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Ultra Wide Band communication for condition-based monitoring, a bridge between edge and cloud computing

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Abstract

Ultra Wide Band (UWB) wireless communications offer a radically different approach to wireless communication compared to conventional narrow band systems in an industrial context. A lot of industrial applications do not require real-time acquisition and uses low data rates, but some scenarios, such as the condition monitoring systems and the control processes require higher data rates (i.e. tens of kHz). General purpose wireless solutions do not compliant industrial standards. This paper discusses the potential of UWB technology for realizing use cases in industry 4.0 and shows the implementation of an UWB sensor network for machine vibration monitoring that is able to acquire and transmit (6.8Mbit/s data rate) accelerometric measures sampled up to 32KHz with a maximum Packet Loss Rate (PLR) of 2.44%. It also shows as UWB could be a valid instrument to connect cloud computing and edge computing even for real time extraction of diagnostic and prognostic features from high-frequency signals. Different experiments have been performed in an industrial and laboratory environment to evaluate the performance of UWB radio for communication in a wireless sensor network.

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1. Introduction

With the advent of smart factories, the large number of sensors and processing capabilities required to monitor and analyse the operating conditions of increasingly distributed factory equipment and processes have led to the need for increasing edge-computing capabilities both for processing and communication, to monitor operating conditions as well features extraction and post processing analytic on cloud. Wireless sensing has become an important aspect in the context of the Industry 4.0. Wireless connections of sensors instead of cables allow the development of co-simulators

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and new types of Cyber-Physical Systems [1] that facilitate flexibility and systems' reconfiguration. Sometimes, many industrial applications do not require real-time acquisition but handle information with low data rates and sensors only need to send a few short packets per hour [2]. However, some scenarios, such as the condition monitoring systems [3] and the control processes, whether they are industrial or not, [4, 5], require much higher data rates, low latency and high reliability [6, 7]. General purpose wireless solutions do not compliant industrial standards, which implies to implement only customized designs specifically focused on industry environment [8]. Wireless industry solutions like the *IEEE 802.15.4* standard (ZigBee, ISA100, WirelessHart, etc.) [9] are not able to solve the reliability or latency demands of special applications. Moreover, other recent wireless solutions like Bluetooth BLE (Low Energy), LoRa (Long Range) and Narrowband-LTE [10] are generally used for smart city applications where in most cases there is no need for high data rates. In this context, our focus is to show that Ultra Wide Band (UWB), which was considered as a main candidate for industry area [11], provides the potentiality to effectively support enabling technologies of Industry 4.0. In order to measure rapidly-changing variables in industrial environments a wireless sensor network based on UWB system can offer a stable solution.

Nowadays, although the UWB is widely used for communication Systems (using UWB techniques and the available large RF bandwidths, UWB communication links has become feasible), radar Systems (short pulses provide very fine range resolution and precision distance and positioning measurement capabilities) and positioning systems (since there is a direct relationship between bandwidth and precision, therefore increasing bandwidth will also increase positional measurement precision), few works have been focused on industrial applications [12]. Moreover these few works are focused on the advantages of UWB compared to other kind of wireless communication in an industrial environment [13, 14]. Instead, this work aims to analyze if UWB communication could be a valid instrument to connect cloud computing and edge computing even for real time extraction of diagnostic and prognostic features from high-frequency signals. This analysis has been done on a specific industrial use case that requires the monitoring of vibration and it is a preliminary analysis focusing on the comparison between the signals locally measured with high sampling rate and the signals received through an UWB transmission.

Therefore, the following objectives have been pursued in this work: firstly, verify if the UWB module used in this research, the DWM1001 by DecaWave, could manage and transmit the amount of vibration collected data to the edge computing gateway while optimizing the power consumption (this feature is associated with the capability of the battery powered UWB DWM1001 module to trigger data collection and communication based on detected motion thanks to the on-board LIS2DH12 accelerometer), then verify the compliant of DWM1001 module for high data rate communication and finally, verify if it could be used for real time notifications of anomalies in a production environment.

The paper is organized as follows. The UWB DWM1001 hardware module, the on-board LIS2DH12 accelerometer and the communication network are described in Section 2, 3 and 4 while in Section 5 are discussed the experimental setup, tests and results of the proposed analysis. Remarks and future works conclude the paper.

2. Ultra Wide Band brief overview

Ultra-WideBand (UWB) is a wireless communication technology for transmitting information characterized by high transmission speed over short-range distances with very low power consumption. This technology differs from conventional radio transmissions because the information is not transmitted by varying the power level, the frequency, and/or the phase of a sinusoidal wave but by generating radio energy pulses. Accordingly the frequency spectrum associated with this kind of waveform is extremely wide, hence the name UWB, in contrast to the narrowband communication archived by modulating a sinusoidal carrier. In detail, the Federal Communications Commission (FCC) in USA defines any device with a –10dB bandwidth of at least 500MHz or a –10dB fractional bandwidth greater than 0.2 (i.e. bandwidth is 20% of the arithmetic center frequency) as an UWB device. [15]. By contrast most narrowband systems occupy less than 10% of the center frequency bandwidth and are transmitted at far greater power levels. For example the 802.11*b* radio system centers about 2.4GHz with an operating bandwidth of 80MHz that is only the 3% of the center frequency.

There are some distinctive advantages of short-range high-bandwidth UWB like high immunity to interference from other radio systems, high multipath immunity along with high data rate and extremely low duty cycles, which translates into low average prime power requirements allowing tags to work autonomously for years [16]. The drawback is that the low transmit power levels together with the ultra-fine time resolution of the system can increase considerably the synchronization acquisition time and the complexity of the receiver. Moreover UWB radio, operating with extremely large bandwidths, must coexist with many other narrow-band signals (TV, UMTS, GPS, etc) avoiding mutual intolerable interference.

3. UWB DWM1001 Module

The DWM1001 module, showed in Figure 1, has been used for vibration data acquisition and it is based on the DW1000 ultra wideband transceiver IC, which is complain with IEEE 802.15.4 – 2011 [17]. This module integrates

Fig. 1. Ultra Wideband node $DWM1001 - DEV$.

UWB and Bluetooth, a Nordic Semiconductor nRF52832 BLE MCU, and a 3-axis accelerometer, within low-power hardware design and software architecture for longer battery life [18]. The main advantages of the module are the several features that enable energy-efficient arithmetic and high-performance signal processing. The nRF52832 is an ARM® Cortex®-M4 processor with floating-point unit (FPU) and a 32-bit instruction set (Thumb®-2technology) that implements a superset of 16 and 32-bit instructions to maximize code density and performance. The accelerometer on board is the LIS2DH12, an ultra-low-power high-performance three axis belonging to the "femto" family, which is micro-machined accelerometers. It has a 14-bit data output, user-selectable full scale from $\pm 2g$ to $\pm 16g$ and it is capable of measuring accelerations with output data rates from 1.6Hz to 1600Hz. The LIS2DW12 has an internal FIFO buffer allowing the user to store up to 32 accelerometric samples for each axis to limit intervention by the host processor. The accelerometer is designed to detect motion while being in low-power mode (with consumption going as low as 2µA), read data in FIFO mode up to 5376Hz in low-power mode (185µA) or 1620Hz in normal resolution mode (185µA).

4. Network Architecture

Figure 2 illustrates the network architecture scheme. A given machine can have multiple sensors, which are connected via UWB links to an Access Point (AP). Several APs are distributed in a factory for radio coverage of all sensors. All APs are connected via wires to a central application server, which coordinates the network resources and performs multiplexing in each cell. Such architecture is of widespread use in industrial wireless networks [19].

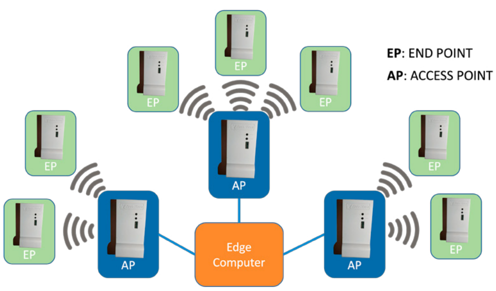

Fig. 2. Industrial star topology.

This type of network architecture is called *Star Topology* where each node, or End Point (EP), connects directly to a gateway. In star topologies, the EPs are not permitted to send messages to each other unlike what happens in a mesh topology where every node can directly communicate with every other node and can act as a repeater to route the data through the network. This feature leads to a fast and simpler network with consistent and predictable performance and that allows low-latency communications between the remote node and the gateway (base station) [20]. In figure 3 is highlighted the star topology system implemented in laboratory.

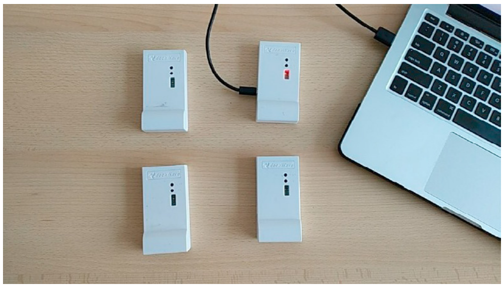

Fig. 3. Star network architecture with four UWB nodes.

5. Test and Preliminary Results

As described before, DecaWave boards have been used to implement a small UWB network to demonstrate the feasibility of proposed analysis. In detail, three type of test have been performed:

- The initial test consists of verifying the UWB platform limit in term of Data Rate and Sampling Rate when integrated in a single hop star network. The test has been carried out without any particular external instruments but only acquiring accelerometer data following two approach: in the first scenario, the accelerometer data have been read and immediately sent via radio to the edge computer, while in the second one, the data have been read from accelerometer, manipulated in order to simulate different sampling rate and data rate and then have been sent to the edge computer.
- the objective of the second test is to have an indicator to check both the correctness of the data produced by the accelerometer and the UWB platform limit in term of vibration detection threshold to wake up the radio module.
- finally, the last test is referred to a real industrial scenario, applying the UWB platform on a production press machine and managing the wake up communication core and the vibration data acquisition.

5.1. UWB Platform Test

Industrial-grade vibration sensors for motors have a sampling rate of 10 to 66KHz or more. Communicating 66000 samples per second with preamble set to 64 bytes and a 23 byte header would require a data rate of around $4.5M$bit/s. Thanks to UWB communications it is possible to have a bandwidth of 6.8MBit/s. In order to measure the effectiveness of the UWB technology for condition-based monitoring, experiments have been run to check directly if UWB modules are able to losslessly transmit accelerometric measures at different sampling rate, without measuring the actual maximum speed of data acquisition. Specifically, tests have been conducted with both sampling from the on-board accelerometer (up to 1620Hz sampling rate for high resolution samples) and a simulation of an higher grade sensor with sampling rate of up to 66KHz, with data rates of 6.8Mbit/s on a one hop one node network, as to test the limits of the platform (See Table 1).

The DWM1001 supports an extended frame mode, which allows for frames larger than 127 bytes but smaller than 1023. For this reason, the tests have been run by sending 31 samples per packet (the maximum FIFO size of the LIS2DH12 accelerometer in the real cases), which amount to 209 bytes per packet considering headers. In Table 1 is shown the relation between the sampling rate and the reliability of packet delivery at fixed communication data rate. The variation of sampling rate has been performed both by setting special microcontroller registers (Real) and by using

Table 1. Experimental results at different sampling rate.

Data rate	Sampling rate	Real or simulated Real	PDR	PLR
6.8Mbit/s	200Hz	Real	100%	0%
	400Hz	Real	100%	0%
	1620Hz	Real	100%	0%
	5376Hz	Simulated	100%	0%
	32KHz	Simulated	97.56%	2.44%
	46KHz	Simulated	49.32%	50.68%
	56KHz	Simulated	49.82%	50.18%
	60KHz	Simulated	0%	100%
	66KHz	Simulated	0%	100%

a dedicate program code (Simulated). In the simulations of an higher grade sensor, the data generation does not have the same sampling rate used by a microcontroller because the data is generated artificially and there is no interrupts management, no waiting times for the A/D conversion or no registers to be read. For this reason, the simulations have been run by assuming the board is able to read from an external accelerometer at the required speed, by replacing the real reading procedure with a sleep for the amount of realtime ticks required to achieve the specified sampling rate. As highlighted in 1, in our experiments, the node can not handle sampling rates higher than $32KHz$ even with a 6.8Mbit/s data rate, but anything equal or below that yields good results. In fact, at sampling rates higher than 32KHz the Packet Delivery Ratio (PDR) drops down from 97.56% to 49.82% while the Packet Loss Rate (PLR) increases from 2.44% to 50.18%.

5.2. Mock-up Test

In order to check the functionality of the accelerometer and the quality of the collected data an oscillating table, available in the i-Labs industry, a Public-Private-Partnership laboratory in Italy which is devoted to technology transfer and cooperation between industry and academia, has been used 4. In detail, the setup consists of an oscillating table supporting only sinusoidal signals, a signal generator, an amplifier and an accelerometer with a sampling rate of 200Hz acting as ground truth. The accelerometer has been attached with an analog interface to an embedded computer in order to acquire and to synchronize the collected data for comparison purposes, while the UWB nodes are placed on the oscillating table and the Access Point is connected to the same embedded computer making up a star topology. Industrial accelerometer sampling rate was $200Hz$, and it had an Analog interface which we could only connect to the

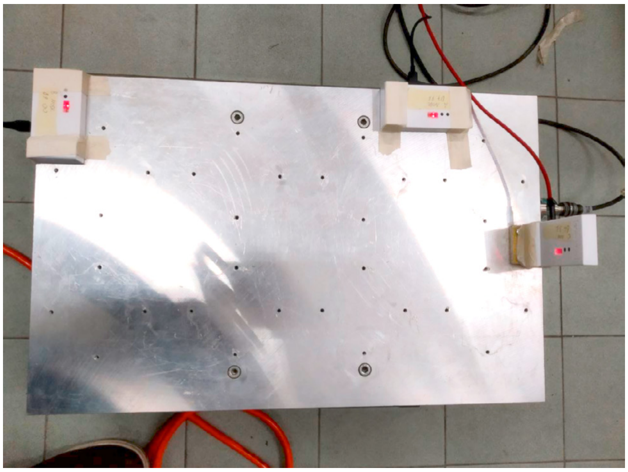

Fig. 4. UWB Mock-up table.

provided PC. The digital outputs of the LIS2DH12 are expressed as two's complement data, left-justified, which means that to store it as a 16 bit integer the value has to be shifted right by a certain amount of bits, based on the resolution of the values selected register (8 bit resolution only requires reading the low part of the 16 bits, 10 bit resolution and 12 bit resolution both require a right-shift by respectively 6 and 4 bits). Synchronizing the timestamps on the collected data has been managed by starting data collection before sending any signal to the table. The table itself started out with large movements before stabilizing around the given sinusoidal signal, which means our collected data for each node contains a peak at the start of the experiment. That peak signals the start of the experiment, from there we skip a few seconds worth of data to get right to the point where the table has already stabilized around the signal we specified through the signal generator to compare the various accelerometer's behaviour. Figure 5 shows the results with the

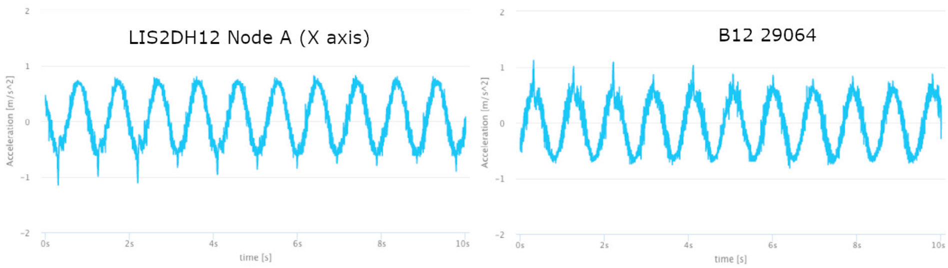

Fig. 5. Experiment with 1Hz sinusoidal signal, at 200Hz sampling rate. LIS2DH12 A Node (X axis) and B12_29064 comparison.

LIS2DH12 set in normal resolution with a 200Hz sampling rate and it is possible to see that the data is consistent with the lab equipment. As we are looking to monitor vibrations, the signal's frequency has been increased as to make the

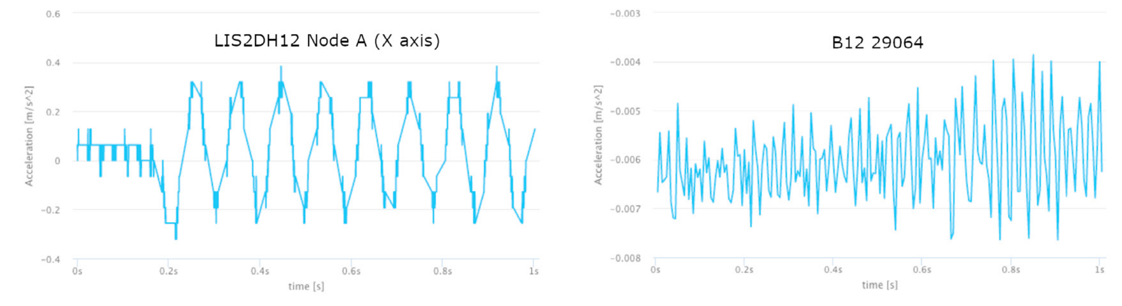

Fig. 6. Comparing behavior of the sensors with a 10Hz sinusoidal signal with an amplitude of 100mV.

movement almost imperceptible to the naked eye. With an amplitude of 1V and frequency 10Hz at the signal generator the table vibrated in place. Even with these settings, the LIS2DH12 is able to detect the pattern with a sampling rate of 200Hz, while the B12_29064 struggles to keep up. Instead, lowering the amplitude at the signal generator to 100mV, when the table barely vibrated in place, a sampling rate of 1620Hz was required to the UWB module in order to keep detecting the pattern while, obviously, the B12_29064 continues to fail (See Figure 6).

5.3. *Real Scenario Test*

As previously stated, the main purpose of the LIS2DH12 inside the DWM1001 nodes is to provide a way to perform motion vibration and inactivity detection. This functionality can be used when deployed in a real network to lower energy usage by collecting vibration data only when the machinery is in a work cycle. A test has been conducted in a real scenario in a plastic injection molding company to see whether the thresholds were applicable in real world scenarios and if the presence of machinery in a working environment would affect packet loss. The industrial environment is rougher with high electromagnetic interference than the bench test. It can have a negative impact on the experiment results, which may be below the current results in the bench test experiments. As shown in Figure 7, an UWB node has been placed on the back of a press machine and 50 meters away from the Access Point.

The results proved that such an architecture can work in a small to medium sized company, while anything larger will

Fig. 7. UWB node collecting data on the press.

require either a multi-hop network or multiple sinks. The node is able to send data only when detecting motion. The nodes (AP and EP) suffered no packet loss, except when the node was in the directly opposite position with respect to the sink, hidden by multiple machines. Better sink positioning would alleviate the problem.

6. Conclusions

This paper investigates the use of UWB technology as a valid instrument to monitor and historicize vibrations in an industrial environment following a non-intrusive way on machines that are not predisposed for such behavior. Different experiments have been performed in a laboratory environment to evaluate the performance of UWB radio for communication in a wireless sensor network. Instead, press machine vibration monitoring was used as a test case to demonstrate the UWB tecnology applicability in real industrial environments. The accelerometer outputs data as expected and the DWM1001 is able to send the entirety of the collected data to the edge computing even in real world scenarios. Moreover, the motion sensing capability of the LIS2DH12 can be used to lower the energy consumption of the nodes and only send data when required. The high data rate of the communications should enable multi-node multi-hop networks if correctly implemented, to allow a full deployed network in an industrial complex to monitor the machine's working routine and functionality. The sampling rate of the accelerometer is not high, but it should be high enough to at least notice anomalies in the machine's working condition even when the machinery does not have an integrated sensor, allowing real time notifications to the company's owner or workers. In addition, further experiments need to be performed such as verifying how the network topology affect on the data transfer between cloud-edge and the ranging, the capability of location a device using UWB technology over a theoretically range under 200 meters, to see whether or not ranging can be performed at the same time as the vibration data collection.

As last conclusion, it should be pointed out that, even though this paper analyzed the potential of UWB communication technology focusing on a specific industrial use case (i.e. machine vibration monitoring) and using an off-the-shelf UWB module that integrates only a 3-axis accelerometer, the same approch could be applied to different industrial scenarios requiring high-frequency monitoring (i.e. electric motor fault detection with Motor Current Signature Analysis), provided that UWB module including the necessary sensors are used.

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