field evaluations with off-the-shelf transceivers. Experimental results in two typical industrial settings show that the excellent multipath performance of UWB largely avoids the need for relay nodes in comparison to ZigBee. This being a key to lower end-to-end latency, which is a main design goal for industrial networks.

II. Experimental Connectivity Study

A. Measurement Environments

The two industrial settings examined have different characteristics but both represent typical multipath propagation environments encountered in industry, where most links are non-line-of-sight. The connectivity properties are assessed at different transmitter-receiver distances in different surroundings. The first setting is

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Fig. 1. Measurement scenario at the Zentrum für Angewandte Luftfahrtforschung (ZAL): Deployment over a large aircraft assembly hangar. The transmitter position is marked with a star in the picture; the receiver node is placed (as shown by the circle markers) at distances from 5.6 m for position 2 to 18.5 m for position 5. The environment is mostly static with workers closely passing by only for positions 2 and 4.

a hangar at the Zentrum für Angewandte Luftfahrtforschung (ZAL) in Hamburg, Germany. As shown in Fig. 1, it is a large hall, where communication distances can be long, reflecting objects are few, and the environment is mostly static. The second setting is a medium-size factory floor at 3M in Villach, Austria, as shown in the top part of Fig. 3. It is a reflection-rich environment with moving workers, cranes, and wagons on the floor introducing time-varying channel conditions; machineries are at shorter distances than at ZAL.

B. Hardware Testbed

In both settings, we deploy EVK1000 boards from DecaWave [8] complying to the IEEE 802.15.4-2011 standard [7]. As performance reference, we also use Z1 ZigBee devices manufactured by Zolertia [12], which comply with the earlier spread spectrum version of the standard. Both technologies are set to transmit over a fixed channel and without power adaptation.

Our measurements test point-to-point links between a fixed transmitter and a receiver placed at different locations that capture typical industry deployments. In all cases, the tests with UWB and Z1 are carried out simultaneously with nodes positioned side by side. As they operate over non-overlapping frequency bands, there is no interference between them, and the same exact environment is measured (e.g., same moving objects during measurements). Packets are transmitted every 200 ms. Losses are registered for each location over approximately 10 minutes, after which the receivers are taken to the next location. Average packet loss rates are computed over a sliding window of 100 packets. Each single transmission is checked to compute the packet loss; no retransmission scheme is used.

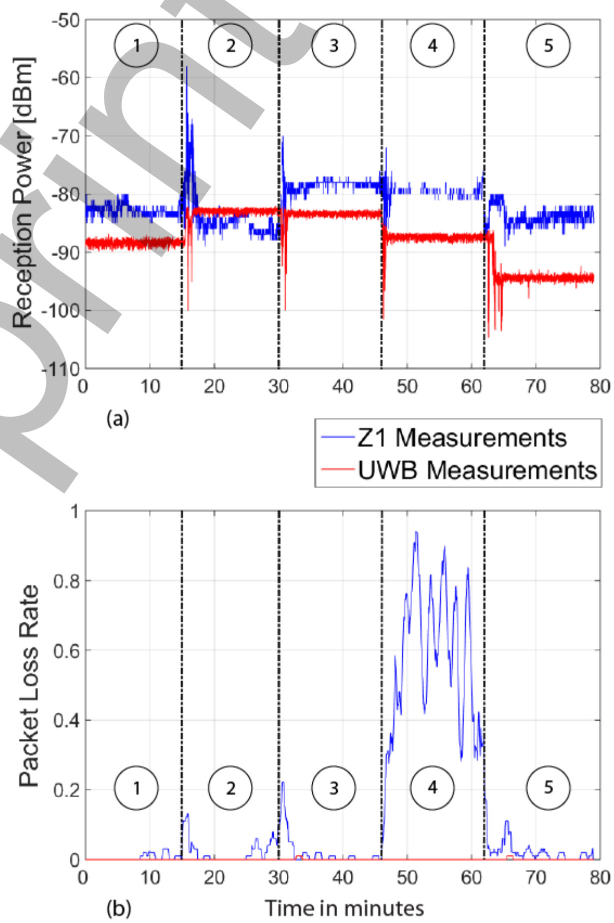

Fig. 2. Measurement results for ZAL deployment. (a) Measured reception power, and (b) Average packet loss rate.

C. Results

Both settings show the same qualitative behavior. In terms of packet loss rate, the ZAL test exhibits lower peaks for both technologies, which we associate to the

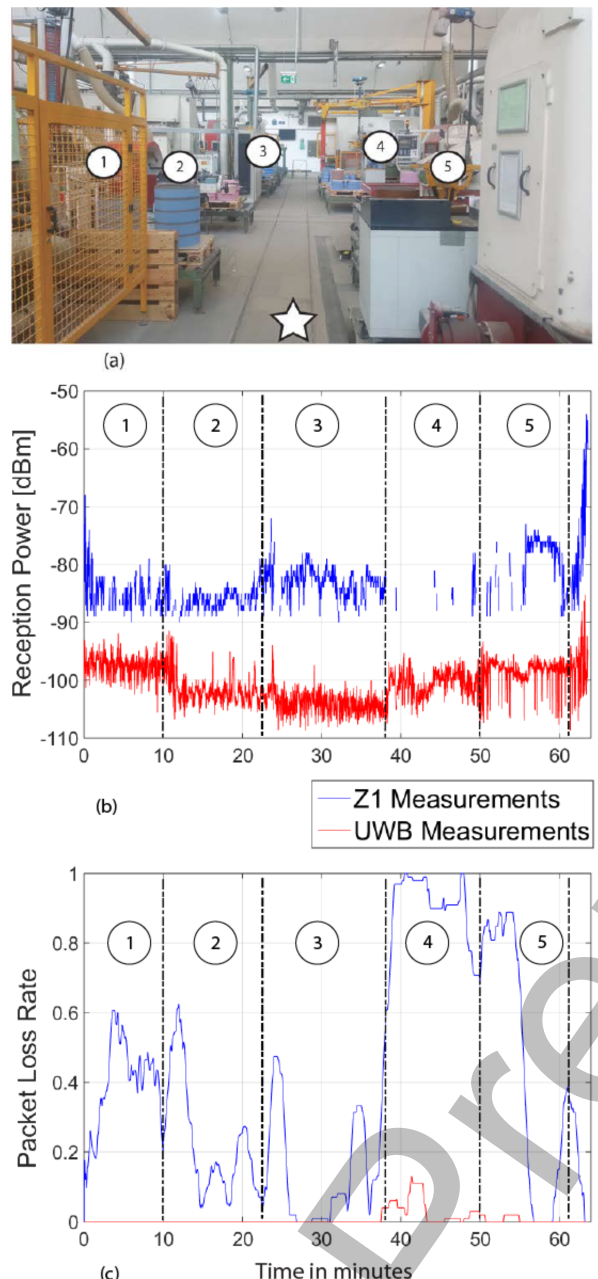

Fig. 3. Measurement scenario at 3M: Medium-size factory hall with moving machinery and personnel. (a) The transmitter position from which the picture is taken is marked with a star; the receiver positions are indicated with circles (distances from 3.5 to 13.4 m for positions 1 and 3). (b) Measured reception power. (c) Average packet loss rate.

less obstructed environment. Measurements at 3M show a maximum loss rate of 13% for UWB and 100% for ZigBee. At ZAL we measured below 3% for UWB and 93% for ZigBee.

Fig. 2 shows details of the ZAL measurements. The received power across locations (delimited by dashed vertical lines) and the associated average packet loss rate are shown in part (a) and (b), respectively. The missing points in part (a), easy to spot for the Z1 nodes at segment 4, indicate moments with lost packets. Z1 nodes exhibit relatively low loss rates at all positions but 4. Position 4 is not the most distant (14.4 m compared to 18.5 m for position 5) but the most obstructed one. Positions 1, 4, and 5 are non-line-of-sight links, but only 4 was measured with people moving in the surrounding. The key observation for this scenario is that UWB nodes show very rare packet loss events, even for position 4 which is highly challenging for ZigBee.

Fig. 3(b) shows the received power across locations for 3M. The average packet loss rate is given in Fig. 3(c). These results highlight the robustness of UWB compared to ZigBee, as significant loss rates are observed at all locations for ZigBee. Non-negligible loss rates occur for UWB only at positions 4 and 5 (15 and 7.1 m from the transmitter). These positions are the most challenging ones, as many workers and a mobile crane obstruct the line-of-sight path. Overall, the loss rate for UWB never exceeds 13%. Z1 nodes show long periods above 40% loss at all tested positions, rising to almost 100% for conditions such as in positions4 and 5. In practice, such frequent losses indicate that at least one relay is needed to reliably reach all test locations. This is consistent with experimental results for cooperative relaying done with ZigBee devices in a similar industrial setting [13].

The use of relays constrains the achievable latency across the network, which is a main performance metric for real time control of industrial processes. Relays not only double the latency but also halve the effective data rate. The superior multipath performance of UWB observed in our experiments has the potential to at least reduce the number of relays and associated overhead.

A conceptual difference of UWB is that it operates outside ISM bands, in contrast to the Z1 nodes (2.4 GHz) and many other industrial technologies. Due to the interference-free environment in our experiments, our results serve as a best performance bound for the general case in which several systems are used in one setting.

III. Previous and Related Work

Our previous publications on experiments with UWB present a proof-of-concept for a sensor network deployed in a mockup of a passenger cabin of a commercial aircraft (see [14], [15]). In addition to our own work, there are two research streams related to the paper at hand: experimental assessment of UWB and industrial wireless network design. To the best of our knowledge, we are among the first teams to link these two streams through proof-of-concept deployments of commercially available UWB transceivers. Very close to our work are bit error rate measurements with DecaWave and WirelessHART boards in an industrial steam heating plant [16]. Furthermore, a complete prototype system of a UWB sensor network with multihop communications and low data rates is presented in [17]. The majority of UWB research, however, has focused on localization [9]–[11]. There exist results in an industry scenario using the same UWB nodes [10] and a localization accuracy comparison across different off-the-shelf UWB nodes [11]. The potential for industrial use of UWB and other technologies is discussed in [1] and [5] in terms of design objectives and challenges from a system level perspective. A theoretical study of relaying with UWB can be found in [18]. Other papers focus on protocol design (see, e.g., [19], [20]).

IV. Conclusions and Outlook

UWB appears to be a promising radio interface to support emerging industrial applications. Experimental results from a proof-of-concept deployment with off-the-shelf transceivers show that UWB outperforms 802.15.4-2007-based nodes in terms of radio range, data rate, and reliability. Further studies are needed to draw firm conclusions. In particular, the energy consumption and robustness against interference between multiple UWB deployments needs to be investigated. Our current work addresses these aspects with emphasis on the energy consumption. UWB does not yet reach the levels of ZigBee and Bluetooth, but the short duty cycle of UWB impulse radio and the extremely low deep sleep mode consumption can facilitate operation on harvested energy.

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