A laboratory exercise on 802.15.4 communication between USRP and XBee

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Abstract:

The lab studies the IEEE 802.15.4 communication standard for O-QPSK (Offset-Quadrature Phase Shift Keying) modulation and demodulation, implemented on a USRP 2922 (Universal Software Radio Peripheral) and enables the detection of communication between off-the-shelf RF modules working under the 802.15.4 standard, using LabVIEW Communications as the programming environment.

Schedule:

Preparation time	3 hours
Lab time	3 hours
Tools	None
Components	Ethernet cable, MIMO extension cable, 2x RF antennas, 2x FTDI cables
Equipment	2x USRP 2922, 2x XBee S1 (can be any off-the-shelf RF module), 2x Parralax XBee adapters (any RF adapter)
Software	LabVIEW Communications, XCTU

Before you come to the lab, it is essential that you read through this document and complete ***all*** of the preparation work in section 2. Before starting your preparation, read through all sections of these notes so that you are fully aware of what you will have to do in the lab. The marking scheme is shown at the end of the lab notes

1. Aims, Learning Outcomes and Outline

This laboratory exercise aims to:

- Expose you to an actual communication standard and allow you to see how standards are written and implemented in real systems.
- Allow you to get familiar with LabVIEW Communications and see how the program operates.
- Allow you to experience real-life O-QPSK transmission and test the reliability of the transceiver system by observing bit error rate (BER) plots, constellation diagrams and eye diagrams.
- Enable you to analyse how different environments influence the performance of wireless communication systems.
- Allow you to actually implement the wireless system by using real RF modules, which are compliant with the 802.15.4 standard.

Having successfully completed the lab, you will be able to:

- Understand the operation of the USRP module.
- Describe the O-QPSK PHY layer of the 802.15.4 communication standard.
- Analyse transmission data between a transceiver system and actual RF modules.
- Understand how changing different parameters of a wireless system affect the actual signal and analyse BER plots.

2. Preparation

Read through this document so you are aware of what you will be expected to do in the lab.

2.1. Preparation Section 1

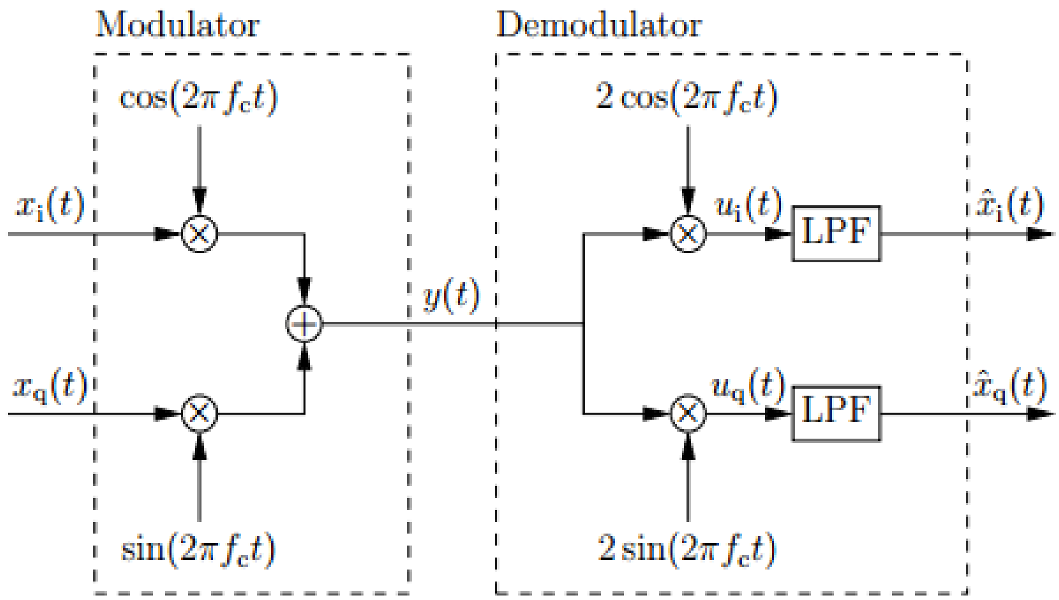

Figure 1. QAM signal processing.

Go to https://www.ni.com/white-paper/12985/en/ and look through the notes for the USRP device and then answer the following questions:

- Task 1: By inspecting Figure 2 from the link provided, briefly comment on the hardware components of the USRP. From this figure, it can be seen that the signal is divided into I and Q phases and is then processed. Relate the signal processing to the QAM modulation/demodulation shown in Figure 1.

2.2. Preparation Section 2

Go to https://standards.ieee.org/getieee802/download/802.15.4-2011.pdf and download the standard. Read sections 1, 8, 9 and 10 in order to answer the following questions:

- Task 2: Which communication layers does the 802.15.4 standard define? What are the applications for the 802.15.4 standard?
- Task 3: Name the blocks of the O-QPSK PHY modulation from the 802.15.4 standard. What is the data rate when operating in the 2,450 MHz band? How many chips/second are needed in order to obtain such a data rate?
- Task 4: Show how the O-QPSK PPDU packet structure is formatted. How many bits form each octet field? How are the bits transmitted – LSB or MSB first?
- Task 5: Explain the structure of the Preamble field.
- Task 6: The SFD is 0xA7 (MSB first) in hexadecimal. Transform it into binary and state the order that the bits are transmitted according to your answer in Task 4?

- Task 7: How many bits are used to represent the frame length of the PHR field? What does it quantify?
- Task 8: What is the maximum PHY payload size (Hint: Look up Table 70 in the standard)? What are the acceptable values for the size of the PHY payload (Hint: Look up Table 72 in the standard)? What conditions should the PHY payload meet according to your answer in Task 4?
- Task 9: Draw a Constellation diagram of O-QPSK and QPSK signals and illustrate the valid transitions between successive constellation points.
- Task 10: Explain the bits-to-chips mapping procedure in the 802.15.4 standard. Give an example of an actual bits-to-chips mapping if the inputted bits are 1100 (Hint: Look up Table 73 from the standard).
- Task 11: Which chips are modulated to the I-phase and which to the Q-phase? How is the offset (Tc) in O-QPSK formed according to the 802.15.4 standard (Hint: Look at Figure 70 in the standard)? What does Tc represent?
- Task 12: Redraw Figure 71 from the standard into your logbooks. What is the sequence of four bits that is represented by this 32-chip sequence (Hint: Look at Figure 70 in the standard)?
- Task 13: Write the bit sequence of the whole PPDU packet structure if the PHY payload is 9 octets (72 bits) long.

2.3. Preparation section 3

Go to:

- https://www.researchgate.net/publication/224281039_Performance_Evaluation_of_IEEE_802154_Physical_Layer_Using_MatLabSimulink
- https://en.wikipedia.org/wiki/Carrier_frequency_offset

From these documents read on how changing different parameters of the transceiver system affects the quality and BER of the signal.

- Task 14: What happens to the BER performance when the SNR is increased?
- Task 15: What does the carrier frequency offset represent and which two important factors attribute to this phenomenon? How does it affect the signal?
- Task 16: Does changing the bits/symbol or samples/chip value affect the BER results?

3. Lab work

In this laboratory exercise, you will observe an O-QPSK transceiver system, which operates under the IEEE 802.15.4 standard and will be able to compare your practical work by doing simulations on a simulator, which tests the reliability of the system. Finally, as part of the additional work you will test the system by using actual off-the-shelf RF modules and observe how they communicate between each other.

In order to begin, set up the USRP modules as shown in Figure 6, which is an example of how the system can be set-up.

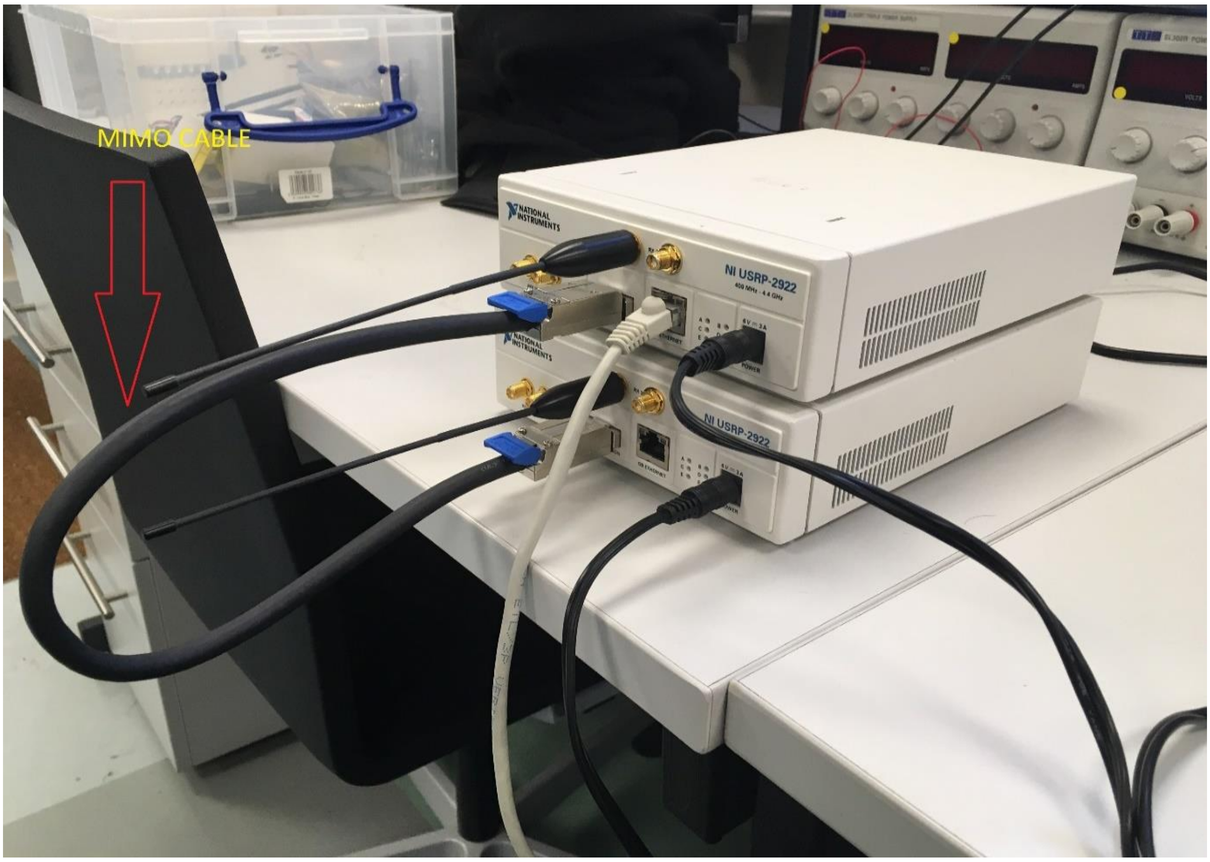

Figure 6. Transceiver USRP set-up.

In this picture, the Ethernet cable is directly connected to the PC. In order to test if the USRP devices are correctly use the NI-USRP Configuration Utility. After finishing the USRP module set-up, open the O-QPSK.lvproject file provided in the folder for this lab, in order to load the transceiver application. Do not forget to press the LabVIEW run button in order to execute the VIs.

3.1.Transceiver testing

After loading the O-QPSK LabVIEW project, open the O-QPSK Tx component, which represents the UI of the transmitter module. You are encouraged to go through the block diagram of the component to get familiar with the way it transmits data. Figure 7 shows the module.

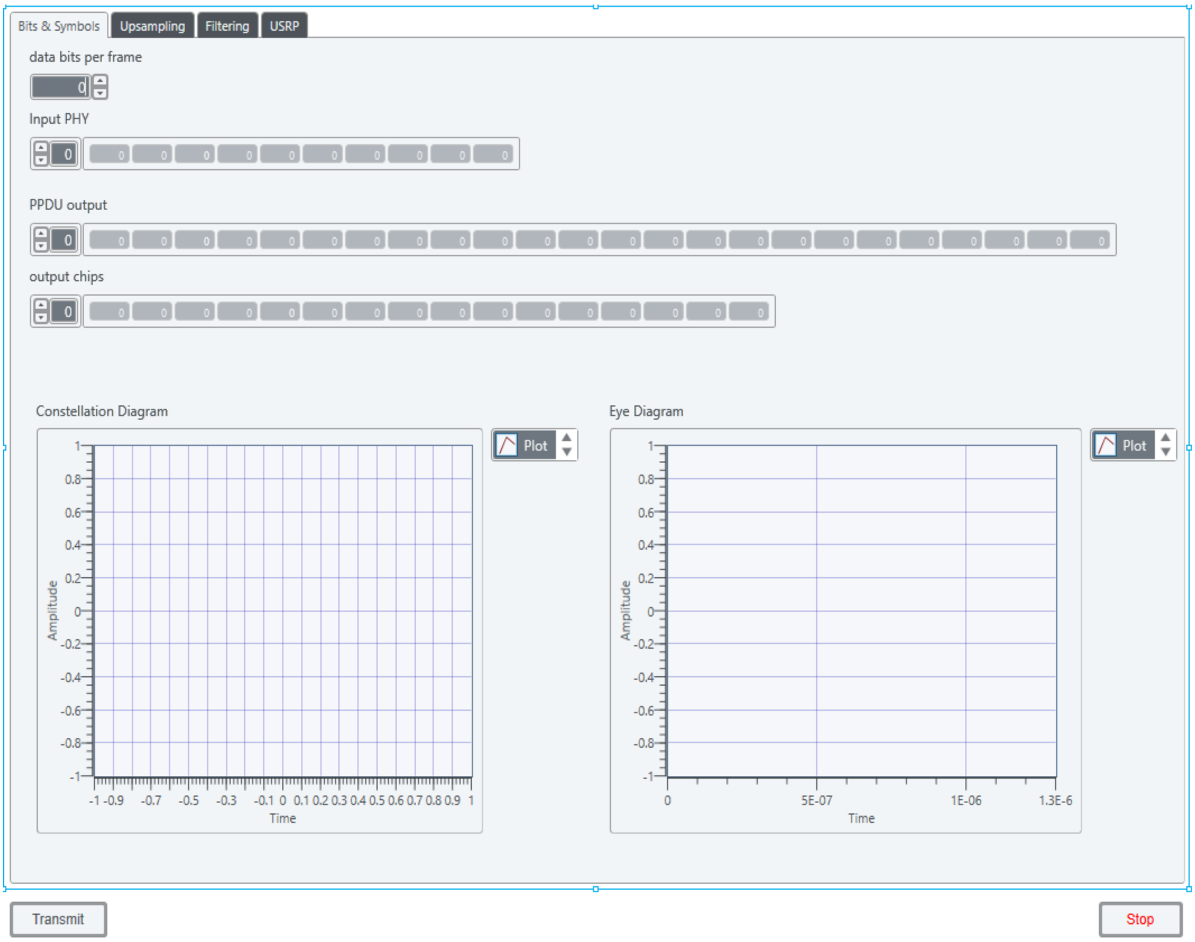

Figure 7. Transmitter UI.

Go through all the tabs in order to see what parameters you can specify before starting the transmission.

- Task 1: What is the allowed range for the data bits per frame field? Try inputting 70, 150 and 1500 and pressing Transmit. What do you observe? Why does 150 give an error?
- Task 2: What should the chip rate be in order to obtain a data rate of 250 kbps depending on your preparation answers?

Select 2 samples/second and 4 000 000 samples/chip and set the carrier frequency to 2.405 GHz. Set the data bits to 512.

- Task 3: Screenshot what you obtain after running the VI?
- Task 4: Look at the PPDU output and explain its structure. Which parts of the LabVIEW code corresponds to which parts of the 802.15.4 standard.

Go to the block diagram of the transmitter module (Figure 13) and double click on Modulation VI. You should see the following screen:

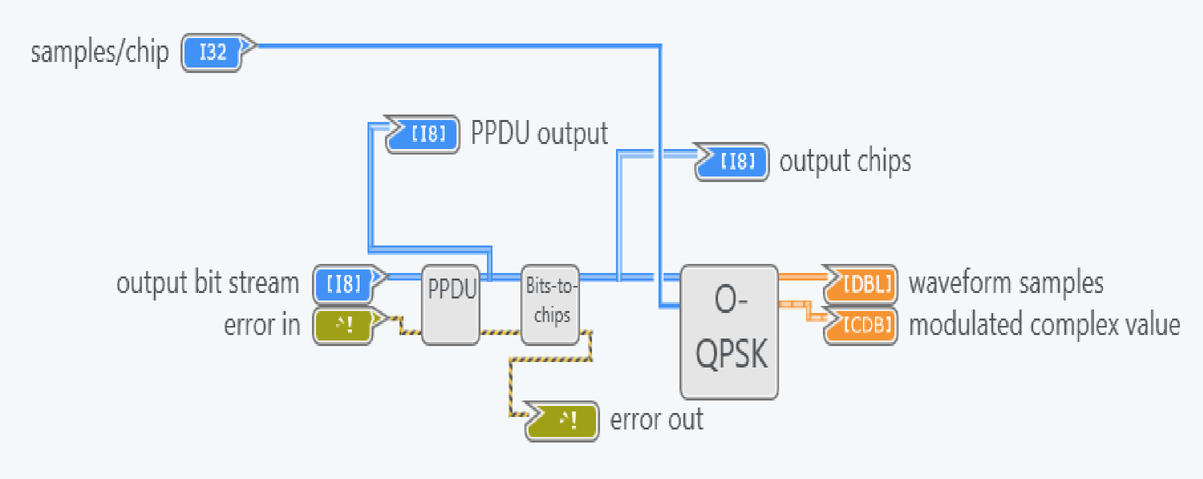

Figure 13. O-QPSK Modulation components.

Double click on the bits-to-chips mapping VI and open its front panel. From the 802.15.4 standard document, you read about how bits are mapped to chips and observed a table, which contained the chip values for the 2.4 GHz O-QPSK modulation scheme.

- Task 5: With regards to that table input the symbol 12 (1100) in binary and observe the chip sequence (Hint: Do you need to input the bits LSB first or MSB first?).

Now go back to the modulation block diagram (Figure 13) an open the O-QPSK VI's front panel. Input a sample/chip value and enter the waveform chip sequence from section 2.2 as input chips.

- Task 6: Screenshot your observations? Show the delay Tc between the I and Q phases.

Now go back to the front panel of the Transmitter (Figure 7) and press the transmit button.

- Task 7: By observing the eye and constellation diagram what, can you conclude about the transmitter? Screenshot your results.

Now open the O-QPSK Rx module from the project files. Set the USRP settings to be the same as the transmitter ones. Play around with the value of the threshold sample magnitude until you reach a value that allows the receiver to only detect a signal when the Transmit button on the transmitter is pressed (Hint: 0.001 should be a suitable value).

- Task 8: Observe the receiver's front panel. Screenshot your observations and comment on them.

3.2.Simulator testing

Now open the Simulator file from the O-QPSK project. Observe all the different parameters and set the data bets to 512, the Eb/N0 offset to 5, samples/symbol to 2, samples per second to 4 000 000, carrier frequency offset to 0, no fading profile. Initially set the minimal error value to 300 in order to obtain a smoother BER plot but in order to save time use a value of 10 for the next questions. Take note of the av. BER value!

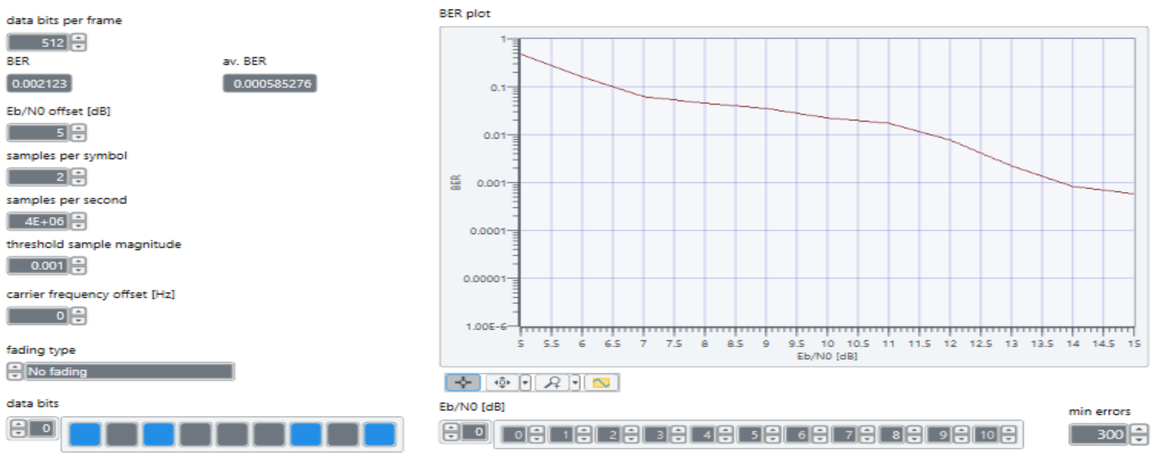

Figure 18. Simulator testing.

- Task 9: Change the values of the samples per symbol to 3 and the samples per second to 6,000,000. Screenshot your results. Now change the values to 4 and 8,000,000 respectively. Record your results. Why does the BER improve as the sample values are increased (Hint: compare the av. BER values)?
- Task 10: Change the value of the Carrier Frequency Offset to 3000 Hz and 3,500 Hz. Run the simulation and record your observations. Why does the 3,500 Hz CFO distort the signal?
- Task 11: Change the fading types to uncorrelated narrowband and to block narrowband Rayleigh fading. Record your observations.

3.3.Actual RF module testing

After testing the transceiver system you will now work with actual RF modules and try to detect communication between them. For this case XBee modules will be investigated together with serial to USB adapters and FTDI cables. XCTU is used in order to interface the XBees and the PC.

3.3.1. XBee set-up

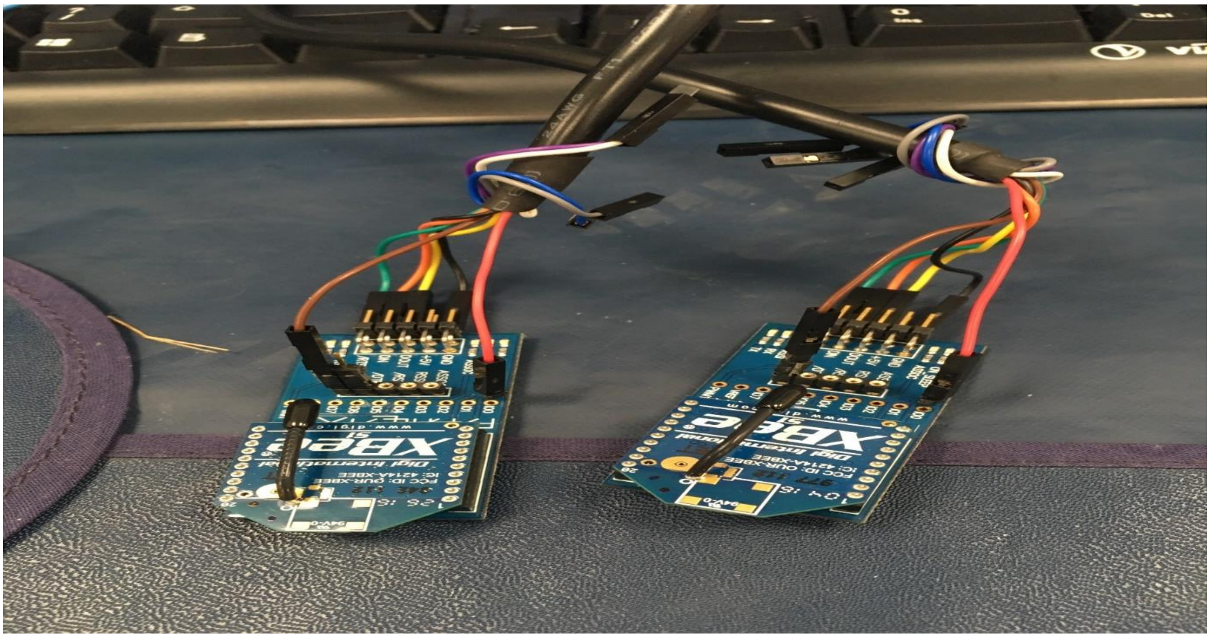

Figure 25. XBee set-up.

Figure 25 shows the set-up of the connection between the XBee devices and the PC. The modules are connected to the PC via FTDI cables (1). The FTDI cables have 10 wires for serial connection each serving a different purpose. For this project, only 6 of them are needed:

- GND (black) – Device ground supply pin.
- POWER (red) – Power output which can be customized to output +3.3V or +5V.
- RTS (green) – Request to send control output (Handshake signal).
- CTS (brown) – Clear to send control output (Handshake signal).
- TXD (orange) – Transmit synchronous data.
- RXD (yellow) – Receive synchronous data.

The XBees are connected to FTDI cables via adapters (2), which have the same pin set-up and serve as a convenient interface for the modules.

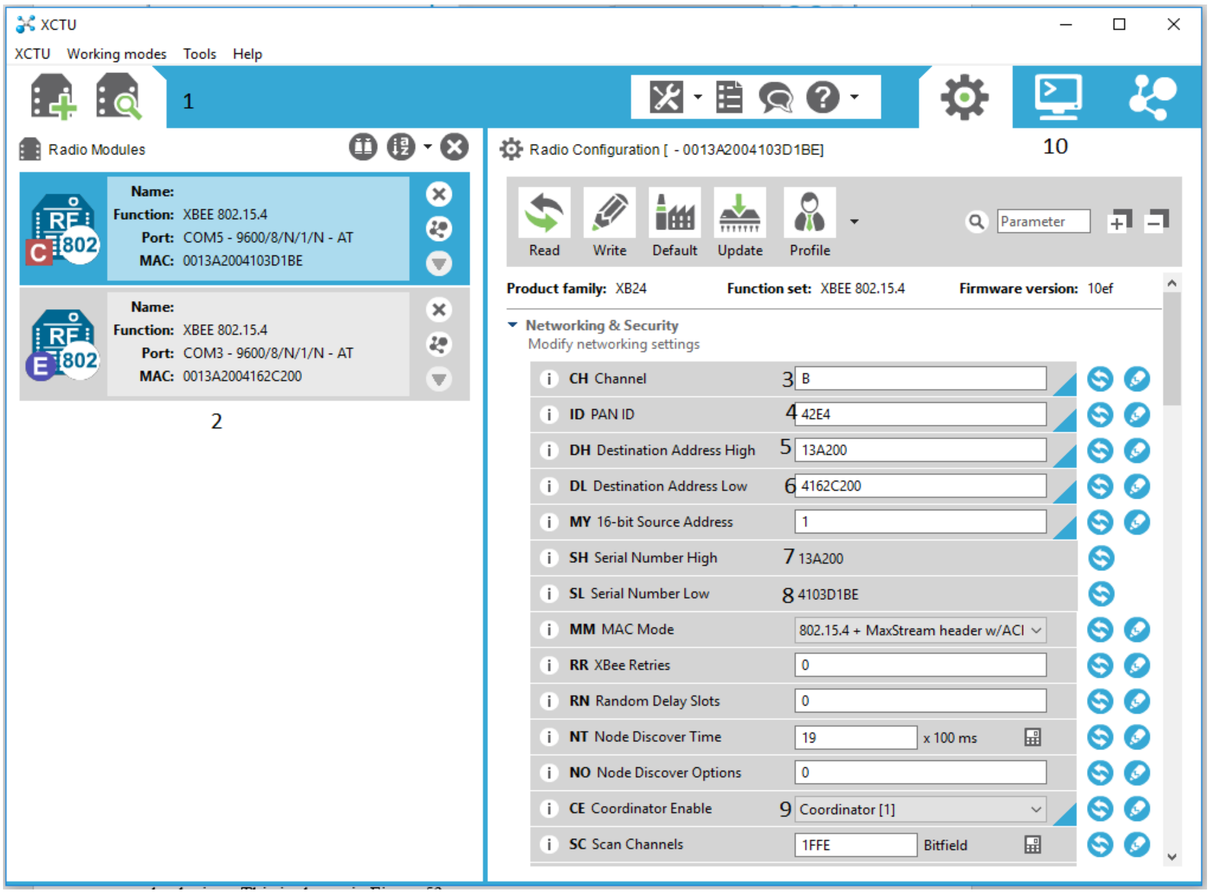

Figure 26. XCTU user interface.

In order to interface the XBee modules with the PC a free multi-platform application, called XCTU, is used. The program is specially designed for XBee modules and offers a simple-to-use graphical interface as shown in Figure 26. The first step for interfacing with the XBee modules is to detect the devices (1). When detected they appear as separate icons in the Radio Modules field (2). In order to establish a connection between the XBee's, their channels (3) and PAN (Personal Area Network) have to have the same value. Here the channel value goes from 0x0B to 0x1A (11-26) which represent the channel numbering of the 2.4 GHz frequency band – $F_c = 2405 + 5(k - 11)$ in megahertz, for k=11,12,..26. Furthermore, the destination address DH and DL (5 and 6) on one of the XBees have to be identical to the serial numbers SH and SL (7 and 8) on the other XBee and vice-versa. In order to meet the 802.15.4 network topology requirements, one of the XBee modules is set to be a PAN coordinator (9) in order to establish a star topology. Finally, the console working mode (10) is entered so that data can be inputted and transmitted between the devices. This is shown in Figures 27 and 28.

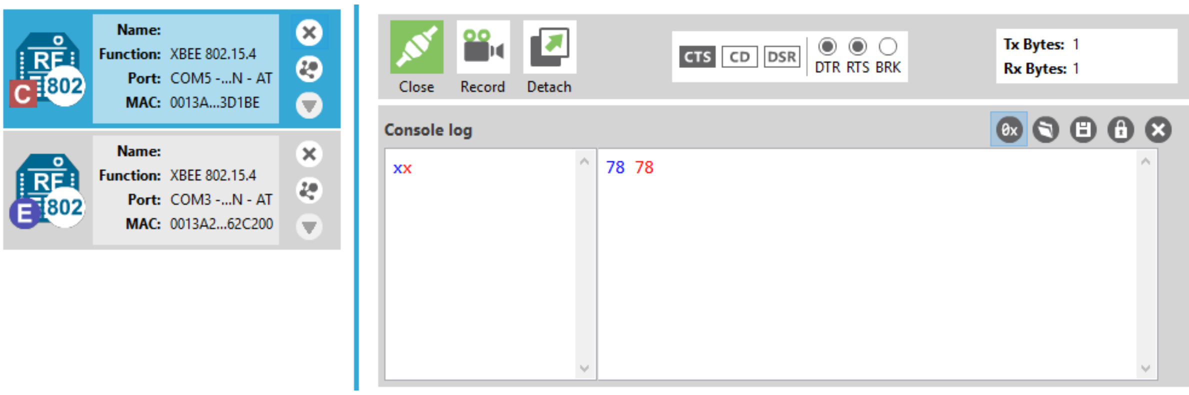

Figure 27. Coordinator sending data (blue) and receiving data (red).

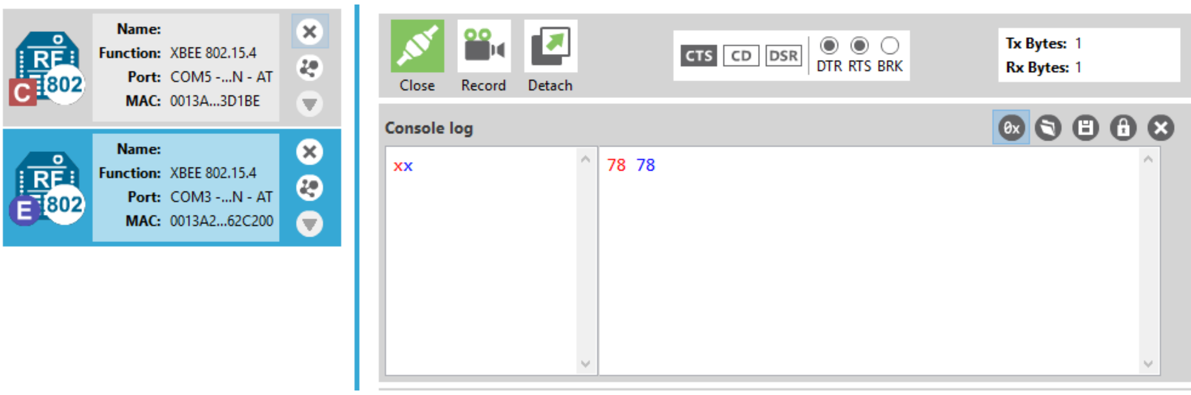

Figure 28. End device receiving data (red) and sending data (blue).

In order to establish a connection between the USRP and the XBees the carrier frequency must be set in order to match the channel of the XBees. From Figure 26 the channel is B which from hexadecimal is 11 → carrier frequency of 2.405 GHz must be chosen (Note: The USRP suffers from high carrier frequency offset, which is more than the 802.15.4 standard can cope with.).

Now run the Rx module and start transmitting data between the XBees. Carefully look at the waveforms and the BER value.

- Task 12: Are the original and the received waveforms identical? If no, why? Manually adjust the receive carrier frequency by 0.01 GHz at a time, both up and down, until you can successfully receive the signal. Screenshot your observations.

Marking Scheme

This scheme serves only for guidance. Supervisors can change it depending on their needs.

	0	1	2	3	4	5
Preparation	No preparation undertaken before the exercise	Very few Preparation section tasks are completed with many mistakes (only 1 section tasks answered)	Some of the Preparation section tasks are completed with many mistakes (1or 2 section tasks answered)	Some of the Preparation section tasks are completed with few mistakes (1 or 2 section tasks answered)	Almost all of the Preparation section tasks are completed with few mistakes (answered at least 2 sections)	All of the Preparation section tasks are completed with no mistakes (all tasks of the 3 sections)
Understanding	No understanding shown during the lab exercise	Very few of the Lab work section tasks are completed with many mistakes (only section 3.1 tasks)	Some of the Lab work section tasks are completed with many mistakes (up to section 3.2 tasks)	Some of the Lab work section tasks are completed with few mistakes (up to section 3.2 tasks)	All of the Lab work section tasks are completed with few mistakes (all 3 sections tasks)	All of the Lab work section tasks are completed with no mistakes (all 3 sections tasks)
Progress	No Lab work section tasks have been completed	Only some of the tasks were attempted (only section 3.1 attempted)	Almost all of the Lab work section tasks are completed (all tasks up to section 3.1)	Almost all of the Lab work section tasks are completed (all tasks up to section 3.2)	Almost all of the Lab work section tasks are completed (all tasks up to section 3.3)	All of the Lab work section tasks are completed (all tasks of the 3 sections)
Logbook use	No documentation of any observations	Many screenshots and notes missing but all sections up to 3.1 have been covered	Many screenshots and notes missing but all sections up to 3.2 have been covered	Some screenshots and notes missing but all sections up to 3.2 have been covered	Very few screenshots are missing in the logbook together with very few notes missing (almost all of the section 3.1 and 3.2 screenshots and their notes)	All of the required screenshots are shown in the logbook together with all the required notes (all of the screenshots and notes required for the 3 sections)