QoS-oriented Integrated Network Planning for Industrial Wireless Sensor Networks

Feng Chen[*†], Reinhard German[*] and Falko Dressler[*]
[*]Dept. of Computer Science, University of Erlangen, Germany
[†]Siemens AG, Industry Automation Division, Germany
{feng.chen,german,dressler}@informatik.uni-erlangen.de

***Abstract*—we present an approach for integrated network planning with QoS estimation in a simulation tool for use in industrial environments. The architecture is based on a wireless planning tool that uses measurements or accurate models of the environment to predict physical layer signal distribution. This tool allows the precise modeling of industrial environments including machinery, walls, and other obstacles. We integrate this tool with a simulation model for performance evaluation of sensor networking protocol. In particular, we use out model of the IEEE 802.15.4 protocol together with the accurate physical layer model to estimate the behavior of intended applications before actually deploying them. The final objective is to allow the network designer to use the toolkit for integrated QoS-oriented network planning.**

I. Introduction

Wireless technology successfully started its way into many industrial application fields including industrial automation. This also includes Wireless Sensor Network (WSN) technology [1] based on standardized protocols. One of such industry standards is IEEE 802.15.4 [2]. Whereas IEEE 802.15.4 based WSNs are designed for low-rate applications, especially stressing energy efficiency, they are also considered for a number of industrial applications with slightly different requirements. For example, the Siemens Industry Automation Devision is currently evaluating such wireless technologies for use in automation environments.

Transceiver chips and even complete sensor nodes that implement this standard are commercially available at an acceptable low cost. According to Willig [3], the IEEE 802.15.4 standard has already become a recognized industry standard. It provides specifications for the Physical Layer (PHY) and Medium Access Control (MAC) sublayer. In this context, ZigBee [4] has recently gained much attention. It is an open specification built on top of the IEEE 802.15.4 standard and focuses on the establishment and maintenance of Low-Rate Wireless Personal Area Networkss (LR-WPANs). One of the main design goals of these standards has been energy efficient operation, whereas hard real-time aspects were not a primary concern. A similar approach to use the lower layer definitions of the IEEE 802.15.4 protocol to define more complex network protocols is WirelessHART [5], which has its primary roots in wired industrial networks.

For application in industrial automation, mainly reliability and real-time capabilities of a protocol are of interest. The reliability of wireless communication basically depends on two

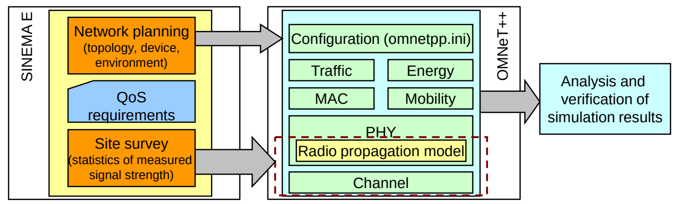

Fig. 1. System architecture: the planning tool SINEMA E is coupled with the network simulator OMNeT++

question [3], [6]. First, the quality of the signals at the physical layer, i.e. possible interference among different networks and between different technologies such as IEEE 802.15.4 and WiFi. Secondly, the channel access of the MAC protocol is responsible for avoiding collisions, at least to a certain degree. Furthermore, the real-time characteristics need to be considered, i.e. the capabilities of the protocol to ensure some upper bounds for any transmission.

Based on our expertise in protocol design and performance evaluation, we addressed the channel access and the statistical protocol behavior in recent research [7], [8]. The work on real-time variants of IEEE 802.15.4 while keeping the physical layer as defined by the standard (i.e., enabling the use of standard conform transceiver chips) lead to the current proposal for the forthcoming IEEE 802.15.4e standard [9].

In this work, we go one step further and address the issue of reliability w.r.t. signal interference between different networks operating in the same area. We are developing an architecture that is composed of a physical layer network planning tool provided by Siemens, SINEMA E. This tool allow to conduct either measurements or simulations to determine the signal distribution in a given environment considering any available machinery, walls, etc. Coupling this tool to our simulation model of IEEE 802.15.4, we finally get a highly precise physical layer model that we use to conduct performance evaluation studies. The final objective is to provide a toolkit that allows the planner to place nodes in a certain environment, to annotate application behavior and performance requirements, and finally to get statistical measures describing the feasibility of the current plan.

Figure 1 shows the necessary modules and their interaction. In the following sections, we briefly describe their operation and the intended outcomes. We believe this coupled planning tool with simulative performance evaluation provides the facility planner and network designer exactly the right way to carefully plan wireless sensor networking applications for use in industrial environments.

II. Scenario and Metrics

In our performance analysis, we focus on limitations w.r.t. industrial application. A number of relevant metrics have been pointed out by Willig [3]. According to this study, the main characteristics of industrial traffic become visible in the following properties:

- The presence of deadlines, i.e. the need to support real-time communication
- High reliability requirements regarding the successful transmission of single messages
- The predominance of short packets, e.g. sensor readings

The proposed standard IEEE 802.15.4e [9] describes a typical scenario: A number of sensor nodes are scattered within an area and associated to a central node to form a star network, which is continuously monitoring industrial processes. Once a certain device detects that particular sensor readings exceed a predefined threshold, a short alarm message must be sent by the device to the central node within a given time frame. Such a time limit is a hard real-time requirement, thus, the network needs to be able to handle also the worst case, when all devices generate alarm signals at exactly the same time. In addition, to prolong the lifetime of the monitoring sensor network, all the devices need to enter a sleeping mode if no critical events are detected. Thus, the following requirements must be met by the MAC protocol – the numbers in brackets are examples from typical automation projects of the Siemens Industrial Automation Division:

- n nodes in a star topology ($n = 20$)
- very short alarm or sensor messages ($1\,\mathrm{Byte}$)
- guaranteed low latency delivery ($d < 10\,\mathrm{ms}$)

As stated before, the main focus is the reliability and the real-time behavior of the wireless communication. Primary metrics to be evaluated include the communication delay; and all the analytical observations focus on this metric. Furthermore, we simulated the loss rate, which is especially relevant for CSMA based communication but also for TDMA cases if queuing effects need to be considered. The goodput and the energy consumption are of secondary interest, whereas our simulation model is fully capable to measure these metrics [7].

III. Physical Layer Planning

We specifically focus on a well planned industrial environment, which can be considered a typical case – dynamic frequency sharing and the unattended operation of wireless networks is usually not allowed in such environments. For example, the frequencies (even open frequencies in the ISM band) are carefully managed and even the use of laptop computers with build-in WiFi or Bluetooth is strictly forbidden.

In factory automation, planning tools are used to ensure proper signal distribution between the deployed nodes [10].

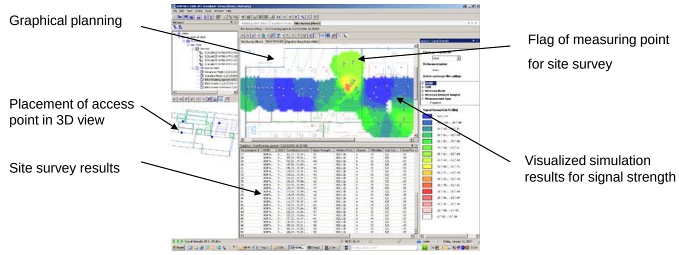

Fig. 2. Physical signal distribution in the planning tool SINEMA E

Such tools are usually relying either on measurements or on raytracing methods as studied since a decade in the field of Wireless Local Area Network. Furthermore, we assume that there are no interfering IEEE 802.15.4 based networks – again relying on the planning tools. Interference with Wireless Local Area Network (WLAN) can be minimized if proper channels are selected. Thus, reliability is then more an issue w.r.t. stochastic noise and random disturbances. Obviously, this cannot be completely eliminated.

The planning process is depicted in Figure 2. The designer first models the environment including all the walls and machinery. Based on this information, the simulation mode can determine the signal distribution in the area. Then, the planner can add the required base stations and sensor nodes. According to this information, the tool can now perform a simulation of the signal distribution. This is shown as the colored area in the middle of Figure 2. Furthermore, measurements can be performed in the real environment (shown as site survey in the figure). Whereas this can only be provided after setting up the automation environment, the measurements provide the best results. For all the point in the area between the measurement points, the signal distribution is either interpolated or adapted from the simulation results.

IV. Network Simulation

Our simulation model of IEEE 802.15.4 is adapted from a former implementation [11], which was built according to an old version IEEE 802.15.4-2003, using the network simulator ns-2. Our implementation in OMNeT++ [12] conforms with the latest version of the standard IEEE 802.15.4-2006. As a minor addition, we installed an Interface Queue (IFQ) module that acts as the buffer of the MAC layer.

Figure 3 shows a graphical snapshot of the simulation. On the left hand side, the environment can be seen consisting of a single PAN coordinator and 20 distributed sensor nodes. On the right hand side, the modeling of a single sensor node is shown. We used this simulation model in a previous study of general performance aspects of IEEE 802.15.4 [7] and identified a number of shortcomings related to real-time capabilities. We were able to show that the protocol specification does not fulfill industry demands for low-latency transmission in terms of guaranteed delay bounds. Therefore, we proposed some modifications of the standard to circumvent these limitations. In all these simulations and analyses, we closely keep to specific requirements relevant to industrial sensor network applications.

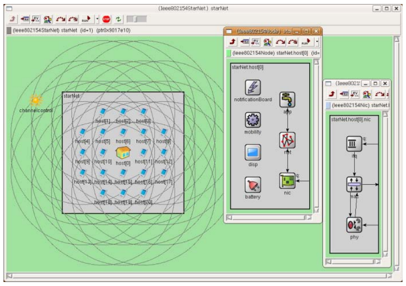

Fig. 3. Simulation model

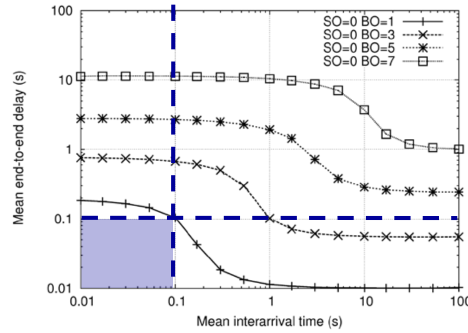

Fig. 4. Selected simulation results: shown is the end-to-end delay for decreasing traffic load and different protocol parameters

We extensively evaluated the Carrier Sense Multiple Access / Collision Avoidance (CSMA/CA) based operation of the protocol, i.e. the use of the Contention Access Period (CAP) slot [7]. Event-based simulation allows to easily explore the protocol behavior for such randomized access. In contrast, the use of Guaranteed Time Slots (GTSs) in the Contention-Free Period (CFP) is highly deterministic. We also implemented and evaluated communications using the GTS-based Time-Division Multiple Access (TDMA) scheme. In the following, we first describe the simulation scenario. Figure 4 shows some selected simulation results. From such performance measures, the behavior of the protocol can be analyzed for different application demands.

Using the coupled network planning and simulative performance evaluation, we allow the modeler not only to define environmental aspects such as the location of machinery, walls, and the wireless communication devices, but also to annotate these with application behavior such as traffic parameters and quality of service demands such as a maximum end-to-end delay. Using these information, we can precisely tune and configure the simulation model according to the scenario under investigation. The final simulation results (usually using some $95\,\%$ or $99\,\%$ quantiles) can be compared with the application demands. This is illustrated in Figure 4 with the thick dashed lines. If, for example, the maximum tolerable delay is less than $0.1\,\mathrm{s}$ and at least a traffic rate of $0.1\,\mathrm{packet/s}$ should be achieved, the adequate protocol configurations can be extracted.

Current working progress includes the use of the physical layer characteristics as provided by the planning tool as a more realistic physical layer in the OMNeT++ simulations. Instead of using a free space radio model, for each radio communication we perform a lookup in the database to determine the expected signal strength at the receiver – or more precisely, we lookup the channel attenuation and apply this to the current transmitted signal. Furthermore, statistical noise is substracted from the results. Whereas this model does not include multi-path effects, the model is much more realistic as it allows to incorporate the signal attenuation effects from walls and other obstacles.

V. Conclusion

We presented a new architecture for more realistic assessment of protocol performance aspects in industrial automation environments. This toolkit, which we apply for industrial wireless sensor networks, consists of a planning tool to model the environment including walls, machinery, and other obstacles, as well as the location of the communicating devices, i.e. the base station and the sensor nodes. Furthermore, the designer can annotate application characteristics and performance demands. Furthermore, a simulation model is integrated to verify whether the application demands are satisfied and for which protocol configuration. The available physical layer signal distribution model from the planning tool is used as a basis for the network simulation in OMNeT++. Future work includes interference measurements in the simulations to assess cross-network and cross-protocol interference.

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