Approach of using Ultra-Wideband-Radio in Industrial Real-Time Ethernet Networks

Kristian Stieglitz, Joerg F. Wollert
Department of Electrical Engineering and Computer Science,
University of Applied Sciences
Bochum, 44801, Germany
{kristian.stieglitz, joerg.wollert}@hs-bochum.de

ABSTRACT

Within the last years, the utilization of wireless solutions for industrial applications has become very popular. Especially in harsh environments, mobile and rotating scenarios, or at positions difficult to access, the advantages of radio technologies are obvious. In addition to that, there is a great potential on saving time and money during planning, installation, and commissioning of plant sections. However, due to the lower capacity and reliability of wireless links compared to wired ones, time critical domains like factory automation or motion control, can hardly be served by radio based solutions. Meanwhile, Ultra Wideband (UWB) a wireless transmission technology for high bitrate more than 480 Mb/s and short range (1-10m), offer opportunities, to meet the requirements of high speed industrial communication systems.

The full paper gives a short overview of important industrial Real-Time-Ethernet (RTE) technologies and the ECMA-368 UWB radio. Furthermore, we present the relevant performance characteristics of ECMA-368 and compare them with the requirements of current RTE-Systems. The paper concludes with the approaches to realize typical use cases of wireless solutions in industrial applications.

Keywords: Real-Time-Ethernet, wireless, ultra wideband, ECMA-368, automation, motion control, RTE-Bright, WSAN

1. INTRODUCTION

Short Range WPAN Networks like Bluetooth or Zigbee gained significant popularity in recent years. Few domains of industrial automation already benefit from using wireless applications. Especially in mobile and rotating scenarios, harsh environments, or at positions difficult to access, the advantages of radio technologies are obvious. In this use cases radio links often offer a lower error probability compared to sliding contacts and cable connections. Specific mobile scenarios are only realizable, based on radio technologies. Furthermore there is a high potential on reducing time and money during planning, installation, and commissioning of plant sections. It has been estimated that common wiring costs in industrial installations are about US $ 130,..,650 per meter and adopting wireless solutions could save 20 %,..,80 % of these costs [1].

Besides the development of radio-based systems for the industrial use, in the last years classic fieldbus systems for industrial automation are slowly been replaced by Real-Time Ethernet fieldbus systems. Current RTE offer significantly shorter cycle times with much higher data rates. Because of this features RTE are very good suitable for the use in factory automation and motion control. However, this performance exceed by far the capabilities of current industrial wireless solutions, which are based on low band wide radio system such as IEEE 802.11/WLAN [2], IEEE 802.15.1 [3] / bluetooth [4] or IEEE 802.15.4 [5].

Further, due to the fluctuating nature of these radio communication channel, the mentioned time critical low latency domains, can hardly be served by radio based solutions [6]. Particularly in industrial environments, with several moving and metallic obstacles, reliable wireless data communications are very difficult to obtain.

In this context, the Ultra Wideband (UWB) radio technologies offer opportunities, to meet the requirements of high speed industrial communication systems. First standards for Ultra-Wideband (UWB) radio technologies have been published in 2006 and 2007. In general, UWB offers the following advantages:

- Low latency times, due to extreme short symbol durations, what additionally offers the possibilities for precise ranging.
- Robust against the effects caused by multipath scattering. Reflection and scattering are frequency selective. Using a high bandwidth reduces the probability of deep fadings over the whole frequency range.
- Energy efficiency, due to the low spectral density power.

Especially the first two statements underline the potential suitability of UWB for low latency real time applications. Possible use cases are:

- Cable replacement in high speed real time Ethernet (RTE) connections (RTE-Bridge).
- Application in wireless sensor/actor networks (WSAN).

ECMA-368 is one of the current available UWB technologies. It defines high data rate UWB and is based on the specifications of the WiMedia Alliance. ECMA-368 is the foundation for a bundle of commercial protocols, like WiNET for TCP/IP support and Certified Wireless USB. Analyses of the ECMA-368 specification as well as practical tests have shown that the standard is suitable for the realization of the mentioned use cases [7].

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The rest of the paper is organized as follow, Chapter two and three gives a short overview of the current industrial RTE-technologies and the ECMA-368 UWB radio and present the relevant performance characteristics of them. In the following Chapter possible applications for UWB Radio in RTE networks would be presented and discussed. The paper concludes with presentation of the used hardware and software framework.

2. MODERN INDUSTRIAL COMMUNICATION SYSTEMS

The traditional fieldbuses and the directly coupled signals are slowly being replaced by Ethernet based communication solutions [8]. The move towards Ethernet as the basic communication platform is mainly based on the efficient price/performance relationship of the technology. Corresponding to Figure 1, the performance of real time Ethernet (RTE) protocols has historically evolved into three generations [9].

The protocols using the whole Ethernet TCP/IP stack and on top a real time specific application layer belong to the first generation. Good examples are Ethernet/IP [10] and Mod-Bus/IDA [11]. Since the whole TCP/IP protocol stack is used, the real time performances are limited. Guaranteed update times of about 100 ms can typically be reached.

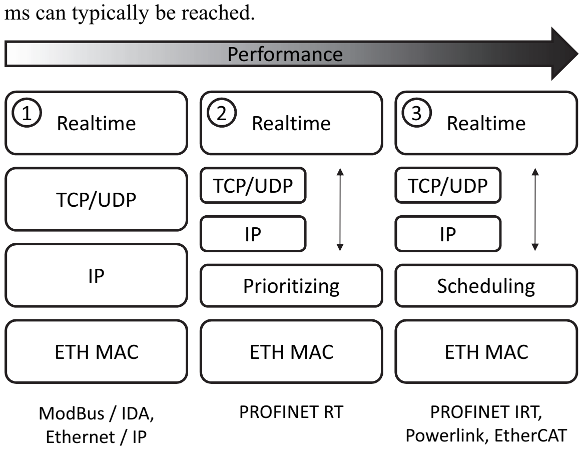

Figure 1: Classification of industrial-Ethernet Protocols[8]

Protocols of the second generation are a tradeoff between native Ethernet standard versus achievable real time performance. The transport and network layers are bypassed in order to achieve a more efficient real time communication. By means of this optimization, update times in the range of about 10 ms can be reached. A good example is PROFINET RT [12].

Protocols which are changing/replacing the original MAC scheme are part of the third generation. For those protocols, specific hardware or software is necessary. Good examples are Ethernet Powerlink [13], EtherCAT [14] and PROFINET IRT[12]. Depending on the protocol, summation or individual frames and cut-through operations are used, in order to exchange process date at extreme low latency times. The update times of third generation RTE protocols reach down to below 250 µs, according to the number of nodes joining a network.

The interested protocols of the third generation roughly can be divided into three functional principles:

Token-based methods: These include the RTE EtherCAT and SERCOS III. In this principle the master note transfers on or more Ethernet frames in a row. These Ethernet frames carry all process data of the slaves. This process data are passing each slave and the last slave sent them back to the master. Physically, the slaves are connected in a ring or linear topology. The process data in the Ethernet frames are processed by the slaves "on the fly". So the Ethernet frames are constantly delayed less than 500 ns. Important for this principle is the need of a full duplex communication.

Request Response Procedures: This includes the RTE PowerLink. In this principle the process data between the master and the slave where transferred in a separate Ethernet frame for each slave. The Master requests the slaves to take over the process output data and to send their input process data back to the master. This method does not require am full-duplex communication.

Consumer Producer process: This includes the RTE PROFINET. In this principle the master determined for each slave at the beginning, when the process data have to be transmitted. The transmission timings are optimized to the network, so that the collisions between the slaves are minimized. In real-time operation, the slaves transmit there process data periodically without further requests by the master. Also the master sends its output process data network optimized to the slave notes. This process requires also a full duplex communication.

		Powerlink	PROFINET IO/IRT	SERCOS III	EtherCAT
Real time Layer					
Real Time over Transport Layer		-	-	-	-
Real Time over ETH-MAC		x	-	-	-
Modified MAC		-	x	x	x
Specific Phy Layer		-	-	-	-
Transmission Times					
IAONA-Echtzeitklasse		4	4	4	4
minimale Zykluszeit [s]		200 µs	250 µs	31 µs	30 µs
Obergrenze des Jitters [s]		< 1 µs	< 1 µs	< 1 µs	< 1 µs
Strategies und Synchronization					
Introduction of TDMA		x	x	x	-
Token based Method		-	-	x	x
Introduction of prioritization		-	x	x	-
Response Request Method		x	-	-	-
On the Fly Frame Processing		-	-	-	x
Synchronisation über Sync-Signal		x	-	x	-
Time Synchronization (like IEEE 1588/PTCP)		x	x	-	x
Topoloegie & Verteiller					
Logic Topologies:	Tree	-	x	-	-
	Line/Bus	x	-	-	-
	Ring	-	-	x	x
Physical Cabling:	Baum	x	x	-	x
	Line/Bus	x	x	x	x
	Ring	-	x	x	x
Distributor:	Hubs	x	-	x	-
	Switches	-	x	-	x
	Special	-	x	x	x
ETH-Standards Conformance					
Standard ETH-Frames Transmission		x	x	x	x
ETH-Standard Allowed in Higher Layer		x	x	x	x
Capping is Compiant with the ETH-Standard		x	x	x	x
Switches are Compliant with the ETH-Standard		x	-	x	-
TCP/UDP/IP-Frames in Network Allowed		x	x	x	-
nRT-Traffic in Specific Time Slots		x	x	x	-
Standard PCs in Network Allowed		-	x	-	-
Cross Traffic Allowed		-	x	x	x
Ether Type		0x88AB	0X8892	0x88CD	0x88A4

Figure 2: Properties of industrial-Ethernet Protocols

The table in figure 2 shows the performance and transmission characteristics of the mentioned RTE. The figure 3 shows the theoretical possible minimum cycle times for the RTEs depending to the number of slaves for different sizes of process data. Practical the following minimum cycle times are currently available:

- 250 ms Profinet IRT
- 200 ms Powerlink
- 50 ms EtherCat
- 32 ms SERCOS III

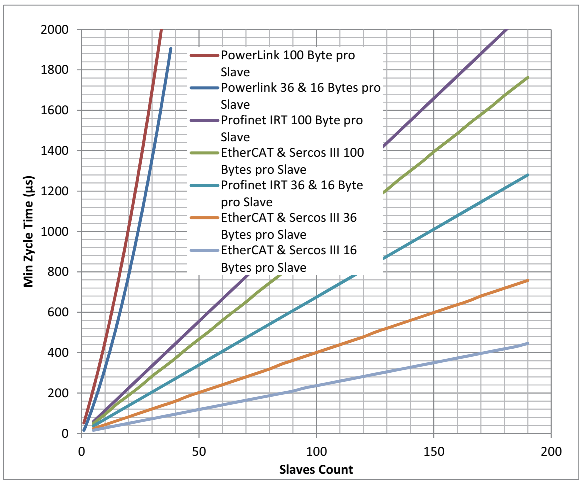

Figure 3: Updatetime of industrial-Ethernet Protocols

3. Ultra-Wideband

The first regulation for UWB devices within a frequency range between 3.1 GHz and 10.6 GHz was published by the FCC in 2002 [15]. The maximum e.i.r.p. power density is limited to 41.3 dBm/MHz. More restrictive regulations concerning the frequency ranges, channel occupation, and maximum power spectral densities followed for Europe, Japan, Korea, and China since 2007.

UWB follows the approach of a parallel utilization of the frequency spectrum with a large band-width and a low spectral density power, hence being immune and appearing as noise to coexisting narrow band technologies [16].

Based on the specifications of the WiMedia Alliance [17], the first UWB standard ECMA-368 [18] was published in late 2006 and is available in version 3.0 since 2008. It uses a Multiband OFDM (MB-OFDM) scheme and supports high datarates of up to 480 Mb/s on the PHY layer. The amendment IEEE 802.15.4a [19] is the second standard for UWB PHY and MAC layers and was published in 2007. The standard uses Direct Sequence UWB, bursts of impulses, to generate signals and aims at a ultra low power and low datarate communication (100 kb/s to 27 Mb/s) with precise ranging capabilities. However, the second standard is unattractive for the use in RTE networks, due to its low data rates.

ECMA-368

ECMA-368 defines high data rate UWB PHY and MAC layers and is based on the specifications of the WiMedia Alliance. The standard builds the foundation for a set of commercial protocols, like Certified Wireless USB (CW-USB) [20], and WiNET for TCP/IP support. The standard defines fourteen 528 MHz frequency bands, which are split up into six band groups. Each band group consists of three bands with the exception of band group five, which consists of only two bands.

Data is encoded using MB-OFDM with 122 sub-carriers (100 data, 10 guard, 12 pilot). The different data rates are realized, using a convolutional code with coding rates of 1/3 to 3/4, time domain spreading (TDS), and frequency domain spreading (FDS). TDS makes use of time diversity, by redundantly transmitting data over two consecutive symbols. FDS makes use of frequency diversity, by redundantly transmitting data over two OFDM carriers. Depending on the data rate, distances between three to ten meters are achieved at an output power of -41.3 dBm/MHz. This is a sufficient range for applications in typical production cells.

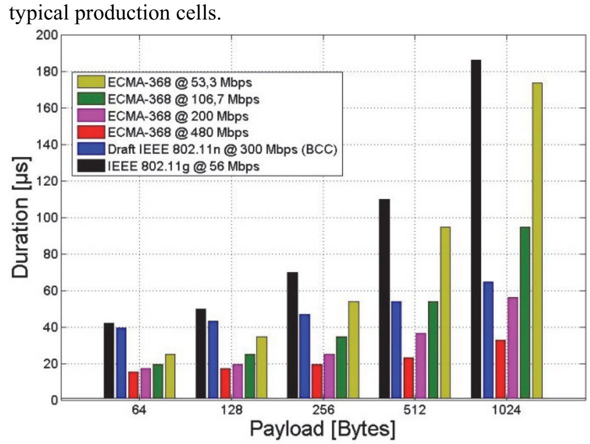

Figure 4. Comparison of the physical transmit durations between ECMA-368, IEEE 802.11g and IEEE 802.11 Draft n [7]

Figure 4 shows a theoretical comparison of the physical transmission duration of ECMA-368 for different datarates, IEEE 802.11g at 56 Mb/s, and IEEE 802.11 Draft n at 300 Mb/s (greenfield) for different amounts of payloads. Because of the shorter protocol overhead, even at 53.3 Mb/s ECMA-368 outperforms IEEE 802.11 Draft n for payload length of > 100 bytes. Thereby, the energy consumption of ECMA-368 is approximately one magnitude lower compared to IEEE 802.11.

The standard specifies a fully distributed MAC layer with no explicit coordinating device. A transmission channel is divided into superframes, each consisting of 256 medium access slots (MAS). Each MAS has a duration of 256 µs. A superframe is composed of a beacon period (BP) at the beginning and a following data period. The BP consists of a variable number of beacon slots with a duration of 85 µs. Within the beacon slots, devices exclusively send beacon frames, containing information on the device. With each device joining a network, called beacon group, the beacon period gets extended by one beacon slot. Two beacon slots are always reserved for devices to join in the future. Beacons are also used to negotiate and coordinate the channel access among the device within the data periods of superframes. The standard defines the two access methods distributed reservation protocol (DRP) and prioritized contention access (PCA).

The DRP gives exclusive access to reserved blocks of MASs for a reservation target and a reservation owner, where the target is a single device and the owner may also belong to a multicast group. Data transmission is always initiated by the target device. Within blocks of non-reserved MAS, devices may access the medium using PCA. PCA is a CSMA/CA scheme.

In summary it can be said that the investigations presented by RTE and ECMA 368 have shown that the realization of the presented use cases should be possible with cycle times well below 1 ms. However, in order to get full access to the PHY capabilities, the following weak points of the MAC have to be overcome:

- Depending on the number of devices, participating in a beacon group, the length of the BP varies between 512 µs and 8.16 ms. At these times, no data transfer is allowed.
- In principle, DRP offers a time synchronised access to the medium, suitable for deterministic real time protocols. But the duration of 256 µs of a MAS is alligned with respect to large payloads. When using frames with small payloads, like it is common for industrial protocols, about 80 % of this time would be left unused.
- PCA gives more flexibility for devices to access the channel. But contention aware protocols do not guarantee a deterministic channel access.

4. INDUSTRIAL USE CASES

Within the scope of the project „Ultra Wideband Interface for Factory Automation" (UWIfac), funded by the German ministry for education and research (BMBF), the feasibility of the following two use cases should be proved:

- **Time synchronized wireless sensor/actuator Network (WSAN):** This is understood as a real-time Ethernet slave who is able to exchange the completely process data of its attached wireless sensors and actuators within a real-time Ethernet cycle (typically 100 µs to 1 ms).
- **Real-time Wireless Bridge (RTE-Bridge):** Descripts a wireless point-to-point connection with an extremely reliable almost delay and jitter free communication behavior within the permitted real time limits.

Time-synchronized wireless sensor/actuator Network:

The requirements to the UWB radio technology are different for both use case. In the use case of WSAN, the RTE is not affected by the wireless technology, because the gateway note is a RTE-Slave of the respective RTE itself. This gateway has its own process data, which stores the input and output process data of the individual radio sensor/actuator notes. Regardless of the RTE-cycle these process data are exchanged between the gateway and the wireless nodes in its own sub cycle. This is a master-slave relationship with a request response communication behavior. For the RTE network the WSAN gateway note looks like an RTE-coupler with a sub-bus. Hence, the requirements for this use case are:

- a minimum cycle time of the sub-bus
- a very reliable radio link

The minimum cycle time of the sub-bus depends on the number of wireless notes. To keep the cycle time small for many wireless devices, the wireless devices can be subdivided to multiple smaller groups each with their own gateway note. Therefore, ECMA-368 offers the possibility to operate multiple systems simultaneously in different radio channels. This parallel operation is very limited for conventional radio systems. In principle, this use case can be realized functional in any case. However, it needs to be tested, if the desired performance can be achieved.

Real-time Ethernet Wireless Bridge:

For the use case RTE-Bridge the requirements to the UWB radio technology are much tougher than to the previous use case. The system affects directly the RTE communication, because it practical replaced a cable connection between two slave-RTE or a network switch or hub. Especially for the RTE of the third generation the demands for a constant time behavior of these network components are very high, to achieve an exact synchronization of the RTE slaves. Assuming that the RTE-Bridge is replaced an Ethernet cable, three requirements are important for the RTE-bridge:

- Full duplex communication
- Jitter- and nearly delay-free transmission of Ethernet frames
- High reliability against loss and damage of the Ethernet frames

It is obvious, that wireless technologies cannot reach these characteristics of a cable. Therefore it is important to find out, how high the requirements for the specific RTE really are.

The full duplex communication is one of the most critical requirements for conventional radio systems. Conventional radio systems are based on a single channel half-duplex communication. That means, when RTE- system requires a full duplex communication, a single-channel radio system wouldn't meet this requirement. RTE which needs a full duplex communication are, SERCOS III, EtherCAT and PROFINET RT / IRT.

Thus, a radio system with full duplex communication has to be designed with two channels, so that each transmission direction has its own radio channel.

The next requirement is the delay and jitter free forwarding of Ethernet frames. Conventional Ethernet wireless bridges operate on the "store and forward" principle. According to this principle, also commercially available Ethernet switches are working. In this case, the incoming Ethernet frame is received completely and temporarily stored before being forwarded. The Advantage of this method is that damaged or unwanted Ethernet frames can be discarded. The Disadvantage of this method is that the Ethernet frame is delayed by at least the time of receiving the whole frame. Thus, the forwarding delay is variable. For radio-based RTE-Bridges this effect is doubled, since the "store and forward" principle is used on the Ethernet and Radio interface. Therefore almost all RTE systems of the third generation only allow hubs or switches how operates according to the "cut through" principle. This principle forwards the Ethernet frame after the first bytes are received. This principle has the advantage that the delay time is not dependent on the Ethernet frame length and thus the forwarding jitter is very low. Therefore the RTE-Bridge should operate according to the "cut through" principle. This means that the RTE-Bridge starts to forward the data to the radio interface after receiving the first bytes of an Ethernet frames. On the receiving side an Ethernet frame is transmit as soon the first bytes arrive on the radio interface.

The next requirement is the high reliability against lose or data corruption of the Ethernet frames. Ethernet frames can be lost or damaged, that applies to radio as well as to cable connections. However, radio connections are not so reliable compared to cable-connections. Since the RTE systems expect the reliability of a cable connection, the RTE Bridge must also satisfy these demands.

RTE systems do not retransmit damaged or lost Ethernet frames again, because the data would be already obsolete then. Instead, RTE systems tolerate a certain number of lost or corrupted Ethernet frames. Thus, the RTE-Bridge has to be at least so reliable that the tolerable number of lost and corrupted Ethernet frame is not exceeded. ECMA-368 already offers a very reliable radio communications.

5. APPROACH DISCUSSION

In the following chapter, three possible solutions for the use case RTE-Bridge would be presented and discussed:

• Transparent RTE-Bridge
• RTE specifically optimized RTE-Bridge
• RTE-Bridge as a gateway between two independent RTE networks

1) Transparent RTE-Bridge:

This approach would provide the best solution. It has the advantage that the entire Ethernet frame is transmitted without any modification so there is no need to implement higher RTE specific protocol layers. However, in this approach the RTE-Bridge have to come the characteristics of an Ethernet cable especially close, because no RTE specific optimization can be done, which would relax the high requirements. These Requirements are:

• Two-channel full-duplex communication over the UWB radio
• "cut through" behavior for the radio and Ethernet interface with constant transmission delays.

The biggest challenge would be to achieve the constant and small forwarding delays, which are needed to get an accurate synchronization of the RTE network.

2) RTE specifically optimized RTE-Bridge:

In this approach the RTE-Bridge would be implemented for each RTE with specific optimization. Depending on the type of RTE it can be decided, whether the high demands of an Ethernet cable can be reduced. In the case of the RTE Powerlink, for example, no full-duplex communication is needed, so that the RTE-Bridge can be realized with a single channel UWB radio. Since in this approach the RTE-Bridge implements the RTE protocol stack, only the necessary process data are needed to be transmitted over the radio interface. That means that the protocol overhead of the Ethernet link layer and the RTE Layer could be cut off for the transmission over the radio. Also the bridge endpoints can be synchronized to the RTE networks cycle time so that the RTE network timings could be corrected by the RTE-Bridge to keep the jitter small. The disadvantage of this approach are the high implementation efforts, as each RTE needs an own implementation.

3) RTE-Bridge as a gateway between two independent RTE networks:

In this approach the process data are exchanged between two independent RTE networks. From the perspective of RTE both radio nodes of the RTE-Bridge are implemented as a RTE slave of the connected RTE network. Both nodes of the RTE-Bridge are exchanging independent from their RTE network cycle time, their own set of input and output process data, so the RTE-Bridge represent a gateway between both RTE network. It is the task of the master controllers in both RTE networks to selected suitable process data for the exchange between the RTE-Bridge notes. The implementation of the RTE-Bridge nodes is RTE dependent. The advantage of this solution is that the RTE networks and their timing aren't affected trough the RTE-Bridge similar to the WSAN use case. Thus, there are no synchronization problems in the RTE network. Since, with this approach the process data can be transmitted independent from the RTE protocol, two different RTE systems can be connected with each other. Therefore, the endpoints of the RTE-Bridge have to be implemented specific to the selected RTE. The Disadvantages of this solution is that two RTE networks must be setup with their own master. Also the endpoints of the RTE-Bridge have to be implemented for every supported RTE protocol. As the exchanged process data have to be processed by both master nodes before they could be transferred to the I / O, the performance potential of this approach is smaller than of the previous approaches. Furthermore, the master nodes are responsible for the timing and synchronization between both RTE networks. Similar to the WSAN use case, in principle this approach can be realized functional in any case. It also needs to be tested, if the desired performance could be reached.

6. HARDWARE AND SOFTWARE

For the prototype development evaluation boards called Anaxo are used. This evaluation board, showed in figure 5, was developed from the Institute of Embedded Systems (InES) of the Zurich University of Applied Sciences (ZHAW) [21, 22]. The board contains an Altera Cyclone III FPGA with four 10Base-T/100Base-TX Ethernet interfaces. The WiMedia compliant UWB module on the evaluation board contain the ECMA-368 UWB PHY RTU7012. This PHY is supporting the band groups 1 and 3 with all data rates from 53.3 Mbps to 480 million Mbit/s [21]. Through the use of an FPGA, other components like a soft-core, the UWB MAC IP and a slave-RTE IP could be programmed in the FPGA without changing the hardware. The used ECMA 386 UWB MAC is a VHDL-IP. This UWB MAC was also developed by InES. Since the UWB MAC has been developed in VHDL, it can be easily optimized to the desired RTE applications.

The UWB MAC can independently read/write data directly from the memory and transmit/receive them over the radio interface. No microprocessor is needed for data processing, which leads to very short transmit and receive delays. For the use with RTE, an Ethernet interface could be implemented in this way that the incoming and outcoming Ethernet data were also read/write directly to the transmission/reception memory of the UWB MAC. Such an implementation could be a possible solution for the first approach of the RTE-Bridge use case. For the use cases WSAN and RTE-Bridge, in the RTE specific variants two and three, commercial RTE-Slave-IPs are available, which can be used for the RTE slave implementation on the FPGA. For the implementation of these approaches a RTE-Slave-IP could be programmed together with the UWB MAC IP into the FPGA and the UWB MAC could be configured in this way, that the MAC could access directly the input and output process data memory of the RTE-Slaves-IP. Since this solution also don't need microprocessor for data processing, an optimum response and delay time could be achieved.

Since EtherCAT is one of the most powerful RTE [23] and a commercial IP for the selected FPGA is available, the presented concept will be tested with this RTE first. If the desired goals could be achieved with this RTE, it can be assumed that this concept is portable to other RTE protocols. The porting effort to other RTE protocols would be low, due to the chosen hardware platform.

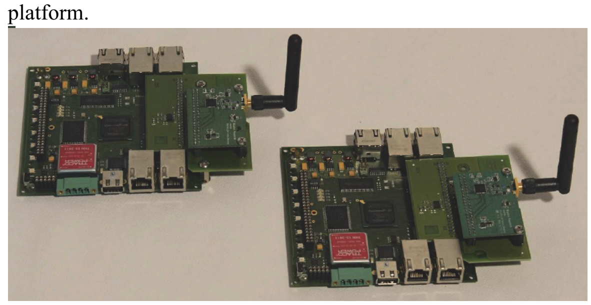

Figure.5. Anaxo – Ultra Wideband Communication Development Kit [21]

7. CONCLUSION

As a whole, one can say ECMA 368 PHY has the capabilities, to achieve a reliable wireless data transfer beyond the timelines given by state of the art industrial wireless solutions. However, without modifying the MAC, it will be hardly possible to get full access to these capabilities. Thanks to the presented hardware platform, these modifications are possible, so the UWB MAC could serve the needs of industrial high-speed RTE communication. For the presented use cases WSAN and RTE-Bridge the requirements for the UWB radio technology were investigated and several possible solutions discussed. In principle, with the chosen hardware platform a functional implementation of the use cases should be possible. With the limited range of about 10 m ECMA-368 is well suited for the local operation within dedicated production cells. With concern to coexisting technologies, the short range actually is of advantage for this use case.

Within the scope of the project „Ultra Wideband Interface for Factory Automation" (UWIfac), funded by the German ministry for education and research (BMBF), further theoretical and practical evaluations of the presented approaches, will be accomplished. Measurements regarding latency, error, and coexistence properties will be accomplished and the results will be published in the future.

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