Modeling and Simulation of Wireless Radio Networks: a Case of Student Seminar Work

Žarko Čučej, Karl Benkič

Abstract – **In high education of telecommunication and automatic control, modeling and simulating complex systems of distributed monitoring and control are proven methods how to teach, learn and comprehend their essentials. The complexity of their use requires students to integrate knowledge from different courses and that's why they fit very well within the individual student project, as part of the seminar work.**

The importance of modeling and simulation in modern engineering is very well known. Recently, with development of new tool, which incorporates parts of real equipment, for xample telecommunication nodes with preprocessing of acquired data or controllers with integrated communication nodes, modelling and simulation have become not only useful to engineers, evelopersor researches but also very attractive to students.

This article presents a case of modeling and simulation of wireless sensors networks using professional simulation tools from OPNET and open-code tools developed by our Ph. D. students.

Keywords – **teaching, learning, simulation, telecommunication, automatization**

I. INTRODUCTION

In June 1999, representatives of 29 European countries and their governments committed to do everything to create a European area of higher education, as the key way to promote the citizens' mobility and employability, and the Continent's overall development. This commitment is known as the declaration of the European Ministers of Education: »*The European Higher Education Area*«, or more popularly the Bologna Declaration. It would give the European higher education worldwide attraction, achieving uniformity, where a student would earn a degree after a minimum of three years and in the second level masters degree. Also, universities should recognize lifelong learning [1].

The Bologna Declaration allows different models of higher education; the decision is left to the universities. According to the data released, most of the EU universities follow a so called 3+2+3 scheme, there are, however number of exceptions, for example model 4+1+3 is used in Serbia and Macedonia, and model 3,5 + 1,5 + 3 is presented in Poland and some other universities. Advantages of 3+2+3 model in Slovenia are according to [1] justified by three objectives:

1) Earn a degree of education in the shortest time possible.
2) Shorten the undergraduate study from four to three years with purpose to gain one year in which the student can already begin with a postgraduate cycle.
3) Establishment of life-long education, provided it is at the postgraduate level.

Žarko Čučej and Karl Benkič are with University of Maribor, Faculty of Electrical Engineering and Computer Science, Smetanova 17, 2000 Maribor, Slovenia.
E-mails: zarko.cucej@uni-mb.si, karl.benkic@uni-mb.si

A. *Impact of Bologna declaration on technical studies*

In many technical disciplines, as it is the case in electrical engineering, computer engineering, and information technology, not so long ago the study has been prolonged from eight to nine semester plus one semester for diploma thesis. On the other hand, the undergraduate Bologna study for the selected model was shortened by two years. Unfortunately, such change is not possible without reducing the level of knowledge.

B. *Necessary changes of pedagogical paradigm*

To minimize the reduction of knowledge, the so-called "excathedra" teaching and considering students as sponges capable to (unlimited) absorption of lecture knowledge, definitely belongs to the past. To be up-to-date with recent developments in engineering and technology, and have good understanding of their basis, requires that students take active part in the studying process.

A promising method, many times well proven in the human history, is "learning-by-doing". Let be emphasized here that necessary conditions for this method are motivated students and professors, adequate equipment and infrastructure. Gained experiences from the preparation and introduction of the study programs according to Bologna declaration show that students motivation, their average grades and student project results are highly correlated. Consequently, the results of the existing average students are far under expectation. For improving the achieved results we looked at two measures:

1) Rephrasing the motto from "learning-by-doing" to "*learning by doing together with tutor*".
2) Dividing students into two groups: the group capable to "learn-by-doing" (the students should have an average grade "very good" or higher), and group, which needs additional support.

Both measures require additional effort from professors or their assistants and to make this happen they need to be motivated in some way.

C. *A case of learning-by-doing*

In preparation of the graduate study program for automatization we have organized a series of projects as part of seminars and as in individual research work, where we tested our capability to provide new pedagogical paradigm "learning by doing together with tutor". Projects goals are the following:

- prepare an example for "learning-by-doing" method
- prepare and build necessary infrastructure and technology for learning and teaching
- prepare study materials and technology usable also in life-long learning

The results will be used in student seminar work. Since modern automatic control is actually based on Network Control Systems (NCS), which combines telecommunication and control technology, we have selected a case of wireless sensor network. Students have done the following on this case:

1) study in prepare basic material about selected wireless sensor network (we have selected ZigBee technology)
2) develop simulation model of ZigBee node in OPNET program
3) made our own hardware for ZigBee node capable of remote upgrading of the firmware
4) test achieved results

Results of enumerated task are summarized in the following sections.

II. ZIGBEE NETWORKS

IEEE 802.15.4/ZigBee is a worldwide open standard for wireless radio networks in the monitoring and control fields. It was developed by IEEE 802.15.4 Task Group and ZigBee Alliance. The standard was developed to meet the following principal needs:

- low cost
- ultra-low power consumption
- use of unlicensed radio bands
- cheap and easy installation
- flexible and extendable networks

The most basic component of IEEE 802.15.4/ZigBee network is the device. Every device operating in network has a 16bit address. This address is allocated by the PAN coordinator when the device is connected to the network.

Three different types of devices can participate in an IEEE 802.15.4/ZigBee wireless networks:

- ZigBee coordinator, which can bridge ZigBee network to other networks and can form the root of the network tree
- Full Function Device (FFD), which can act as an intermediate router, passing data from other devices
- Reduce Function Device (RFD), which is only smart enough to talk to the network

ZigBee or Personal Area Network (PAN) coordinator is a central node in every IEEE 802.15.4/ZigBee network which maintains overall network knowledge and control, and collects data from all other nodes. Router is a node which can besides its sensoring functions can relay network traffic from other nodes towards PAN coordinator. The FFD supports all functions and features defined by IEEE 802.15.4 standard and it can work in three operating modes, serving as a personal area network (PAN) coordinator, a router, or an end device. End-device is RFD which measures certain variables and sends them through network to PAN coordinator.

Nodes in network are usually randomly deployed, without careful planning therefore they need to establish some kind of network organization, which is called a network topology. Three basic types of network topologies defined by IEEE 802.15.4 standard are: star, mesh and cluster-tree topology (Fig. 1).

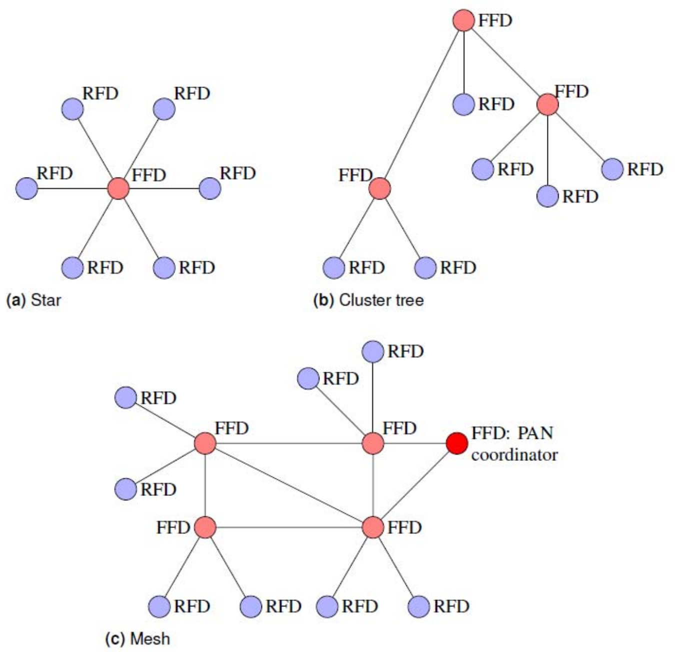

Figure 1. ZigBee topologies.

In the star topology, communication is centralized. It is established between one FFD which serves as a PAN Coordinator and several RFD. The main advantage of the star topology is its simplicity, but drawbacks are lack of peer-to-peer communication and small coverage due to limited radio range. In the mesh topology every FFD can communicate with any other FFD within its radio range. Data sent to the PAN coordinator use a multi hop communication. The main advantage of the mesh topology is adaptability and scalability, but for multi hop communications an advanced routing algorithm is needed. The cluster-tree topology is a compromise between the first two topologies. FFD represent the central points of clusters which are connected to the PAN coordinator. In communication sense, FFDs in the mesh and cluster-tree topologies in communication sense represent routers. More data about ZigBee can be found in [11].

A. *ZigBee protocol Stack*

ZigBee protocol stack consists of four layers. Every layer is connected to its neighboring layer by Service Access Points (SAP). In the stack the Physical (PHY) and Medium Access Control (MAC) layer are defined by the IEEE 802.15.4 standard [10], while Network (NWK) and application layers are defined by the ZigBee Alliance [11] (Fig. 2).

B. *Physical Layer (PHY)*

The Physical layer provides two services: the PHY data service and PHY management service interfacing the Physical Layer Management Entity (PLME). The PHY data service enables the transmission and reception of data units (PPDU) across the physical radio channel. The features of the PLME are activation and deactivation of the radio transceiver, Energy Detection (ED), Link Quality Indication (LQI), channel frequency selection and Clear Channel Assessment (CCA).

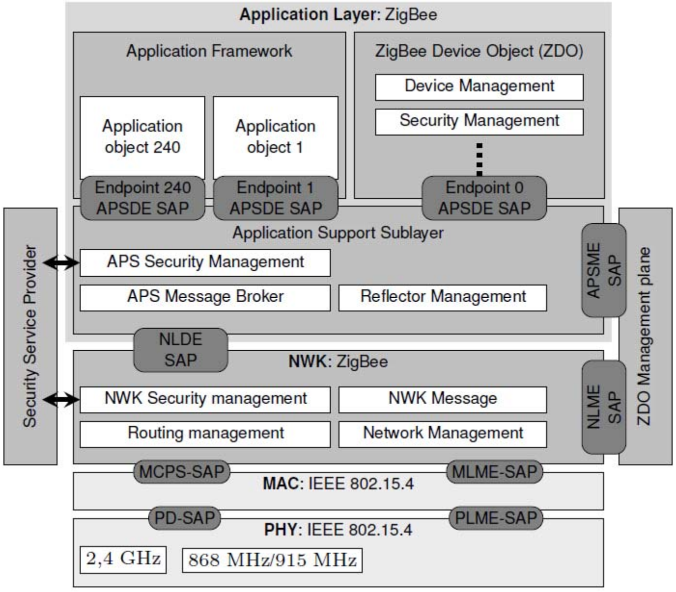

Figure 2: ZigBee protocol stack.

enables the transmission and reception of data units (PPDU) across the physical radio channel. The features of the PLME are activation and deactivation of the radio transceiver, Energy Detection (ED), Link Quality Indication (LQI), channel frequency selection and Clear Channel Assessment (CCA). Physical Package Data Unit (PPDU) format consists of three parts (Fig. 3):

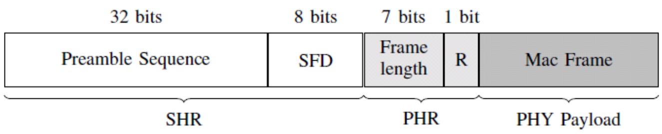

Figure 3: Physical package Data Unit (PPDU) format. SHR; synchronization, SFD: start-offrame delimiter, PHR: packed header, R: Reserved.

SHR: Represents 32-bit long preamble sequence used for synchronization and 8-bit long Start Frame Delimiter (SFD) which signals the start of data transmission.
PHR: Represents 8 bit long Packet Header, where first seven bits determine length of PHY payload, the eight bit is reserved for future usage.
PPL: Represents 0 to 127 bytes long PHY Payload in which the MAC frame is placed.

C. *Medium Access Control Layer (MAC)*

MAC layer supports two operating modes which are selected by network coordinator:

- Beacon enabled mode
- Non-Beacon enabled mode

In Beacon enabled mode, PAN coordinator schedules all traffic between devices associated to that network. It creates super frame structure which is limited by beacons (Fig. 4).

Super frame consists of an active period which is optionally followed by an inactive period. The beacons are used to synchronize the attached devices, identify the ZigBee network and describe the super frame structure. Active period is divided into sixteen equally sized time slots. They are shared between Contention Access Period (CAP) and Contention Free Period (CFP) with up to seven Guaranteed Time Slots (GTS).

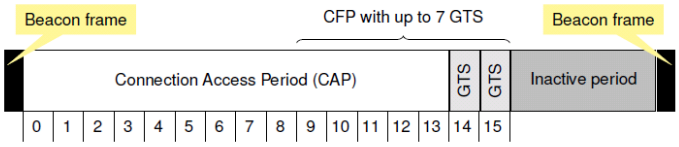

Figure 4: The IEEE 802.15.4 super frame format. CFP: Contention Free Period, GTS: Guaranteed Time Slots.

Any device wishing to communicate during the CAP should compete with other devices using a slotted CSMA/CA mechanism. The GTS always appears at the end of the active super frame part starting at a slot boundary immediately following the CAP. The PAN coordinator allocates these GTSs to the nodes that requested it, and any node can occupy more than one GTS slot. During the inactive portion, the coordinator is not interacting with its associated end devices and may enter a low-power mode.

D. *ZigBee Network layer (NWK)*

The NWK layer is responsible for managing the network formation and routing. Routing is the process of selecting the path through which the message will be relayed to its destination device. The ZigBee coordinator and the routers (FFD) are responsible for discovering and maintaining the routes in the network, while ZigBee end devices (RFD) cannot perform route discovery.

The ZigBee coordinator or a router will perform route discovery on behalf of the end device. The NWK layer of the ZigBee coordinator is responsible for establishing a new network and selecting the network topology (tree, star, or mesh). This layer is also responsible for allowing nodes to join or leave network.

E. *ZigBee Application layer*

The application (APL) consists of three parts: Application Support (APS) sublayer, Application Framework (AFG) with up to 240 Application objects in a single device, and ZigBee Device Object (ZDO). APS sublayer is used to interact with network layer and for data encryption.
ZDO is responsible for establishing connection between APS sublayer and appropriate application object. Manufacturers develop the application objects to customize a device for various applications. Application objects control and manage the protocol layers in a ZigBee device.

The ZigBee standard offers an option on how to use application profiles in developing an application. An application profile is a set of agreements about application-specific message formats and processing actions. The use of the application profile allows further interoperability between the products developed and produced by different vendors for a specific application. If two vendors use the same application profile for their products, the product from one vendor will be able to interact with products manufactured by the other vendor as though both were manufactured by the same vendor.

III. SIMULATION MODEL OF IEEE 802.15.4

The basic tool for learning and exploring features of wireless sensors networks is the same in other area of engineering simulation. For the purpose of simple telecommunications examples we use free available OPNET Academic Guru program packet. It has many basic models built-in, although ZigBee nodes are not among them. So one of important student task has been to develop or find free available simulation model for nodes according to IEEE 802.15.4 standard.

Browsing internet they found simple model developed by IPP-HURRAY Research Group in Portugal [12]. Further, the student task was to describe the found model and write instructions for its use. Since this model supports only the star topology (which is used the most in control engineering), a plan for the future is to expand the model with capability to use cluster-tree and mesh networks.

This model implements physical and medium access control layers defined in the IEEE 802.15.4 standard. The model has two types of nodes:

- Analyzer node
- Sensor node.

The analyzer node, called wpan_analyzer_node, serves for collecting statistics about overall network traffic. It is composed of receiver (Rx) and sink which logs on to the network traffic. The sensor node, called wpan_sensor_node, can be configured as PAN Coordinator or End Device (RFD). Sensor node only supports Beacon-enabled mode with slotted CSMA/CA MAC protocol. Sensor node structure has four functional blocks (Fig. 5).

1. The Physical Layer consists of wireless radio transmitter (Tx) and receiver (Rx) which operates at the 2;4 GHz frequency band with data rate of 250 kb/s. The wireless signal is modulated by Quadrate Phase Shift Keying (QPSK) technique with transmission power of 1 mW for 0 dBm.
2. The MAC Layer uses slotted CSMA/CA and GTS mechanisms. The GTS data traffic (i.e. time-critical traffic) incoming from the application layer is stored in a buffer with a specified capacity and dispatched to the network when the corresponding GTS is active. The non time-critical data frames are stored in an unbounded buffer and are transmitted to the network during the active CAP based on the slotted CSMA/CA algorithm. This layer is also responsible for generating beacon frames and synchronizing the network when a given node acts as PAN Coordinator.
3. The Application Layer consists of two data traffic generators (i.e. Traffic Source and GTS Traffic Source) and one Traffic Sink. The Traffic Source generates unacknowledged and acknowledged data frames transmitted during the Contention Access Period which use slotted CSMA/CA. The GTS Traffic Source can produce unacknowledged or acknowledged time-critical data frames using the GTS mechanism. The Traffic Sink module receives frames forwarded from lower layers and performs the network statistics.
4. The Battery Module computes the consumed and the remaining battery energy The default values of the power consumption are set to those of the MICA mode specification.

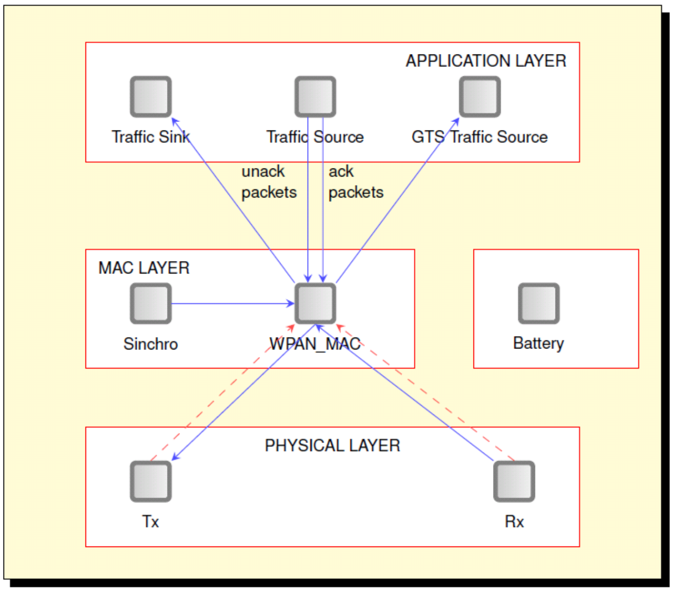

Figure 5: Structure of WPAN sensor node

IV. SPARCGRAPH

For higher ISO/OSI layer protocols (topology control and routing) modeling and partly simulations the students use our own tool called SPARCSOFT™. SPARCSOFT™ is part of the AeWSN project (Fig. 6), which is basically a testbed for wireless sensor network and consists of:

- WSN nodes.
- Pc with base station module (PAN coordinator).
- SPARCSOFT module.
- Graphical user interface.
- Commercial programs for modeling, simulation, visualization and software development.

The SPARCGRAPH module is intended to be used more as planning, modeling and testing/evaluating tool rather than simulation tool. Therefore SPARCGRAPH supports only few basic methodologies of simulating. There are many starting scenarios how SPARCSOFT can be used. Let us consider two different approaches:

- WSN nodes are not deployed and can be deployed later depending on the topology selected.
- WSN nodes are randomly deployed. Students must find optimal topology due to specific demands (latency, energy saving, redundancy. . .).

In the first scenario students try to find (manually) an optimal topology depending on the given demand. First of all students chose the scenario size and place the nodes on the SPARCGRAPH GUI panel. After placing the nodes, they select the maximum transmission power and channel model to be used. When finished the SPARCSOFT calculates and draws the virtual sensor network (Fig. 8).

With the analysis tools provided by SPARCGRAPH™ students can determine the connectivity, power consumption and other similar parameters. With moving the nodes and/or changing the node parameters they can create optimal topology for the problem.

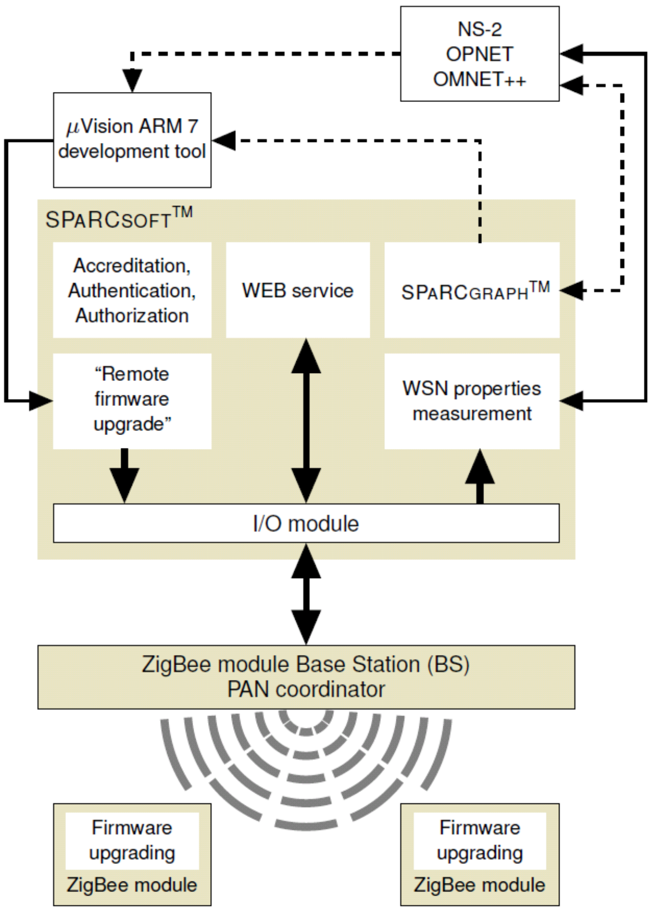

Figure 6: AeWSN project overview

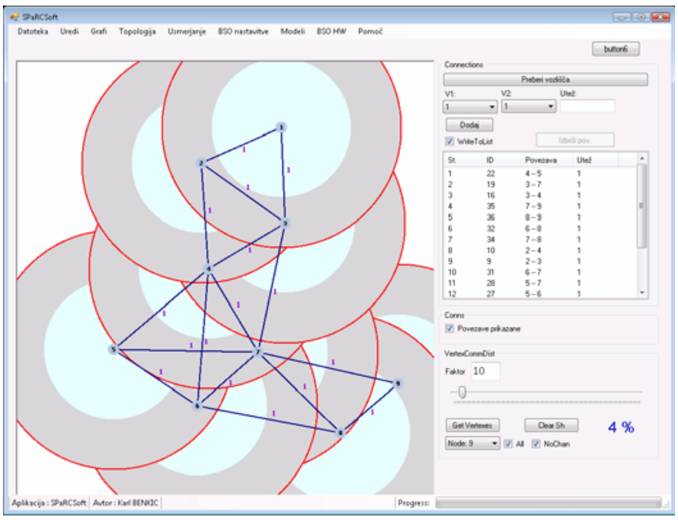

Figure 7: SPARCSOFT™ screen shot

In the second scenario nodes are already randomly placed over area (students can use "Deploy nodes randomly" option in SPARCGRAPH™). In this scenario students try to find the optimal topology with the SPARCSOFT tool for already deployed nodes base on the given demands. Majority of the students use and try different algorithms which are already coded in the tool. Other, advanced students can try and code their own algorithm in order to find an optimal topology. To do so, they can use certain primary algorithms (e.g. Minimum Spanning Tree, Connectivity...) from SPARCSOFT using common programming techniques (calling functions, override, inheritance etc.).

After planing and modeling, students can simulate and confirm their topology in one of the simulating tools (NS-2, OMNET++ or OPNET) and/or use their topology on real network. To use topology on the real network, the student must code firmware for the WSN nodes (based on ARM7 or CORTEX CPUs) called SPaRCMosquito. To do so, we offer them digital software library that has majority of the codes needed to operate the SPaRCMosquito.

When the firmware is written, it can be flushed over the network using SPARCSOFT tool. Students can now measure the network parameters and compare them with the simulation results.

V. Some Results

A part of results of the described student projects work have been published at international workshops [3]–[5], the another part have been used as reports for individual research work [7]–[9] or diploma thesis [6]. Among them we have selected two results which are described in following subsections.

A. *Remote control of Zeppelin*

The task was to design the remote control of Zeppelin powered by three servomotors (Fig. 8). The control task is performed on personal computer, application is written in LabView program.

Figure 8: Zeppelin Z4500

B. Monitoring patients in a hospital

The task was to shown the simulation of ZigBee network consisting of one PAN Coordinator node and three RFD End Device nodes which collects ECG signal from patients. Network is laid inside virtual hospital room where each node is in radio range of all other nodes (Fig. 9). RFD nodes measure the ECG signal.

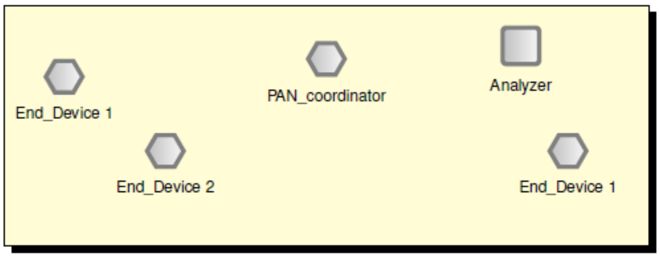

Figure 9. Layout of virtual hospital room with simulated wireless sensor network.

There were sampled in rate 360 Hz with 11-bit resolution. The impact of various values of prediction order in predictive compression on node power consumption was studied with simulation in OPNET.

VI. CONCLUSION

To comprehend the principles as well as the method for engineering work it is important to possess skills for using computers and adequate programs for modeling and simulations. For this purpose we extensively use Matlab, LabView, Opnet as well as our own programs developed by Ph. D. students for research and study wireless sensors networks.

During the preparation for the forthcoming graduate program according to Bologna declaration we have performed a number of student individual research work where we have tested feasibility of the seminar work with more complex projects. With such seminars we expect the students to obtain:

- hands-on experiences,
- competence in engineering tasks

Important results from the series of student projects are materials, tools and equipments for e-learning, blended learning system and support, as well as permanent development of new parts and modules for them. Therefore students are primarily required to learn to learn about a wireless sensor network, simulation tools, programming, microcomputers, signal processing etc. This way they are forced to obtain a “full picture” of every day engineering tasks which will come in their professional life in the future. future professional task.

REFERENCES

[1] Maks Tajnikar. Bolonjska deklaracija: Zgled za resen družbeni premislek. Delo, 23. oktobra 2004, Sobotna priloga, str.20–21.

[2] Andrej Pogacnik. Zakaj se je evropa odloˇcila za Bolonjsko shemo študija. Mnenje. Delo, 18. oktobra 2004. Priloga šolstvo, str. 12.

[3] Karl Benkič, Peter Planinšič: Custom wireless sensor network based on ZigBee, Elmar 2008, Zadar, Croatia.

[4] Karl Benkič, Marko Malajner, Aleksandar Peulić and Žarko Čučej: AeWSN - education wireless sensor network. Elmar 2008, Zadar, Croatia.

[5] A. Peulić, U. Pesović, K. Benkič and Z. Čučej: Performance analysis of improved ZigBee wireless network by simulation. IWSSIP 2008, Bratislava, Slovakia.

[6] Dragan Kusić: Wireless sensor network ZigBee. Diploma thesis, University of Maribor, Faculty of electrotechnical engineering and computer science, Maribor 2008.

[7] Uroš Pešović: Wireless sensor Networks. Seminar work at subject: “Sistemi daljinskega vodjenja” at prof. Žarko Cˇ ucˇej, january 2008.

[8] Uroš Pešović: ECG Predictive coding. Seminar work at subject: “Procesiranje procesnih, slikovnih in video signalov” at prof. Peter Planinšič, July 2008.

[9] Uroš Pešoviˇc: Opnet simulation of IEEE 802.15.4/ZigBee wireless sensor networks. Individual research work at doc. dr. Jože Mohorko,University of Maribor, Faculty of Electrical Enginerring and Computer Science, April 2009.

[10] IEEE 802.15.4 Standard-2003: “Part 15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (LR-WPANs)”. IEEE-SA Standards Board, 2003

[11] ZigBee Alliance: ZigBee Specification. http://www.zigbee.org/

[12] Petr Jurcík, Anis Koubâa: The IEEE 802.15.4 OPNET Simulation Model: Reference Guide v2. Technical Report HURRAY-TR-070509

[13] N. Kimura and S. Latifi. A Survey on Data compression in Wireless Sensor Networks. International Conference on Information technology: Coding and computing(ITCC’05).

[14] F. Marcelloni, M. Vecchio: A Simple Algorithm for Data Compression in Wireless Sensor Networks. IEEE communications letters, Vol. 12, No. 6, June 2008.

[15] Ricardo Augusto Rodrigues da Silva Severino: On the use of IEEE 802.15.4/Zigbbe for Time-Sensitive Wireless Sensor Network Applications. Master thesis. Porto, October, 2008

[16] Shahin Farahani: ZigBee wireless networks and transceivers. Newnes publications 2008, ISBN: 978-0-7506-8393-7.

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