Evaluation of Ultra-Wideband Radio for Industrial Wireless Control

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***Abstract*—This paper investigates the use of ultra-wideband (UWB) radio for communication in industrial wireless sensor networks (WSNs). OpenWSN is an open-source IPv6 mesh network protocol stack based on IEEE 802.15.4 time slotted channel hopping (TSCH). We adapted OpenWSN to operate an UWB physical layer based on the DecaWave DW1000 UWB transceiver. Experiments were conducted in an industrial steam heating plant environment and an office/laboratory environment to measure the bit error ratio (BER) performance of UWB. The performance of an OpenWSN network using the UWB physical layer was experimentally compared against WirelessHART, an existing industrial wireless automation standard. We found that UWB is a feasible medium for industrial wireless communication in both environments. Experimental results indicate that OpenWSN over UWB achieved better reliability in guaranteed time slots than WirelessHART in an office environment, while WirelessHART lost fewer packets than OpenWSN over UWB.**

I. Introduction

Many industrial processes use control networks for automating a plant, process, factory, or machine. Wired networks are commonly used although wireless sensor networks (WSN) and wireless sensor and actuator networks (WSAN) are becoming increasingly popular as a way to reduce installation costs and increase flexibility [1].

The use of wireless communication poses challenges for industrial automation due to its lossy nature. Industrial environments are typically harsh for radio frequency (RF) signals due to multipath fading, slow/fast fading, and interference from equipment such as motors, drives and welding [2]. These factors may also vary over time and cause a higher *bit error ratio* (BER).

Two competing WSN standards for industrial process automation are ISA100.11a and WirelessHART. These standards were developed in parallel, with WirelessHART released in 2007 and ISA100.11a released in 2009. Both standards operate in the 2.4 GHz *industrial, scientific and medical* (ISM) band based on the physical layer defined in IEEE.802.15.4-2006.

Ultra-wideband (UWB) radio is defined as an intentional radiator with a bandwidth of at least 500 MHz, or with a fractional bandwidth greater than 20%. To prevent interference due to the high channel bandwidth, regulations limit the power spectral density of UWB transmissions to -41.3 dBm/MHz [3] [4] . Although many different radio technologies may be defined as UWB, in this paper we focus on *impulse-radio* UWB (IR-UWB). The characteristics of IR-UWB provide several benefits compared to narrowband radio [5]:

- The extremely short pulse duration ($\leq$ 2 ns) results in strong resistance to multipath fading encountered in industrial environments.
- Due to the extremely low power spectral density the spectrum can be shared with narrowband users without causing interference.
- Resistance to interference from narrowband communication due to the high channel bandwidth.

UWB has been previously considered for industrial wireless communication (see e.g. [6], [7]). The ranging performance of an IR-UWB system in a heavy machines laboratory has been experimentally evaluated in [8].

A. Contributions

We present an experimental evaluation of the performance of IR-UWB radio for communication in an industrial environment. Our paper makes the following contributions:

- We have ported OpenWSN, an existing IPv6 mesh network protocol stack based on IEEE 802.15.4e TSCH, to use an UWB radio.
- We experimentally measured the BER of UWB communication in industrial and non-industrial environments.
- We experimentally measured and compared the performance of an UWB-based mesh network to a WirelessHART network.

II. Background

A. WirelessHART

WirelessHART [9] is a WSN for industrial process automation designed as a wireless implementation of the highway addressable remote transducer (HART) protocol used in wired fieldbus networks. The media access control (MAC) layer uses *time division multiple access* (TDMA) in which all devices are synchronized to time slots with a fixed duration of 10 ms, combined with channel hopping over 15 channels. Each time slot permits one device to transmit a single data packet to another device, and for the recipient device to transmit an acknowledgement packet. Collisions are minimized by scheduling devices to communicate in specific slots, called *guaranteed time slots* (GTS). Devices can request *services* from the WirelessHART network manager which permit the device to send packets in the network at a specific update rate. The network manager allocates GTSs to fulfil the requested bandwidth required by all the services, including retries, which enables determinism.

B. Safety Considerations

Some industrial communication networks are responsible for the transport of messages containing data which is relevant to the safety of the system. The occurrence of an undetected error, such as a message containing one or more incorrect bits, may cause the safety function dependent on the message to encounter a dangerous failure. An occurrence of an undetected error is known as a *residual error*.

IEC 61508 [10] is a general standard for functional safety for electric, electronic, and programmable equipment. The standard defines requirements and methods in order to meet a specific *safety integrity level* (SIL). Each of the four SILs defines a level of safety, with higher SILs having a lower probability of a dangerous failure.

IEC 61784-3 [11] defines common principles for communication systems that transport safety-relevant messages in accordance with the requirements defined in IEC 61508. It defines techniques for dealing with deterministic and stochastic errors that may occur in communication networks. Specifically, messages sent between two safety-related devices must not be modified, delayed, lost, or unordered as required by the safety function.

A common technique to protect against message corruption is a *cyclic redundancy check* (CRC) which adds redundant data to each packet to allow the recipient to detect corrupt packets. CRCs, however, cannot detect every possible combination of perturbed bits in a received message. A residual error occurs when the CRC check fails to detect a corrupt message. The probability of a residual error is dependent on the bit error probability. IEC 61784-3 defines the maximum *residual error rate* per hour of operation w.r.t. the bit error probability, as follows:

$$\wedge_{SL}\ (Pe) = R_{CRC}\ (Pe) \times v \times m \quad (1)$$

where:

- Pe is the bit error probability. Pe cannot exceed 10^{-2} for SIL level 3 applications.
- $\wedge_{SL}\ (Pe)$ is the residual error rate per hour of operation w.r.t. Pe.
- $R_{CRC}\ (Pe)$ is the residual error probability of the CRC w.r.t. Pe.
- v is the number of safety-related messages transmitted per hour of operation.
- m is the number of recipients of the message between the source and destination.

C. Network Performance Metrics

In this paper we measure UWB performance using four metrics: information bit error ratio, packet loss ratio, packet acknowledgement ratio, and network latency.

As mentioned in Section II-B, the bit error probability, Pe, must be less than 10^{-2} for SIL 3 applications. Pe can be estimated by measuring the *bit error ratio* (BER) over a suitably large amount of transferred bits. IEEE 802.15.4 UWB uses a combination of a Reed-Solomon and systematic convolutional coding scheme to improve the BER by detecting and correcting bit errors. The *information bit error ratio* (IBER) is calculated as the number of incorrect bits ε divided by the total number of received bits n after error correction [12].

Many industrial processes require messages to be received in a timely fashion in order to operate correctly. For example, if sensor readings arrive too late then they may not reflect the current state of the system. Similarly, messages that fail to arrive may reduce system performance. Packet loss and latency in a WSN are influenced by a variety of factors including: low-power transmission, variable transmit power, multi-hop transmission, noise, radio interference, and node mobility [13]. The *packet loss ratio* (PLR) is calculated as the number of lost packets divided by the total number of transmitted packets. The number of lost packets is calculated as the number of successfully received packets subtracted from the total number of transmitted packets.

Motes in a TSCH and WirelessHART network communicate with one or more neighbouring motes in order to route messages through the network. The communication reliability across the link between each pair of motes in the network can vary significantly across the network due to varying distance and environmental factors on the wireless signal propagation. The link reliability between two motes can be quantified by measuring the number of packets that are successfully acknowledged across the link. After transmitting a data packet in a WirelessHART and TSCH network, the transmitting device listens for an acknowledgement packet. If no acknowledgement is received, then either the data or acknowledgement packet was lost or corrupted and the transmitting device should retry the transmission at the next opportunity. The *packet acknowledgement ratio* (PAR) is the percentage of transmitted packets that were successfully acknowledged. It is calculated by a mote as the total number of acknowledgements received from the target mote divided by the total number of packets sent to the target mote. A higher value for the PAR indicates a more reliable link. WirelessHART reports the PAR as the *link stability*.

III. Adaptation of OpenWSN to UWB

To perform the mesh network experiments described in Section IV we used the OpenWSN stack. OpenWSN [14] is an open-source implementation of an IPv6 protocol stack for the Internet of things (IOT) based on 6LoWPAN, the IEEE 802.15.4e TSCH MAC layer and 2.4 GHz physical layer. The protocol stack provides communication based on the constrained application protocol (CoAP) and user datagram protocol (UDP). Packets are routed according to the Internet engineering task force (IETF) IPv6 routing protocol for low power and lossy networks (RPL) [15].

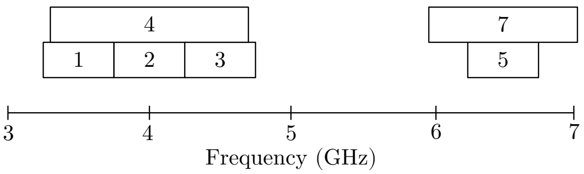

Fig. 1: UWB channels supported by the DecaWave DW1000.

TABLE I: Mapping of OpenWSN channel number to UWB channel configuration.

OpenWSN channel	UWB channel	Preamble code	PRF (MHz)
0	1	9	64
1	2	10	64
2	3	11	64
3	5	12	64
4	1	1	16
5	2	3	16
6	3	5	16
7	5	4	16

We adapted OpenWSN to use an UWB physical layer based on the DecaWave DW1000 UWB trasceiver [16]. The adaptation mainly involved providing a new implementation of the radio application programming interface (API) for the DecaWave DW1000 transceiver chip. Modifications were also made to the MAC layer to support a reduced number of channels, as OpenWSN is designed for 2.4 GHz radios using 16 channels. The DW1000 UWB transceiver, however, supports just six UWB channels as shown in Fig. 1.

Our UWB physical layer implementation for OpenWSN maps 8 logical channels (numbered 0 – 7) to 8 UWB channel configurations. Each channel configuration must be orthogonal to avoid cross-channel interference. UWB channels 4 and 7 have a higher bandwidth and overlap channels 1, 2, 3 and 5 respectively. To avoid cross-channel interference we use only channels 1, 2, 3 and 5. The DW1000 also supports preamble codes with two different pulse repetition frequencies (PRF) of 16 MHz and 64 MHz. DecaWave have experimentally demonstrated [17] that two radios transmitting on the same UWB channel interfere with each other only when the transmitters are using preamble codes with the same PRF. This permits mapping two OpenWSN channel configurations to the same physical UWB channel with different PRFs, i.e. one configuration uses a PRF of 16 MHz and the second uses a PRF of 64 MHz. The resulting mapping of OpenWSN channel numbers to the UWB channel configuration is shown in Table I.

All configurations shown in Table I use the same data rate of 850 kbps and preamble length of 1024 symbols. These values were chosen as preliminary testing indicated reasonable performance with these values, and the packet transmit time is short enough to fit within the 15 ms OpenWSN time slot duration.

IV. Experimental Evaluation

This section describes the two experiments that were performed, the test equipment used, and the environments in which the experiments took place.

A. Experiment 1

The DecaWave DW1000 supports several possible configurations for the UWB radio which affect the BER: three different data rates (110 kbps, 850 kbps, and 6.81 Mbps), 6 UWB channels (channels 1 – 5 and 7), and 2 PRFs (16 MHz and 64 MHz). This results in a total number of 36 different configuration combinations. In this experiment we measured the IBER for all 36 configuration combinations. For each test configuration the IBER is measured over $4.6 \cdot 10^7$ transmitted bits. Each packet has a length of 127 bytes, resulting in a total of 45276 packets transmitted for each test configuration. All test configurations use the maximum preamble length of 4096 symbols to achieve the longest possible communication range.

The receiving radio must know the correct message to be able to count the number of incorrect bits. We used a fixed repeating message to avoid needing to synchronize the transmitter and receivers. Each packet contains a fixed bit pattern of alternating ones and zeroes. This pattern was chosen so that there are an even number of ones and zeroes, as the probability that a 1 is pertubed to a 0 may not be the same as for a 0 pertubed to a 1 [18]. The last two bytes of the packet contain the CRC-16-CCITT sequence, which is 08 C8.

B. Experiment 2

In experiment 2 the mesh network performance of OpenWSN using the UWB physical layer is compared against a WirelessHART network. The network latency and PLR are measured from two scenarios:

- *Scenario 1*: The first scenario simulates a WSN where each mote in the network periodically generates a packet and transmits it upstream through the network to the test application running on the computer connected to the network gateway. Latency and packet loss is measured only in the upstream direction.
- *Scenario 2*: The second scenario sends round-trip packets through the network to measure latency for both upstream and downstream directions. Packets originate in the test application running on the computer connected to the network gateway, which sends packets downstream to individual motes. Upon receipt of the packet, the target mote transmits a response packet upstream back to the computer. The PLR is measured from the number of responses received and the total number of packets transmitted.

In scenario 1, 900 packets are transmitted at a rate of 1 packet every 2 seconds, resulting in a test duration of 30 minutes. In scenario 2, 600 packets are transmitted at a rate of 1 packet every 5 seconds with a test duration of 50 minutes. The longer inter-packet period in scenario 2 is due to reduced bandwidth available in both the OpenWSN and WirelessHART networks in the downstream direction. For both scenarios in experiment 2, OpenWSN was configured to use a data rate of 850 kbps, and the WirelessHART data rate was 250 kbps.

C. Hardware

We used the following equipment for the UWB and WirelessHART testing:

- *DecaWave EVB1000*: An evaluation board for the DecaWave DW1000 UWB transceiver. It features an external UWB antenna, a DW1000 transceiver, an ARM Cortex-M3 microcontroller, an LCD, and a micro-USB connector. We used 6 EVB1000 boards in our experiments.
- *SmartMesh WirelessHART SDK*: A WirelessHART evaluation kit available from Linear Systems. It features a WirelessHART network manager and five WirelessHART motes. The network manager and motes are pre-programmed with the WirelessHART stack provided by Linear Systems.
- *Arduino Due*: An Arduino variant featuring an ARM Cortex-M3 microcontroller. Each Arduino Due board communicates with a WirelessHART mote via a serial link in order to send and receive packets to the WirelessHART network.

For experiment 1 only the DecaWave EVB1000 boards are used. The ARM microcontroller on the EVB1000 was programmed with test firmware to measure detailed statistics on received packets, such as the number of bit errors. During experiment 2, the DecaWave EVB1000 boards are programmed with the OpenWSN protocol stack. The default configuration values were used for the WirelessHART network manager and motes.

The experiments are run by test applications running on a laptop computer connected to the WirelessHART network manager and one of the EVB1000 motes. The EVB1000 mote connected to the computer is configured as the root of the OpenWSN network and provides an IPv6 bridge through which packets can be sent to and from the OpenWSN mesh network.

D. Environment

The experimental evaluation was performed in two locations on the UNB campus. The first location is an office/lab environment in the UNB ITC building. This building contains offices, laboratories, and server rooms for the Faculty of Computer Science across four floors. Our experiments were performed on the lowest level, located one floor below ground level. The floor plan is presented in Fig. 2. The second location is an industrial environment at the UNB central heating plant. The heating plant provides steam to the UNB and Saint Thomas University campuses, as well as the Doctor Everett Chalmers hospital. The heating plant contains five large industrial boilers to produce steam which are fueled by wood, oil, or natural gas. The plant also contains many pipes to carry fuel, water, chemicals, and steam. The boilers are controlled by programmable logic controllers (PLCs) which are connected to the control room via a wired network. Further details of the experimental environments are available in [19].

UWB and WirelessHART radios are placed at five different in each environment. At each position one UWB radio and one WirelessHART radio are placed within 10 cm of each other.

TABLE II: Straight line distance (m) from T1 to positions R1 – R5.

Environment	R1	R2	R3	R4	R5
Office	11.61	10.52	11.87	12.98	12.46
Industrial	24.60	34.93	33.33	19.91	14.19

The wireless mote locations in both environments are illustrated in Fig. 2. The position of the WirelessHART network manager and OpenWSN gateway are marked as T1. Positions R1 – R5 mark the position of each UWB and WirelessHART radio pair. For experiment 1, T1 marks the position of the transmitter and motes R1 – R5 are configured as receivers.

The radio positions R1 – R5 were chosen to encounter varying signal reception quality w.r.t. messages transmitted by the radio at T1. The straight line distance between the antennas from T1 to each radio R1 – R5 is listed in Table II, as calculated from measurements along cartesian axes using a measuring tape.

V. Experimental Results

A. RF Measurements

RF measurements were taken at the position T1 in both environments. The measurements were conducted before the start of each test when all UWB and WirelessHART devices are powered off in order to measure the background noise levels. At least 20 sweeps of the frequency ranges were measured for averaging. The measurements were performed in the 2.4 GHz ISM band from 2.4 GHz to 2.483 GHz used by the WirelessHART radios, and from 3 GHz to 7 GHz used by the UWB radios. Full details of the RF measurements can be found in [19].

At the UNB ITC building, the maximum average power on Wi-Fi channels 1 and 6 was -61.3 dBm and -61.5 dBm respectively. At the UNB central heating plant, the maximum average power on Wi-Fi channels 1, 6, and 11 was -63.2 dBm, -62.4 dBm, and -64.8 dBm, respectively. The average power in the 2.4 GHz ISM band was -80 ± 11 dBm at the UNB ITC building, and -79 ± 9 dBm at the UNB central heating plant. The peak power at the UNB ITC building was -50.7 dBm at 2.408 GHz, and the peak power at the UNB central heating plant was -57.1 dBm at 2.408 GHz.

The measurements in the 3 GHz – 7 GHz band are almost identical in both environments. The average peak power in the UNB ITC building is slightly lower at -82 ± 25 dBm compared to -81 ± 25 dBm at the heating plant. The average power in the UNB ITC building is also slightly lower at -118 ± 2 dBm compared to -117 ± 3 dBm at the heating plant. In both environments, two strong peak powers were measured at 4.05 GHz and 6.1 GHz with peak powers of -40 dBm and -17 dBm, respectively. The average power at these frequencies, however, is very low at -118 dBm and -116 dBm, respectively.

B. IBER Measurements

The IBER and packet loss measurements from experiment 1 at the UNB ITC building and the UNB central heating plant are presented in Table III. The IBER in these results is calculated from the sum of ε and n measured from all packets sent using

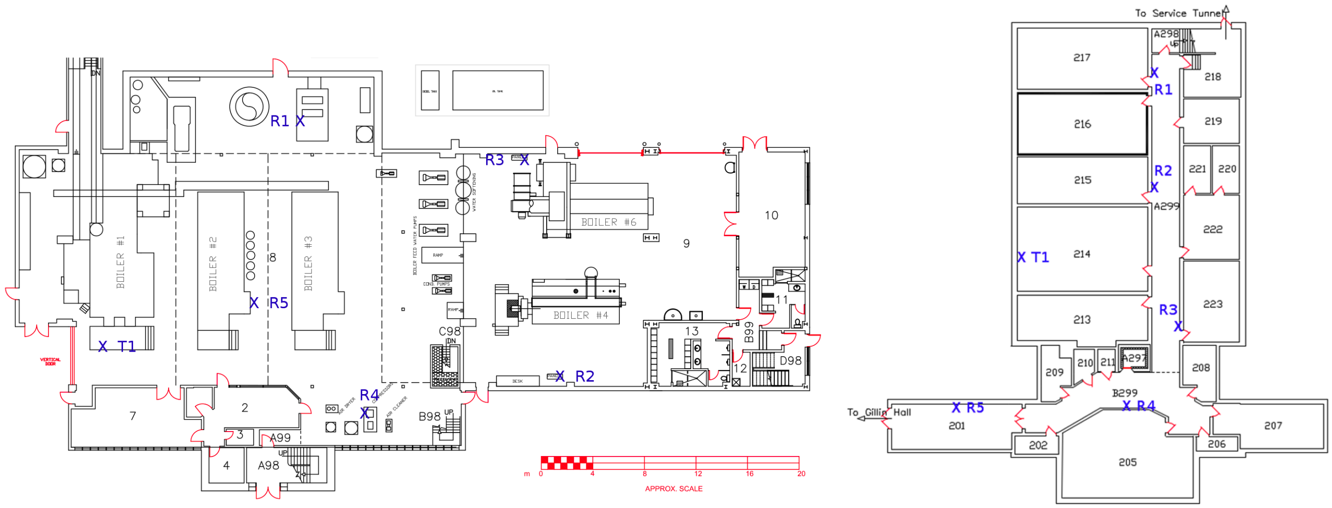

Fig. 2: Floor plan and mote placement at the UNB central heating plant (left) and UNB ITC building (right).

the same data rate. The measurements for position R4 in the UNB central heating plant environment are not available due to a hardware fault.

In both environments, the IBER and PLR increases as the data rate is increased. The most extreme difference in PLR is position R1 in the office environment, where the PLR is 11.03% at 110 kbps compared to 92.85% at 6.81 Mbps. The measurements using the 6.81 Mbps data rate indicate that reliable UWB NLOS communication is only possible in our environments within 14 m, provided that there are few obstructions. Positions R2 and R3 in the office environment, however, were able to achieve reliable communication with the IBER below $3 \cdot 10^{-7}$ and less than 0.1% of packets lost. Test configurations using the data rates at 110 kbps and 850 kbps measured significantly better IBER and PLR for most mote positions, with the IBER below $4.2 \cdot 10^{-4}$ at 850 kbsp and $1.2 \cdot 10^{-5}$ at 110 kbps. The PLR also improved at the lower data rates although the PLR is less than 10% only for the motes closest to the position T1. This indicates that a multi-hop network topology would be necessary for reliable communication with all motes in our test environments.

C. PAR Measurements

Table IV shows the average PAR for all measurable links in the OpenWSN and WirelessHART networks in experiment 2. For the WirelessHART network, the PAR is measured by the network manager software and is reported as the link stability. In the OpenWSN network, the PAR is calculated as described in Section II-C, based on the packet counts measured by each mote. OpenWSN measures the number of packets sent and acknowledged within each GTS, as well as the values for all communication to each neighbouring mote using any time slot (i.e. shared slot or GTS).

The results in Table IV show that in the OpenWSN network, communication occurring within both shared and GTSs is significantly less reliable than communication occurring only within GTS. The reduced reliability in shared time slots is due to contention with other motes attempting to use the time slot at the same time, as well as the OpenWSN MAC layer occasionally attempting to communicate directly with neighbouring motes with which direct communication is unreliable.

The average PAR for GTS communication in OpenWSN indicate that the UWB physical layer provides reliable communication in the office environment, where 99.55% of packets sent in a GTS are successfully acknowledged. In the industrial environment, the UWB GTS PAR drops significantly to just over half of all packets being acknowledged. On the contrary, the PAR performance of WirelessHART increases by 13.34% when moving from the office environment to the industrial environment.

D. Packet Loss

Table V presents the number of end-to-end upstream (in scenario 1) and round-trip (in scenario 2) packets that were lost. In both scenarios, WirelessHART outperformed OpenWSN as no upstream packets were lost, and less than 1% of round-trip packets were lost. The OpenWSN network lost no more than 2% of packets in the office environment, but lost up to 18% of packets in the industrial environment. This is likely caused by the drop in the UWB PAR when moving from the office environment to the industrial environment. Both OpenWSN and WirelessHART attempt to send each packet up to 4 times before dropping the packet, which results in lower end-to-end packet loss compared to the per-link reliability measured in the PAR.

E. Network Latency

The average latency measurements for packets in the upstream and downstream directions are presented in Table VI. The upstream latency is significantly lower than the downstream latency in both the OpenWSN and WirelessHART networks. Downstream packets in OpenWSN can only be sent in shared time slots as GTSs are only allocated in the upstream direction. This causes more transmission retries for

TABLE III: IBER and PLR measurements in the office and industrial environments.

Environment	Data rate (kbps)	R1		R2		R3		R4		R5	
		IBER	PLR	IBER	PLR	IBER	PLR	IBER	PLR	IBER	PLR
Office	110	$3.30 \cdot 10^{-6}$	11.03%	0.00	0.03%	0.00	0.03%	$6.25 \cdot 10^{-6}$	51.68%	$5.21 \cdot 10^{-1}$	99.99%
	850	$3.20 \cdot 10^{-5}$	18.89%	0.00	0.01%	0.00	0.02%	$8.73 \cdot 10^{-5}$	66.93%		100%
	6810	$1.49 \cdot 10^{-3}$	92.85%	$2.96 \cdot 10^{-7}$	0.05%	$2.96 \cdot 10^{-7}$	0.09%	$4.67 \cdot 10^{-1}$	99.94%		100%
Industrial	110	$3.51 \cdot 10^{-6}$	34.05%	$4.74 \cdot 10^{-6}$	29.00%	$1.15 \cdot 10^{-5}$	89.65%			$3.71 \cdot 10^{-7}$	1.25%
	850	$9.67 \cdot 10^{-5}$	50.62%	$7.63 \cdot 10^{-5}$	45.77%	$4.19 \cdot 10^{-4}$	97.40%			$2.90 \cdot 10^{-6}$	1.88%
	6810	$2.71 \cdot 10^{-1}$	99.92%	$7.50 \cdot 10^{-3}$	99.09%	$5.07 \cdot 10^{-1}$	99.98%			$9.87 \cdot 10^{-5}$	26.91%

TABLE IV: Average PAR for OpenWSN and WirelessHART mesh networks.

Environment	OpenWSN (any slot)	OpenWSN (GTS only)	WirelessHART
Office	76.68%	95.55%	71.21%
Industrial	40.66%	54.4%	84.55%

TABLE V: Number of upstream and round trip packets lost.

Environment	OpenWSN		WirelessHART	
	Upstream	Round trip	Upstream	Round trip
Office	45 (1%)	31 (2%)	0 (0%)	10 (< 1%)
Industrial	538 (12%)	214 (18%)	0 (0%)	1 (< 1%)

TABLE VI: Average upstream and downstream latency (ms).

Environment	OpenWSN				WirelessHART			
	Up		Down		Up		Down	
	μ	σ	μ	σ	μ	σ	μ	σ
Office	84	74	819	893	395	399	2107	1546
Industrial	146	114	960	925	486	343	1782	1300

downstream packets due to contention among motes. Motes in the WirelessHART network request a service to allocate enough upstream bandwidth to send 1 packet every 2 seconds. We were not able to allocate a similar service in the downstream direction. During testing it was observed that the network manager is able to send 1 downstream packet to each mote approximately every 2.5 seconds.

VI. Conclusions

This paper investigated the use of UWB radio for use in industrial WSNs. OpenWSN was adapted to an UWB physical layer based on the DecaWave DW1000 UWB transceiver, which permits communication via IEEE 802.15.4 TSCH. We performed experiments in an industrial and office/laboratory environment to evaluate the performance of UWB radio for communication in a WSN. The mesh network performance of OpenWSN/UWB was compared against a WirelessHART network.

Our results show that the observed UWB IBER is suitable for communication according to IEC 61784-3 for 110 kbps and 850 kbps data rates. Excessive packet loss may occur in NLOS scenarios at distances as short as 11 m, depending on the amount of obstruction. We demonstrated that UWB can feasibly operate in an IEEE 802.15.4 TSCH network in an industrial environment. Compared to WirelessHART, OpenWSN/UWB achieved lower latency, but higher packet loss due to worse link reliability. In the office environment involving shorter distances, OpenWSN/UWB achieved higher link reliability than WirelessHART. The results indicate that UWB can provide better link reliability than WirelessHART, although the range for reliable communication is shorter for UWB than WirelessHART.

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