Design Support for Robust Wireless Sensor Network Applications

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Abstract

Wireless sensor networks (WSNs) get increasing importance in application areas like home automation, facility management, health care, and ambient assisted living. Applications on WSNs are expected to utilize a large number of nodes in heterogeneous environments. They are too complex to be developed in the traditional way of prototyping and debugging. In fact, new techniques are needed to support the design of WSN applications efficiently. *dresden elektronik ingenieurtechnik gmbh* and *Fraunhofer EAS* cooperate in a joint project to develop a design platform for these applications. This design platform comprises a simulation framework and an emulation platform. Simulation is an important method to decrease design time and to increase design quality. This is crucial for the application areas mentioned above since very high reliability and robustness are required. The WSN simulation framework extends existing network simulation approaches. It is complemented by an emulation platform which can form test systems of up to 1000 nodes with different configurable topologies. The aim is the emulation of typical application scenarios to test load situations and corner cases as well as to parameterize the simulation models. Combining the simulation framework and the emulation platform it becomes possible to analyze very complex WSN scenarios and their application level robustness to be expected prior to the actual implementation of the systems. The paper introduces this design platform, discusses some challenges, and presents first results.

1 Introduction

Currently, the market for wireless sensor networks is growing rapidly in several application areas. A number of manufacturers offer low-priced and energy-efficient hardware and software solutions, from integrated radio chips to ready-to-use sensor and radio boards. This makes it possible to build intelligent networked systems for automation (building and industrial automation), health monitoring and assisted living, environmental technologies, logistics, or condition monitoring. The utilization of wireless communication offers great flexibility and cost-efficient installation of those systems compared to wire-based realizations.

However, the growing complexity of these systems and the wireless nature of the communication channel pose some major challenges for system engineers planning and implementing such systems. For example in building automation, applications on WSN are expected to utilize a large number of nodes forming one single network. Even simple applications with light and shutter switches and temperature and humidity sensors per room will accumulate in some hundred rooms to several thousands of nodes within a whole office building. If this infrastructure will be further used and extended for distributed control applications, e.g. air conditioning, the complexity of such a system will be enormous. This is particularly crucial for the mentioned application areas since those applications have to work reliable and robust to a much higher degree than typical wireless consumer systems.

It will not be feasible to develop and implement those networks and applications in the traditional way of prototyping and debugging. Rather, new design support technologies are necessary and have to be provided throughout all stages of the development process. This requires a modeling strategy and environment which covers several levels of abstraction, from pure functional models to detailed models featuring specific network stacks and precise channel behavior. The specifics of a dedicated (e.g. building or industrial) environment have to be considered. Eventually, the actual implementations have to be setup, parameterized, and tested, e.g. to ensure a stable and reliable behavior even in critical load situations, as much as possible prior to the system roll-out in the target environment.

Simulation is an important method to achieve these goals. Hence, a large number of academic publications deal with evaluation of wireless networks. There are many different simulation tools available in this area, each of them with a more or less active community [18]. The most known one is the network simulator ns2/ns3 [5] which is widely used in academia. OPNET is a commercial network simulator with many available modules but limited extensibility [1]. OMNeT++/OMNEST is a discrete event simulator (free only for academic use) which can be extended easily [16; 3]. A number of frameworks exist which provide appropriate means and models for network simulation, e.g. MiXiM [12]. The most important focus of research activities on these areas has been routing mechanisms, protocols, and topologies [17]. In addition, special topics like energy consumption modeling [8; 19], microcontroller utilization [20], or wireless networked control systems (WNCS) [7] are examples for related research topics. Consequently, a lot of knowledge and methodologies are available from the academia. However, it remains a big challenge to provide design support technologies as described above for integrated practical usage in real technical developments [9]. Special attention has to be turned to the credibility of the simulation experiments [15], which requires (beside others) an in-depth validation of the simulation models. Emulation techniques can help to contribute to this issue.

This paper presents a design platform for wireless sensor networks. Section 2 introduces some terms and specifics and describes the purpose of the design platform. Section 3 gives an overview of the system concept. Then, section 4 discusses some challenges and limitations and how to overcome them, and reports implementation issues.

2 Specifics, Terms, and Purpose of the Design Platform

In order to meet the requirement to design *robust* WSN systems as introduced in section 1 some further specifics and terms have to be considered.

2.1 Specifics of WSNs

A wireless sensor network can be seen as a spatially distributed sensor-actuator system which utilizes a (wireless) ad-hoc network for data transmission. This also implies the common potential connectivity problems as a consequence of the general wireless nature of the shared communication medium [14]. Specifics of WSNs in many application areas are the large number of miniaturized nodes (as motivated in section 1), which is expected to grow continuously as the applications become more pervasive. This suggests not only very low costs per node, but also hard restrictions with respect to the energy consumption. WSN nodes must often be able to get their energy from batteries which will never have to be changed during the lifetime of the nodes or must be completely energy autarkic using energy harvesting technologies.

Therefore, WSN nodes are resource constrained and have to use transmission energy efficient protocols. Among others this implies relatively small data rates (250 kbit/s in case of IEEE 802.15.4) and low-complexity communication protocol stacks. On the other hand, only little or moderate mobility of a few nodes in the network has to be dealt with in most application areas.

The more complex the network itself gets the more it becomes sensible to use the same network infrastructure by different automation tasks or applications. With the traditional OSI layered view of networks this wouldn't be a problem. But recalling the limited resources of the network and the nodes itself, this will be the most challenging design issue for building automation applications. These applications will compete for the resources in terms of energy, data rate, and processing power. Even though e.g. a typical IEEE 802.15.4/ZigBee stack itself has a strict OSI compliant architecture, the different OSI layers cannot be considered as completely independent. Rather, the impact of the very nature of the applications has to be regarded in a cross-layer view already during the design process of an automation system [14].

2.2 Technical Realization of Nodes

Currently, the most widely used communication standard for WSNs is IEEE 802.15.4 [10]. Like all IEEE 802.x standards it covers only the physical transmission and the medium access control layer. On top of this standard, a number of networking standards like ZigBee [21] or WirelessHART [6] are available. Other communication protocols are under investigation or in use for WSNs, e.g. IPv6 over Low power Wireless Personal Area Networks (6LoWPAN) [2] or various proprietary protocols. Regardless of the actual communication protocol used and the future development within this field, the specifics of WSNs as discussed in this paper for IEEE 802.15.4 based networks will remain valid in general.

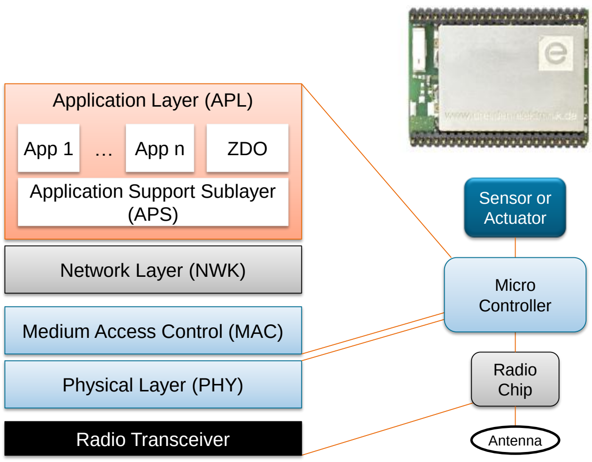

Figure 1: Realization of a ZigBee node

As shown in Figure 1, a WSN node generally consists of the sensor(s) or actuator(s), a radio transmitter chip with antenna, and a microcontroller. Most of the communication protocol stack will usually be implemented in software and runs together with the actual application(s) on the microcontroller. Depending on the application to be implemented on such a node, the microcontroller will typically be an 8-bit controller with limited resources (e.g. 8 kB RAM, 128 kB FLASH operating at 4 or 8 MHz clock frequency).

2.3 Robustness

The term *robustness* is used in a broad meaning also in technical systems. It has to be differentiated from related terms like *fault tolerance* or *reliability*. Moreover, if we want to simulate and evaluate the robustness of a system we need precise technical parameters to setup useful simulation experiments. Therefore, we use the definition of *Quality of Service* (QoS) parameters in technical systems [11] and specify what QoS from application or, moreover, user perspective means for the systems to be investigated. Conditions may occur inside or outside the system which do not match the normal operation conditions and which may affect the required QoS from user perspective.

The robustness of a WSN application is the ability of that (distributed) application to operate within the required QoS parameters even if the WSN does not work in the specified behavior in all parts of the network. [9]

2.4 Aims of Simulation and Emulation

The WSN simulation framework extends existing network simulation approaches. It takes care of the following tasks:
- Evaluate the reliability and application-specific robustness of an entire WSN application and of measures to improve them.
- Perform a holistic simulation (application(s), sensor/actuator behavior, communication, and environment).
- Implement models of real-life communication stacks for interoperating applications in simulation and WSN implementation.
- Handle the trade-off between mastering the complexity and, consequentially, the need for a significant speed-up on one hand and the necessary accuracy of the simulation on the other hand.

In addition to these general modeling and simulation tasks, evaluation of WSN applications covers further aspects, like modeling and tracking the energy consumption of nodes and the degree of utilization of other resources as processor load and main memory.

The simulation framework is complemented by an emulation platform which is needed to solve the following problems:
- Emulation of typical application scenarios of WSN nodes to test load situations and corner cases.
- Validate and parameterize the simulation models to investigate systems which scale beyond the maximum size of the emulation platform and to efficiently perform variant simulations.

3 System Concept

Figure 2 shows the general architecture of the design platform. The emulation part connects a number of WSN nodes either over the air or with a cable-based RF interconnection system. Furthermore, the nodes are connected via Ethernet with a control system/test server. This system server is responsible for the provision of test cases and the regarding automatic configuration of the WSN nodes and the emulated network topology and allows monitoring and maintenance. Since only the communication of the WSN nodes is emulated in hardware, models and/or stimuli for sensor data, actuator responses, and environment behavior have to be supplied.

The simulation part of the platform may use the same sensor, actuator, and environment models as well as the same test cases. The models of the WSN nodes may use the same communication stack and application layer software as the real hardware nodes in the emulation platform. To increase the achievable size of the simulated network, models at higher abstraction level can be used alternatively. Furthermore, communication models providing the behavior of the radio channel and tracking the actual connections of the nodes are necessary.

The emulation and simulation platform interact in order to achieve the aims mentioned in section 2.4. But they can also be used separately to solve dedicated problems during the design process.

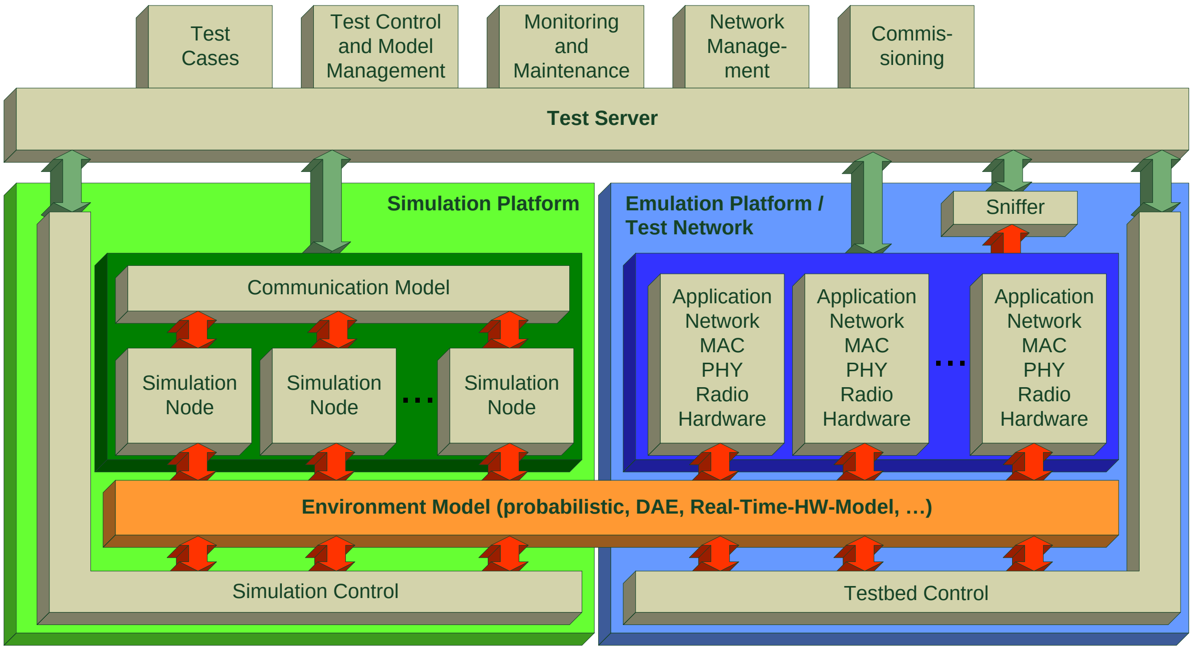

Figure 2: **Architecture of the WSN design platform**

3.1 WSN Simulation Framework

We use the discrete event simulation environment OMNeT++ [3] for our WSN design support framework. Apart from providing the actual functional models, a number of general tasks have to be solved for modeling and simulation of wireless ad-hoc networks: e.g. managing the actual connections on the shared medium, generic handling of the channel and the communication layers, dealing with spatial location, and mobility of nodes. On top of the simulator OMNeT++, the wireless simulation framework MiXiM [13] provides base classes, models, and mechanisms to handle these issues.

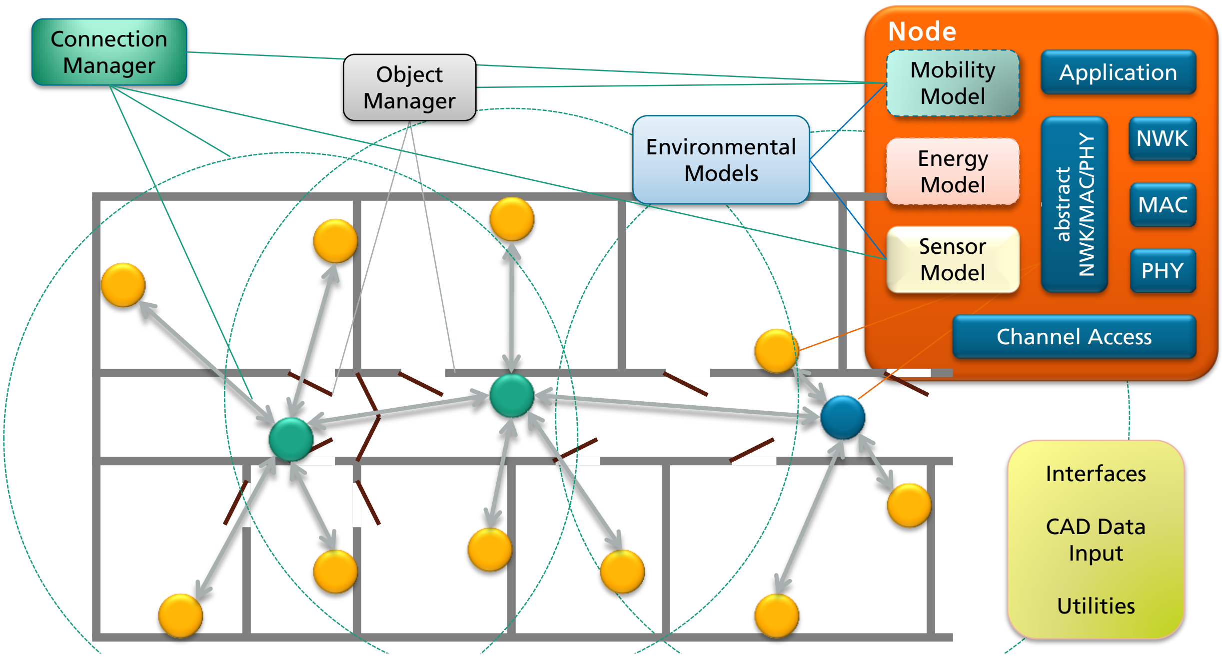

Figure 3: **Modules of the simulation framework, WSN nodes, and POS in a building environment**

This base framework has to be extended in order to achieve the aims defined in the previous sections. In particular, a special object manager handling the obstacles within the radio channel (e.g. walls in a building) efficiently and different models representing the behavior of WSN nodes (communication stack, mobility, energy, sensors) have been developed or extended. Additionally, the simulation platform provides interfaces to the emulation platform, for input of CAD data etc. Figure 3 gives an overview of the modules of the simulation framework.

3.2 Emulation Platform

The emulation platform consists of up to 125 panels. They can be connected to form test systems of up to 1000 nodes with different configurable topologies. The radio communication between the nodes is realized either over the air or through cables. Even a mixed usage is possible.

The main building block of the emulation platform is a panel with a RF splitter and an RF interface. Each panel can carry up to eight radio modules – the DUTs. The radio part of the modules will be connected to the RF interface (see Figure 4) and the microcontroller of the modules to the management system of the panel. In a wired approach, the panels can be connected in variable lengths and topologies by splitters and combiners forming the entire system. In a wireless approach, the panels can be equipped with antennas – or even the on-board antenna of the DUT can be used – to setup the system. However, in a wireless approach, the network topology becomes dependent on the location of each panel related to the others.

Figure 4: RF-interface of the emulation platform

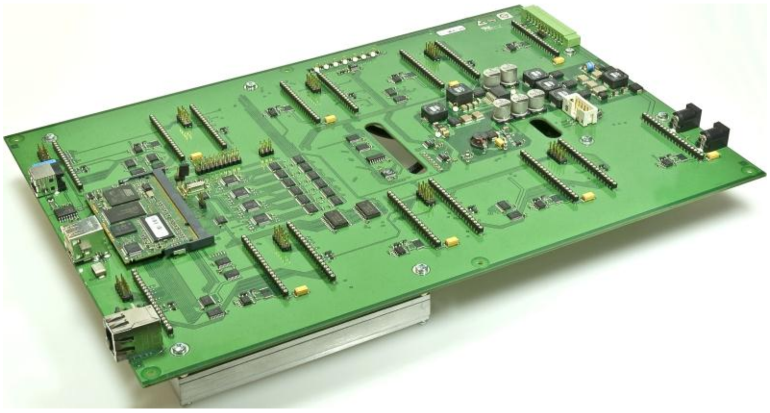

Figure 5: Panel module of the emulation platform

Each panel contains its own management system which controls the activities of the nodes and cooperates with the test server. The management controller is responsible for dynamic firmware handling of the WSN nodes, for time synchronization, for controlling the attenuation unit of the RF interface, for power consumption measurement, and many more. The node interface design always includes an adapter to connect the specific node to the panel. This cheap adapter enables the panel to work with all kinds of WSN nodes from different manufacturers. Currently, radio boards by *dresden elektronik* with ATmega controllers and RF212 radio chips or ATmega128RFA1 single-chip modules are used for the development and validation of the emulation platform. Figure 5 shows the described panel.

4 Challenges and Limitations

This section exemplifies some challenges within the development of the design platform and reviews some preliminary results.

4.1 Channel Modeling

As already mentioned, a wireless network shares a common transmission medium – the channel. Thus, each node is connected physically to each other (independently from the logical network structure as depicted in Figure 3). However, which nodes actually may receive signals from other nodes depends on their radio coverage (or personal operating space POS as indicated by circles in Figure 3) which again will be influenced by the characteristics of the channel. In the simulation framework based on MiXiM, all possible physical connections are maintained by a module called *connection manger*. If a certain packet is actually transmitted, it will be received by all nodes connected with each other by that connection manager. Then, each node determines the received power and the quality of the signal (e.g. signal to noise ratio, bit error rate) by evaluating a dedicated channel model.

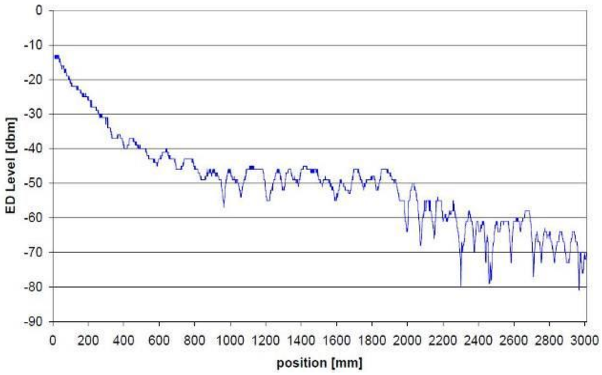

Figure 6: Drops in signal reception due to multipath propagation

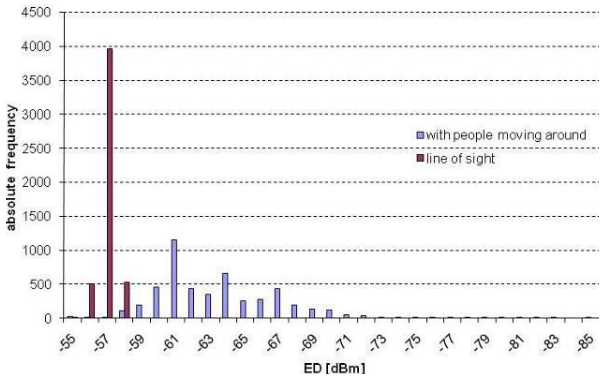

Figure 7: Distribution of ED with and without people randomly but continuously walking round the nodes

This channel model has to take care of several effects:

- Multi-path reception will affect the signal reception. Figure 6 shows the signal strength measured in an office environment depending on the distance (without any obstacles in between). Due to the multi-path transmission occasional drops in signal reception of up to 20 dB can be observed. This effect has to be taken into account within the simulation by varying the channel model parameters statistically for sensitive nodes and checking the functionality at network and application level (a kind of monte-carlo simulation).
- Disturbances and interferences may occur. This can be caused by the simple fact that people are walking around and possibly affecting the channel behavior. Figure 7 shows the distribution of the received signal strength (energy detection level – ED) of 5000 packets sent with 3 dBm and received in a floor at 12 meters distance over a period of about 155 seconds with two people randomly but continuously walking around between the nodes. This effect has to be considered in the channel model by statistical means again.
- The signal is attenuated by obstacles, e.g. the walls inside a building. Therefore, simple path loss models as often used within wireless simulation are not sufficient. Instead, a multi-wall model is used. It considers the attenuation of the walls of different types and thickness in addition to the normal path loss.

4.2 Obstacles

Obstacles like walls in buildings need special attention in network simulation, since their modeling is performance critical especially if we have to consider also moving nodes. In general, for each possible connection between two nodes the obstacles have to be identified. In order to have a flexible mechanism to get the attenuation values for the multi-wall channel model, we implemented an obstacle manager which uses a powerful optical ray-tracer, the open-source renderer

PoVRay [4]. The attenuation of the obstacles is modeled as a transparency for the light rays. An advantage of this solution is the potential to model even complex objects by describing also the structure of the surface and characteristics of the inside.

The ray-tracing based object manager supplies its connection related accumulated attenuation values to the connection manager each time a change in the spatial distribution of the nodes (and possibly the objects/obstacles) occurs. At a minimum, this has to be done once at the beginning of a simulation for a static network. If one node moves, the procedure has to be repeated for all affected nodes and their connections to the moving node. The PoVRay based object manager calculates the attenuation and the distance the beam covers through the wall. The attenuation characteristics of the walls have to be determined for a given building. This can be done automatically for each type of wall using the design platform's built-in features.

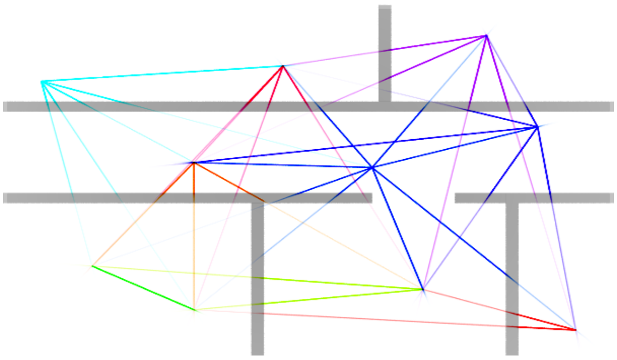

Figure 8: Optical ray-tracing for evaluating obstacles between connecting nodes

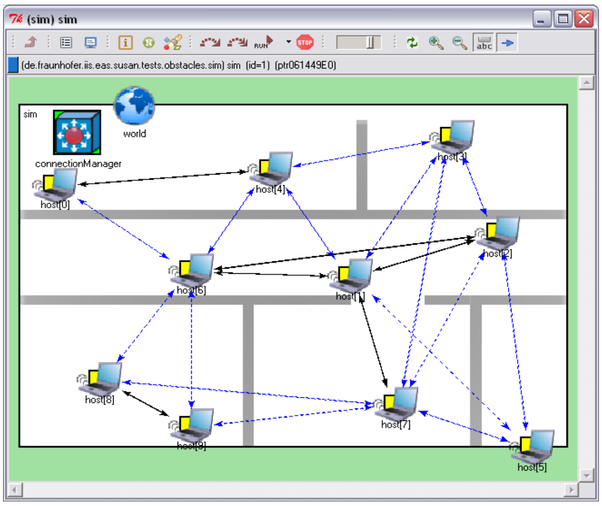

Figure 9: Connections with consideration of ray-tracing for multi-wall model

Figure 8 visualizes the optical ray-tracing for a setup of 10 nodes, rendered by the PoVRay module which is integrated into our simulation framework. Figure 9 shows the consequences for the physical connections. With the standard MiXiM connection manager, most of the nodes would have a pairwise connection (except nodes on opposite edges of the playground). But with our extended connection/object manager the physical connections are reduced as shown in Figure 9.

4.3 Emulation Platform

One of the most challenging parts of the emulation platform is the configurable RF connection of the panels and thus the radio modules. If we assume the panels to be connected in a star layout of three lines of up to 46 panels using a simple splitter, we have 92 panels from one end to the other. With a generous link budget of 100 dB and a rather ambitious 20 dB loss from each node of the panel to the RF out of the panel, the RF interface cannot have an insertion loss of more than 0.5 dB including connectors and cables. Measurements with the specially designed RF interface of the panels showed, that an insertion loss of 0.85 dB to 1.3 dB – depending on the frequency band – is possible, but the necessary 0.5 dB is not.

Therefore, a modified topology for the emulation platform with cable-based RF connection will be used. The panels will be connected in a star layout of nine lines of up to 14 panels each. With this layout and with 8 WSN nodes per panel, test networks with up to 1000 nodes can be realized within the emulation platform. To achieve even larger networks, a combined approach with wired and wireless RF connections is possible.

Another aspect of the emulation platform addresses the node synchronization. In order to precisely follow the flow of events within the network, e.g. packets, each packet throughout the entire network needs to be provided with a correct timestamp. Since the network cannot be covered by a single sniffer, means of synchronization between the different (sniffing) nodes are necessary. The panel enables either a software based adaptive approach using the test server or a hardware synchronization mechanism with one panel management controller acting as master for all network nodes. The hardware mechanism supplies a maximum clock of 1 MHz to all nodes via the RF connection of the panels, enabling node synchronization with µs precision.

5 Summary and Outlook

In this paper, we presented a new design support platform for wireless sensor network applications. This platform shall help to develop complex WSN systems efficiently and with predictable reliability and robustness. Methods of simulation and emulation can be combined. The paper discussed some technical challenges for the design platform and how they can be solved.

Currently, this design platform is under development in a joint research project. First results are available. Future work will include extended support for different network stacks, alternative models for more complex systems to be handled, and support for different sensor and actuator behavior as well as various application environments.

Acknowledgement

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