INDOOR POSITIONING WITH UWB TECHNOLOGY

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Introduction

One of today's most popular topics is the indoor positioning. Since GPS is widespread and used on a daily basis, we have already experienced how many modern applications a system like this may have, but a solution which would be cheap enough and easy to install is yet to be found.

However, based on the experiences of the last few years, the UWB technology could be an ideal candidate for this role. The usage of picosecond long pulses even in an environment rich in reflections enables the separation of components arriving on different paths due to multipath propagation. Thus, the time of arrival of a pulse at the receiver can be defined with proper accuracy.

During my research I'd like to design and implement an UWB positioning system for only demonstrational purpose. This paper is intended to present my work on this topic so far.

UWB technology

UWB radio (also known as impulse radio) is fundamentally different from the currently widely used, traditional radio, which modulates a continuous sine wave in amplitude, frequency or phase, therefore making them suitable for carrying information.

In the case of UWB radio, narrow (in the time domain) pulses are emitted, and the position of these pulses carries the information. As a consequence of narrow pulses the bandwidth of the transmitted signal is high, hence its name (Ultra Wideband).

There were efforts to standardize UWB, but still there is no uniformly accepted definition. The first organization that came out with a plan regarding the regulation of UWB transmissions was the FCC, which is responsible for the allocation of frequency bands in the US. As of today, in most of the developed countries propositions exist on this topic. Regulations in different countries may differ in detail, but agree on fundamental issues.

In the following, I describe the FCC standard for UWB transmissions:

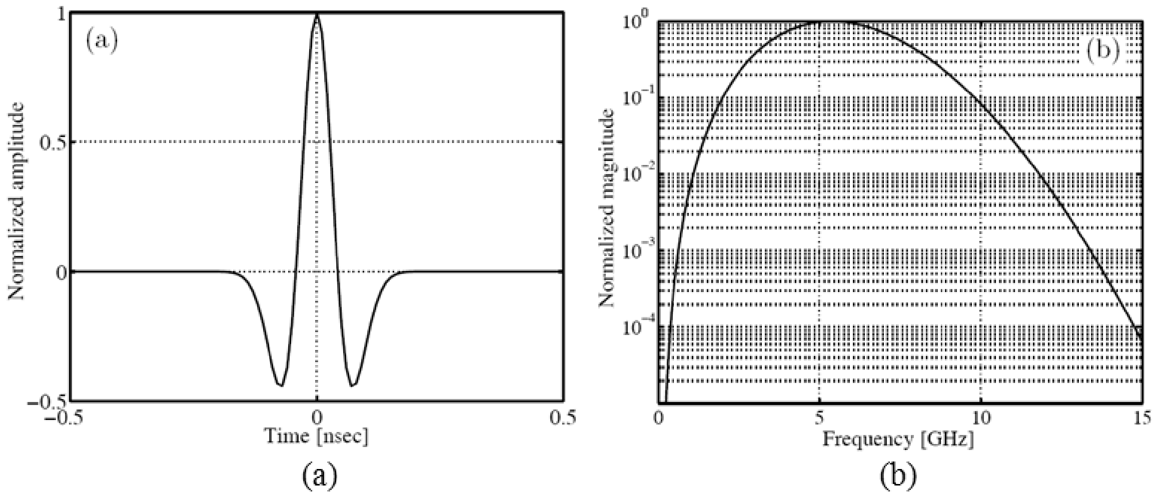
Any wireless system constitutes UWB if its bandwidth is higher than 500 MHz, and the transmission has at least 0.2 relative bandwidth (bandwidth is measured between the -10 dB points).

For communication and positioning purposes only the frequency band between 3.1 and 10.6 GHz can be used.

Other limitations of the transmitted signal power:

The peak power in any 50 MHz wide part of the signal bandwidth cannot exceed 0 dBm.

The average power in any 1 MHz wide part of the signal bandwidth cannot exceed -41.3 dBm.



UWB impulse in time and frequency domain

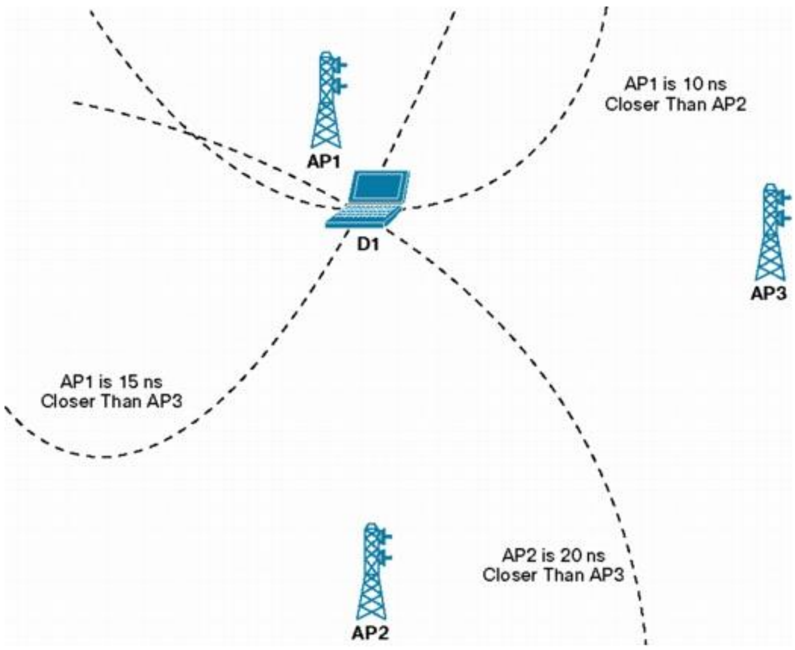
Positioning

Determining the relative position is actually an equivalent of determining the distance or direction from fixed points. The received signal level (RSS - Received Signal Strength) and direction based (DOA - Direction of Arrival) methods will not be discussed in the following, because they are out of the scope of this document.

There is another approach which is similarly to the procedure based on the received signal level makes it possible to determine the distance between the receiver and the transmitter, based on the time of flight.

The so-called TOA, i.e. Time of Arrival method is able to determine the distance between the two devices knowing the speed of electromagnetic wave propagation from the exact moment of receiving the signal. The disadvantage is that there must be synchronization between the sender and receiver, a common internal clock have to be shared. Considering the relatively short distance, an otherwise not significant phase difference between two clocks can cause unacceptable errors. This problem is eliminated by a different time measurement method, the TDOA, or Time Difference of Arrival.

Here the fixed receivers are synchronized, the timing of transmission is arbitrary. A processor registers the arrival time for the different receivers. As the positions of receivers are known, the position of the transmitter could be algorithmically calculated from the time difference values. The method requires a minimum of four receivers in the case of three-dimensional positioning, in two dimensions this number could be reduced to three, but the position of receivers must be the same in altitude.

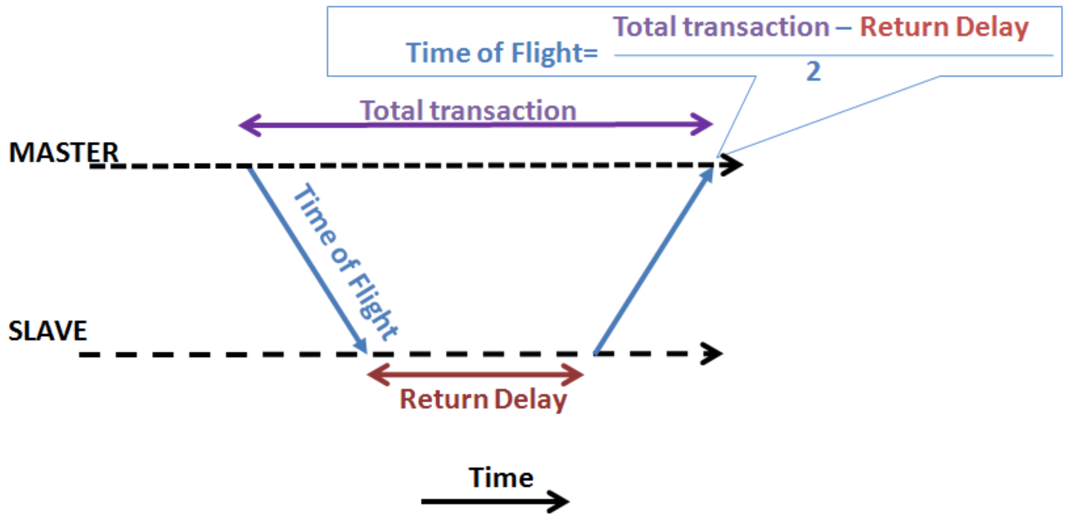


TDOA with hyperbolic curves

Besides the above-discussed TOA and TDOA procedures the so-called Two-Way Ranging method is also well-known. The core of this concept is that the fixed reference points and the portable device communicate back and forth; there is no assigned transmitter and receiver side. The portable, i.e. user device determines its distance from each reference point, and then based on the distance information calculates the exact location. Applying Two-Way Ranging also requires three reference points in two-dimensional case, however to calculate the three-dimensional position, at least four are needed.

The distance data is formed in the following way:

the user device registers the internal counter position, then sends a message to a selected reference point. The reference point launches a counter, and when is finished processing the message and ready to respond, stops the counter, and registers the time elapsed during the process, then sends this registered value back to the sender. Once the response is received, the user device stops its own counter and registers the time elapsed since the start. This time is equivalent to the sum of the round-trip time and the internal delay of the reference point, which is known, since the reply message contains it. From this, the TOF - Time of Flight can be calculated, which if multiplied by the electromagnetic wave propagation velocity, gives the distance between the two devices as a result.



Two-Way Ranging time chart

Indoor positioning using UWB technology

When it comes to indoor positioning the biggest problem is that in the vast majority of cases we are talking about environments rich in reflections, which makes it impossible to estimate the distance for example on the basis of the received signal level, which could be a convenient way in other cases. This is due to the superposition of multipath propagated components, or the detection of reflected waves instead of direct ones. The overlapping of these components also prevents the proper detection of the time of arrival of a received signal, so the operation of systems where timing is critical could be unpredictable.

Although there are ongoing attempts to use the 2.4 GHz ISM band operating widely supported communication standards (e.g. Wi-Fi, Bluetooth) for this purpose, because of the reasons mentioned above, a breakthrough in this field is yet to be achieved. However, with the UWB technology, these problems could be eliminated. The extremely narrow pulses do not lap over each other and, therefore, the signal from the direct path clearly detectable, as it comes in

first, thus if an appropriate channel model is set up, a distance estimation can be made on the basis of received signal strength.
However, UWB is capable of much more than the technologies mentioned above: due to the narrow pulses it has very high resolution in time, which determines the positioning accuracy. With UWB technology a resolution of 40 ps has been reached already, which corresponds to 1.2 cm spatial accuracy. Thus, the use of impulse radio makes it possible to apply TOA, TDOA, Two-way Ringing methods in indoor environment, while the same couldn't be achieved with radio standards developed for narrowband communication.
Furthermore, UWB is ideal for indoor positioning because it does not disturb other electronic devices because of the very high bandwidth and low power, thus it can be safely installed in places where it is a critical requirement, not to cause interference, for example hospitals.

The concept of the system

During my research I intend to design and implement an UWB positioning system, which uses TDOA algorithm. The core of the concept was DecaWave's brand new DW1000 type, small size, low power UWB transceiver IC, which is commercially available since mid-2014. The ICs are controlled by separate control units that are Arduino Due microcontroller boards. These boards transmit the extracted data to a central processing unit via an USB port. This processor is a micro-computer Raspberry Pi, which is responsible for determining the position. It also performs the synchronization of the UWB radios with a synchronization signal.
The task involved the design of the circuit responsible for synchronizing multiple UWB radios, the microcontroller control design, and PCB design.

The DW1000 IC

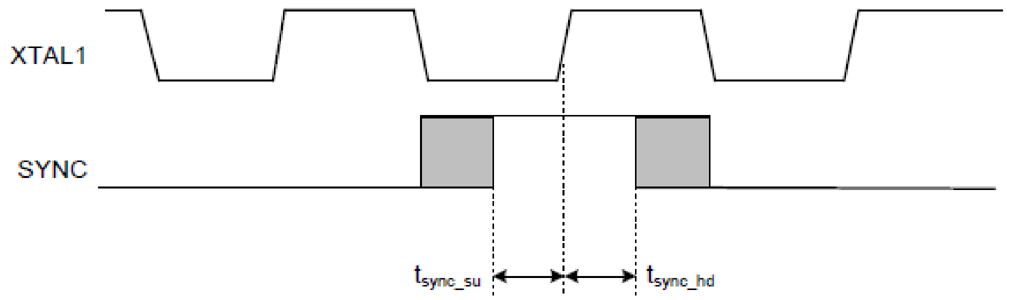
The IC is compliant with FCC and ETSI standards. Between 3.5 and 6.5 GHz 6 RF channels are supported, the transmitter power is adjustable. The system clock frequency is 38.4 MHz. The IC supports sleep and deep sleep modes, with 2 microamper and 100 nanoamper consumption, respectively. The supply voltage is 3.3 V. For present application it is also important that the TDOA and the Two-Way Ranging methods are supported. DW1000 is accessible via SPI interface from the outside. The IC itself is in a 6x6 mm 48-pin, QFN case. It is worth mentioning that the DecaWave has another product, the DWM1000, which is a

module mounted with the necessary external active and passive component, thus it doesn't requires any hardware designing, could be directly connected to a microcontroller via SPI. For the above-mentioned system this module is not an option, because some legs of the IC are not accessible from the outside that are important in terms of the application.
An important question is whether the IC has an internal counter with adequate speed to be used for indoor purposes, or not. The answer is yes, the internal counter's frequency is 64 GHz, and according to the manufacturer accuracy up to 10 cm is available.

Implementation of the concept

To implement The TDOA algorithm it takes four individual DW1000 radio ICs, which operate necessarily in sync with each other, so a common clock source is needed. The most obvious solution for this problem is to distribute the signal of an external crystal oscillator with a clock divider IC. I have already mentioned that some legs of the DWM1000 module are not accessible that would be important. These are the clock inputs of the chip, i.e. XTAL1 and XTAL2.

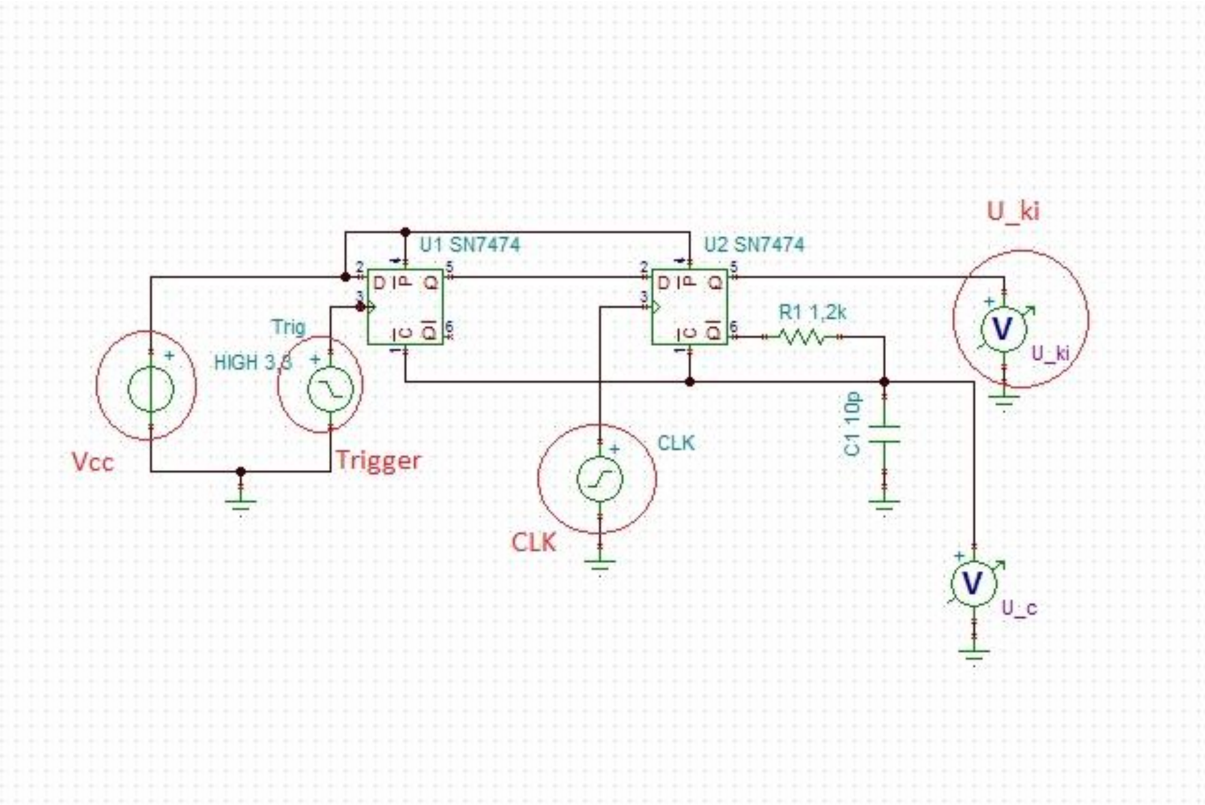
It is also important to ensure that the 64 GHz internal counters launch simultaneously. The counters could be initialized with an impulse on the SYNC input. The timing of this event is shown below:



Synchronizing the DW1000

Parameter	Min	Typ	Max	Unit	Description
t_{SYNC_SU}	10			ns	SYNC signal setup time before XTAL1 rising edge
t_{SYNC_HD}	10			ns	SYNC signal hold time after XTAL1 rising edge

The table above defines the rectangular pulse timing requirements on the SYNC input. To the proper timing the reference clock signal should be used apparently. For this problem I designed a circuit consisting of two D flip-flop. The wiring diagram is shown below:



The circuit which produce a rectangular pulse required by synchronization

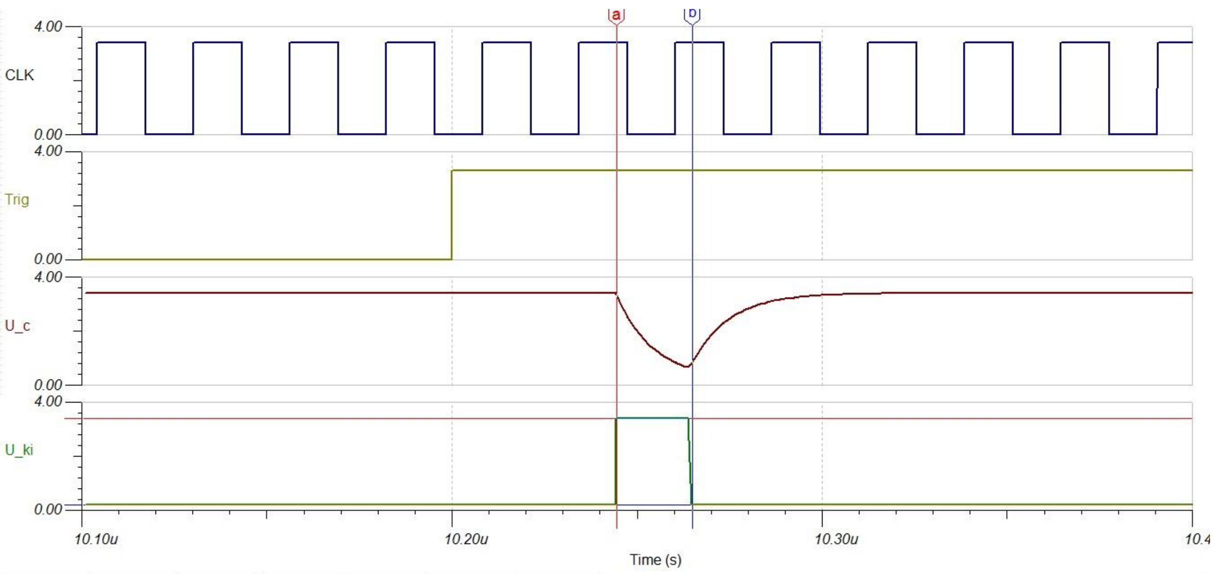
The principle of operation:

Preset is at both D flip-flop constantly high, thus activating the Clear (active low) output goes low immediately (negated output goes high), regardless of the value of the clock. The first flip-flop input is connected to high, output is low until the clock input receives a rising edge. This rising edge will be the trigger signal.

When the trigger signal arrives, the output goes to high, which is connected to the input of the second flip-flop. The second flip-flop's clock input is connected to the system clock, which is 38.4 MHz. Thus, at the rising clock signal change in the input force the output to go high. However, at the time the output changes, the output negation also goes from high level to a low level. This negated output is fed back to the Clear of the second flip-flop, which also goes to low, pulling the output to low level, creating a rectangular pulse on the system output. However, if the input of the second flip-flop is invariably high, the flip-flop periodically creates these pulses at the output, which is not desirable. To prevent this, the feedback must

be connected to the first flip-flop Clear, which disables the input of the second flip-flop. So - as only one rising edge arrived on the system input – on the output does not appear more than one rectangular pulse.
However, because of the position and duration of the rectangular pulse in time depends only on the delay of the internal components, there is no guarantee that the SYNC input receives valid pulse. To keep the timing under control, to the second flip-flop's negated output an RC time constant is connected, where the value of R is variable (potentiometer). This way the RC time constant can be adjusted to affect the signal transitions on Clear inputs, so the pulse width of the rectangle on the output can be controlled.

The following figure shows the clock, the randomly arriving trigger signal, the Clear signal, and the wider output square wave pulse.



During the simulation I set the time constant to meet the criteria of the SYNC input.

Each of the radios is controlled by a separate microcontroller via SPI interface, because considering the available tools the goal can be achieved this way the most easily. The available controllers are Arduino Due 84 MHz microcontroller boards, which don't have enough resource to manage four high-traffic SPI data connection simultaneously. In addition, the Arduino controller boards power the radio circuits.

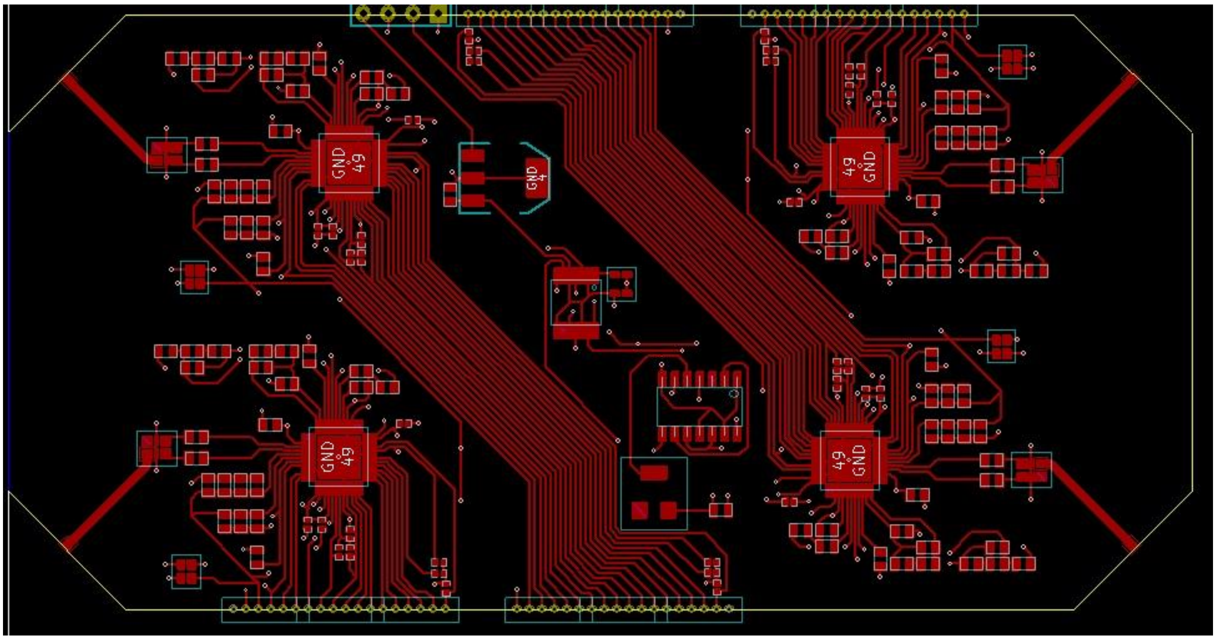
The DW1000 datasheet discusses active and passive external elements which are to connect to the IC, and gives specific recommendations to the individual elements. Because of the greater circuit complexity, I stayed with the manufacturer's circuit design and the components recommended by them, for optimal functionality to be achieved.

PCB design

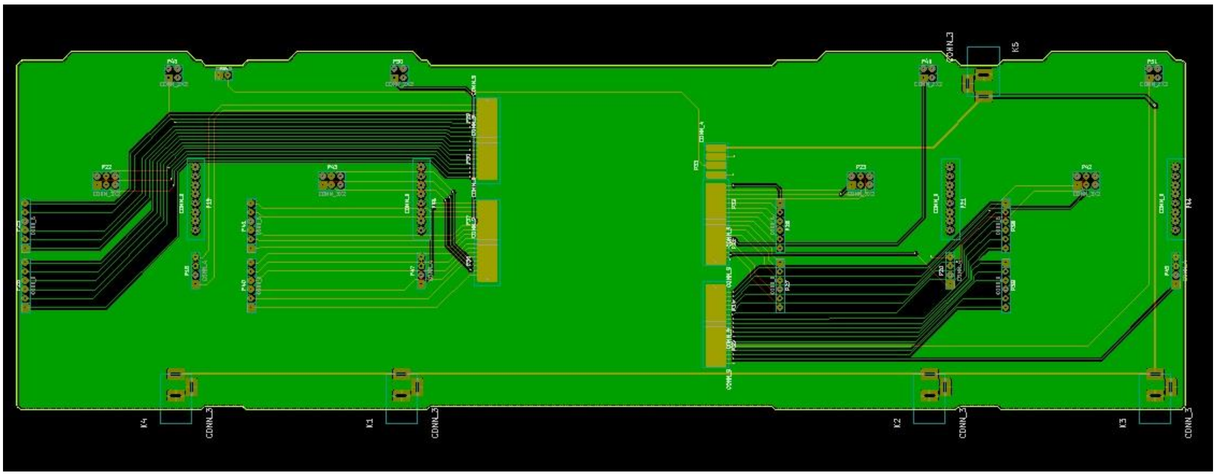
Due to the relatively high frequency of the UWB radio special carrier was used, developed for microwave circuits. The exact type Rogers RO4003C, thickness is 0.406 mm, the metal thickness is 17 um. Since the ICs used to transmit and receive GHz frequency signals, at the alignment of the antenna should also be considered that the length of tracks comparable with the wavelength, so microstrips are needed to be designed.

The microstrips width based on the parameters of the carrier was determined with the Txline toolbox of AWR Studio software. At the edge of the carrier there are four SMA connectors mounted, which enables to connect arbitrary antenna to the ICs. The system has an additional PCB as well, but in this case the carrier is a general purpose FR4. The microwave carrier could be connected to this PCB by soldering. The function of this is to connect the microwave circuit to the four pieces of Arduino Due.

In the pictures below you can see the two PCB design:



The microwave PCB



The FR4 PCB, in the middle is the place of the microwave PCB

Aspects taken into account when selecting the components

As it was already mentioned above, active and passive components required to operate the radio IC were chosen from the datasheet of DW1000. However, the following components require considerations:

Crystal:

The main criteria were that the supply voltage should match the supply voltage of the remaining active components, i.e. 3.3 volts. Furthermore, accuracy was also important, the criteria was that no more than 2 ppm should be the frequency error. On the basis of these considerations I chose the 7Q-38.400MBG-T crystal.

Clock divider IC:

Apart from the corresponding supply voltage, it was important that the jitter, i.e. the phase error is less than that can cause considerable errors in synchronization. The same applies to the output-to-output skew, i.e. the phase difference between the outputs. The corresponding part was chosen to keep these values possibly under a picosecond. The number of outputs should be at least 5, because apart from the 4 ICs, D flip-flops also need to have a separate clock signal. I chose the following part on the basis of the criteria above: CDCLVC1106PW.

Flip-flops:

I was looking for a part, where two flip-flops are encapsulated into a single case.

Future plans

At the deadline of the submission of this document the system is still under development.
In the following semester I will continue the development of the system hardware and I'd like to develop the embedded software, and also a GUI for the system.
If we could create a truly functional, real-time, precise system, then it proves that the UWB technology might be the key to indoor navigation. If the ability of this technology becomes widely known, there is a chance that in the near future portable devices equipped with UWB chips appear (typically mobile phones) and this will have a significant impact on people's daily lives.