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# Advanced Communication Solutions for Reliable Wireless Sensor Systems

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## 1. Introduction

State-of-the-art Wireless Sensor Network (WSN) technology enables design and implementation of novel, intriguing applications that can be used to address numerous industrial, environmental, societal and economical challenges and thus, the importance and potential of WSNs are constantly growing. Wireless sensor nodes constituting a WSN consist of a sensor interface, microcontroller, memory and battery units together with a radio module. Hence, wireless sensor nodes are able to carry out distributed sensing and data processing, and to share the collected data using radio communications. In the beginning the development of wireless sensors was driven by military applications but the introduction of civilian wireless sensor systems has greatly diversified application domain which has further boosted research efforts in the field of wireless sensor networks. Present state of the evolution of wireless sensor nodes allows utilization of smart sensors to enhance the performance and robustness of WSNs.

From the communication engineering point of view the large number of possible applications, see e.g. (Römer & Mattern, 2004), introduces unforeseen problems for which classical communication solutions are not suitable while smart sensors give us tools for finding answers to these new-found questions. Furthermore, a large number of communication protocols have been designed for specific applications but the lack of generic solutions brings up problems with respect to large scale economic success. Since versatility of WSN applications is unimaginable and the amount of possible operation scenarios is unlimited, designed protocols should be suitable for various purposes of use. Consequently, scalability and flexibility of technical solutions are extremely important to enable economic feasibility of energy-constrained wireless sensor networks.

The chapter discusses new communication protocols and state-of-the-art design methodologies as well as good practices that together enable reliable operation of various wireless sensor networks. We especially focus on reliability issues since many WSN applications are located in troublesome environments. For example, in the context of industrial WSNs reliability has been denoted as one of the fundamental design goals

(Gungor & Hancke, 2009). In this chapter we only consider so called media layers, i.e. physical, data link and network layers, and exclude upper layers. Naturally, research efforts in the field of WSNs include various other aspects as well and we direct an interested reader to see (Yick et al., 2008) and (Akyildiz et al., 2002) for comprehensive surveys.

The main contributions of this chapter include a review of current technologies used in wireless sensor networks and of the state-of-the-art solutions. We also discuss and propose novel communication protocols to enhance the performance and reliability of smart sensor systems. In each of the sections we present a comprehensive literature review and give the main references for an interested reader to further pursue on the topics. In the end of each section current state-of-the-art solutions will be introduced along with measurement and/or simulation results.

The chapter is outlined as follows. First, we review several existing physical layer methods that can be used to improve the reliability of WSNs and discuss utilization of antenna diversity in this context. After this, we cover possible media access mechanisms to guarantee data transmissions by considering both, single- and multi-channel systems. Next, solutions for enhancing reliability on the network layer are studied. Finally, we will investigate some practical WSN applications, mainly focusing on wireless automation and control, with a full-scale simulator to validate and justify the proposed designs.

## 2. Physical Layer and Diversity for Reliability

The main task of physical layer algorithms is to enable reliable delivery of bit streams over physical medium by carrying out transmission, reception and signal modulation. Other objectives include cooperation with the Media Access Control (MAC) layer to ensure error-free communications and providing channel information for MAC layer to make operational decisions. Due to the inherent characteristics of WSNs, physical layer solutions have strict limitations in terms of energy consumption and processing power compared to traditional wireless systems. Hence, the sensors' hardware abilities have to be taken into account while designing physical layer solutions.

In the context of wireless sensors, several options for transmission medium exist. Optical communications, such as laser and infrared, can be exploited if a line-of-sight connection between a transmitter and receiver is available. On the other hand, in underwater WSN applications acoustic communications are used due to the signals attenuation properties of water (Akyildiz et al., 2005). Nevertheless, undoubtedly most of the current WSN applications use radio frequencies and exploit global, unlicensed frequency bands, for example the Industrial, Scientific and Medical (ISM) band, for communications. Therefore, we focus exclusively on these particular frequency bands in this chapter.

This section consists of two main parts. In the first part we present and discuss existing physical layer methods, such as signal multiplexing, modulation and error coding, by focusing especially on reliability issues. In the second part we consider exploitation of antenna diversity in advanced sensor systems and present measurement results which imply that antenna diversity should be exploited to improve reliability in WSNs.

## 2.1 Bandwidth, Multiplexing and Modulation

In general, physical layer techniques in WSNs can be divided into three different classes based on bandwidth requirements: narrow band, spread spectrum and ultra-wideband (Yick et al., 2008). As the name indicates, narrow band systems utilize only a small portion of spectrum which approximately corresponds to the used symbol rate. Although bandwidth efficiency is the strength of narrow band systems, i.e. achieved data rate over bandwidth is high, narrow band systems are very vulnerable to interference, jamming and fading. As a consequence, narrow band systems cannot provide robust and reliable communications. Moreover, Orthogonal Frequency Division Multiplexing (OFDM) is a digital modulation scheme which divides the data into several streams and then transmits each stream on an individual subchannel. In OFDM, subchannels are closely-spaced while still ideally orthogonal. Each of the subchannels can be treated separately (e.g. modulation) and hence, data rate of each subchannel is equal to narrow band systems using the same band. Although OFDM is widely used in wireless communications, complexity and processing power requirements of OFDM are unacceptably high for current sensor nodes.

In spread spectrum technologies the bandwidth of the original signal is expanded over a wider frequency band using a spreading function. In fact, the spreading function defines the used bandwidth and thus, the final bandwidth is independent of the bandwidth of the original signal. Spread spectrum systems are characterized by low transmission powers and robustness to narrow-band interference. In addition, impairments caused by multipath fading of signals can be cancelled effectively compared to simple narrow band systems. Spread spectrum signals appear as noise-like signals at unwanted receivers and therefore, the technology offers resistance against jamming and eavesdropping as well. Furthermore, since the data signal is spread over a wider frequency band for transmission and transformed back to the original format at the receiver using the same spreading function, spread spectrum approaches offer *spreading gain* which is defined by the transmitted bandwidth divided by the information bandwidth. By multiplying the received signal with the particular spreading code the desired signal can be raised over the noise floor which helps detection and thus, enables multiple users to access the same band simultaneously.

Ultra-wideband (UWB) systems utilize even wider frequency bands than spread spectrum technologies. UWB systems spread data signals over frequency bands of gigahertz and as a result, UWB devices use low transmission powers such that UWB signals are buried under other signals without interfering existing systems. In general, UWB technology is suitable for short-range data transmissions. However, development of UWB technology in the field of WSNs has been slow and large-scale deployment of UWB technology in WSNs is still to be seen, even though the IEEE 802.15.4a standard includes an UWB option (IEEE 802.15.4a, 2007). To conclude, spread spectrum technology has several advantages compared to other approaches in the context of reliable communications in WSNs and thus, it is natural that spread spectrum is the most popular physical layer method used in existing WSNs.

Frequency Hopping Spread Spectrum (FHSS) and Direct Sequence Spread Spectrum (DSSS) are the main methods in the class of spread spectrum technologies. In the basic form of DSSS the signal is multiplied by a fixed code to spread the original data signal over a wider band. Several wireless communication systems exploit DSSS such as IEEE 802.11b (IEEE

802.11, 2007) and IEEE 802.15.4 (IEEE 802.15.4, 2006). On the other hand, FHSS devices hop on different frequency channels based on a predetermined pseudorandom code during the operations. Advanced version of the basic FHSS is used in Bluetooth, which is based on (IEEE 802.15.1, 2005), where hopping patterns are adjusted depending on the experienced channel conditions such that better quality channels are exploited more often.

In digital communication systems digital bit streams are transmitted over analog channels. For this, bits have to be transformed from digital representation form to analog symbols. This digital-to-analog conversion is carried out by digital modulation which can be done in several ways, such as using phase (PSK), frequency (FSK) or amplitude shift keying (ASK). Moreover, if at least two different phases and amplitudes are used, we have quadrature amplitude modulation (QAM). In general, the more digital bits an analog symbol represents the higher the data rate, however, in the meantime reliability is compromised since the probability of symbols' misinterpretation increases. Hence, while choosing the used modulation scheme a trade-off between data rate, reliability and transmission range has to be made. For example, in the 2.4 GHz band IEEE 802.15.4 utilizes Orthogonal-QPSK and spreading is enforced by using 4 bits to select 1 out of 16 different 32-bit code words.

## 2.2 Coding for Error Control

Due to the rigorous energy consumption constraints minimization of transmission powers is extremely important in WSNs. Reduction of the transmission power decreases the Packet Delivery Ratio (PDR) due to the nature of the radio environment such that fewer packets can be received. However, lower signal to noise ratios can be compensated by error control coding and thus, reliability of packet transmissions can be improved. On the other hand, efficient error coding allows longer hop distances with the same transmission power while sufficient PDR is maintained.

In wireless communication systems error correction schemes can be divided into three categories based on operation principles: Automatic Repeat and Request (ARQ), Forward Error Correction (FEC) and Hybrid ARQ (HARQ). If a packet transmission fails for some reason and the packet cannot be decoded properly at the receiver, the straightforward solution is to retransmit the entire packet again. This kind of approach is called Automatic Repeat and Request (ARQ). The purpose of Forward Error Correction (FEC) approach is to enhance error resiliency by including redundant information to packets such that decoding is possible even though some bits are misinterpreted. By combining both of these approaches we get Hybrid ARQ (HARQ) schemes which aim to improve reliability by adding redundant bits in an incremental fashion depending on the number of experienced packet losses. HARQ -based schemes can be further sorted into two categories, Type I and Type II, depending on the information included in retransmitted packets. In Type I HARQ -schemes receivers do not store packets whereas in Type II HARQ -schemes packets are stored which enables soft combining of multiple packets.

Several FEC algorithms have been developed during the evolution of communication systems. For example, convolutional codes are utilized in countless applications to provide trustworthy delivery of packets by adding redundancy to bit streams. Each  $m$  bit stream is converted to  $n$  symbols such that the input stream is convoluted with the impulse response

of the encoder. Several research articles consider the applicability of convolutional codes for WSNs, see e.g. (Sankarasubramaniam, 2003), and the general conclusion is that the power consumption of such codes is too large for WSNs. Furthermore, by exploiting rateless codes, such as Raptor codes (Shokrollahi, 2006), near optimal performance can be achieved. Nevertheless, rateless codes are in general unsuitable for WSNs since extremely large payloads are required for efficient operations and usually payloads in various WSN applications are relatively small.

The most prominent class of FEC codes in WSN applications encompasses of BCH codes. BCH codes are linear, cyclic block codes which use especially selected generator polynomials for encoding. Decoding of BCH codes can be done in an efficient manner which makes such codes feasible for sensor systems. Codes in this class can be designed to match the requirements of various applications. This kind of flexibility enables effective utilization of error codes. For example, the Reed-Solomon codes, which are extensively exploited in communication networks, belong to this category of error coding. To summarize, although several FEC codes have been designed to optimize the performance with respect to certain radio environments, packet sizes and reliability constraints, in the end BCH codes seem to be the most suitable for WSNs (Vuran & Akyildiz, 2009). However, even though decoding can be done in low complexity, the encoding process is typically computationally intensive and requires special purpose digital signal processors. Hence, most sensor systems are not using any kind of FEC currently. Instead, only Cyclic Redundancy Check (CRC) is used for error detection, where a check sum is calculated from the raw data using a predetermined code.

### 2.3 Antenna Diversity

Co-existence of high power wideband wireless local area networks (WLANs) and low power wireless sensor networks on unlicensed ISM bands is challenging. Several studies have investigated the coexistence problem of IEEE 802.11 family radios (WLAN) and IEEE 802.15.4 (WSN) radios, see e.g. (Polepalli et al., 2009). The general conclusion is that coexistence on the same band is possible if there is enough spatial separation between the systems or channel utilization of the WLAN is below a certain threshold. In case of IEEE 802.11b/g transmitters, three IEEE 802.15.4 channels are “sub-orthogonal” to the WLAN channels. That is, they only experience adjacent channel interference which is at least 30 dB lower than the interference on the signal band. For IEEE 802.11n, the situation gets worse and there could be only a single IEEE 802.15.4 channel which experiences solely adjacent channel interference. Hence, in the worst case, there could be only one channel available for IEEE 802.15.4 sensor network operation which should be utilized as efficiently as possible. Because of the propagation environment antenna diversity could be utilized to mitigate the effects of fading and guarantee reliable packet delivery.

Potential of spatial diversity has not been fully exploited yet in wireless sensor networks and only some efforts have been done in this direction. In (Shin et al., 2007) experimental results to evaluate channel dynamics and delay spread of 2.4 GHz systems in an indoor multipath environment are presented whereas in (Shuaib et al., 2006), a dual band double-T printed monopole is developed and tested for 2.4 GHz and 5.2 GHz operating frequencies. Therefore, to assess the physical properties of a real radio environment and investigate the

use of antenna diversity in WSNs, measurements using real nodes were carried out in an industrial warehouse.

The measurement setup consists of a sensor node equipped with a CC2431 (802.15.4 PHY) radio module connected to an Anritsu 50  $\Omega$  2.41-2.45 GHz portable antenna. Four receivers (compact ceramic antennas) are arranged in an array and placed at distance of 0.0625 m from each other, which is half the wavelength at 2.4 GHz. Channel 26 is used since it experiences minimal interference from other wireless devices and fading is the main cause of packet drops. Fig. 1 shows the percentage of packet drops experienced by different receivers. The data is collected at 3 different industrial environments and since the antennas are at least half a wavelength apart from each other, each receiver sees independent fading. Therefore, the percentage of successful packet reception varies for each receiver and in each location different antenna gives the best performance. Thus, we conclude that use of antenna diversity significantly improves the reliability of WSNs if the antenna which experiences the least packet drops is chosen. Antenna diversity can be utilized if the sensor nodes are large enough so that at least two antennas can be fitted or an external antenna attached to the node and can be easily implemented on any commercial radio simply by applying a RF switch.

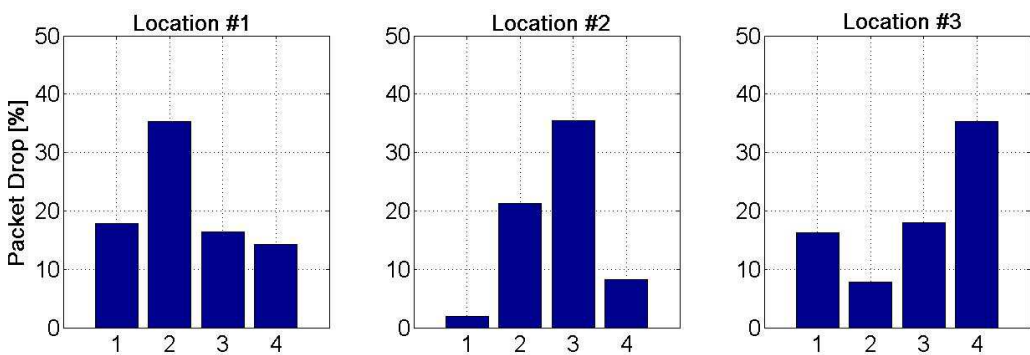


Fig. 1. Measurement data from a field test at an industrial warehouse. Indexes on x-axis represent individual antennas.

2.4 Summary

In this section we discussed several physical layer solutions which impact on reliability in wireless communication systems. First of all, the chosen bandwidth should be large enough such that narrow band interference does not deteriorate the performance significantly. Moreover, spread spectrum techniques enable low transmission powers and simultaneous multi-user spectrum access on the same frequency band. We also showed measurement results from industrial environments which imply that antenna diversity should be exploited in WSNs to guarantee sufficient packet delivery ratios regardless of the receiver’s location.

3. MAC Protocols for Guaranteed Access

The main objective of the Medium Access Control (MAC) layer is to enable collision-free transmissions in an efficient manner. During the development of WSNs, research efforts in

the field of access mechanisms for single-channel wireless sensor networks have been extensive. However, the performance of WSNs could be improved by exploiting multiple frequency channels simultaneously to ensure robustness, minimize delay and/or enhance throughput. Naturally, special characteristics of WSNs have to be taken into account while designing suitable MAC protocols such as limited transmissions powers, available energy and hardware abilities. Various WSN applications have distinct requirements for a MAC protocol. For example, real-time applications have strict delay constraints while in some applications it is important to maximize network lifetime. Nevertheless, for all applications it is extremely important to ensure reliable packet delivery which can be enhanced on the MAC layer by providing collision-free transmissions. With these issues in mind it is justifiable to have a generic MAC solution that can be tuned depending on the requirements of a particular application to enable economic success of WSNs instead of designing a new protocol for each emerging application.

In principle, orthogonal data transmissions can be achieved using various traditional methods. First of all, Frequency Division Multiple Access (FDMA) technique distributes data transmissions on different frequency bands which are orthogonally spaced, i.e. bands do not overlap. Moreover, the main purpose of Time Division Multiple Access (TDMA) schemes is to avoid collisions by ensuring that each user has its own time slot when to transmit data. Combination of FDMA and TDMA is used for example in GSM systems to provide orthogonal multi-user access. In case of spread spectrum systems Code Division Multiple Access (CDMA) can be exploited. In CDMA each user has its own orthogonal spreading function to provide efficient packet reception at the receiver. Third generation mobile phone systems exploit CDMA to enable spectrum access for multiple users simultaneously.

In order to assure proper and effective use of both single- and multi-channel communications, channel ranking is required to find out the most suitable channels for transmissions. In this section we first consider single-channel MAC protocols designed especially for WSNs. Secondly, the most common multi-channel MAC approaches for ad hoc networks will be reviewed. In the end we present our novel multi-channel MAC design along with a new channel ranking algorithm. We show theoretical and simulation results to justify our approaches.

### 3.1 Single-Channel MAC Solutions

Since present WSN implementations are able to utilize only one carrier frequency at a time, most of research work has concentrated on single-channel systems. In consequence, innumerable single-channel MAC protocols have been proposed for WSNs exclusively. We direct an interested reader to see (Bachir et al., 2010) for a comprehensive literature review on the topic. Usually single-channel MAC protocols are divided into the following classes based on the operation characteristics. Scheduled MAC protocols utilize TDMA on a single frequency whereas contention-based MAC algorithms do not reserve resources in advance. In addition, hybrid MAC schemes aim to exploit the benefits of both approaches to optimize the performance.

Scheduled algorithms divide time into multiple time slots such that only a single transmission can take place in a collision domain. The strength of this kind of approach is that in case of stable channel conditions, fixed network topology and periodic packet arrivals, transmissions can be scheduled in an optimized manner and no overhead is induced due to resource negotiations. Ideally scheduled systems do not suffer from collisions and can guarantee fixed delays, however, such systems require precise time synchronization which complicates system design. In general scheduled MAC protocols perform well under high traffic loads while suffering from network topology changes, irregular generation of packets and inaccurate timing.

Traditional contention-based MAC schemes used in wireless systems are ALOHA and Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). The basic operation of ALOHA is simple. If a node generates a packet it will try to transmit immediately. In case of a collision the packet is delayed and retransmitted later on. To improve the throughput time can be divided into multiple time slots such that packets can be sent only in the beginning of a time slot. On the other hand, CSMA/CA systems first sense the channel to see whether it is idle or not and then exchange resource request and response messages before the actual data transmission. This kind of message exchange mainly eliminates the *hidden node problem*, which means that several nodes that cannot hear each other transmit simultaneously leading to packet collisions at the receiver, experienced by ALOHA. Although CSMA/CA is widely used in different wireless systems, such as in IEEE 802.11 networks, its performance degrades under high traffic loads.

A hybrid MAC solution is used in IEEE 802.15.4 networks which consists of beacon periods, Contention Access Periods (CAPs) and Contention Free Periods (CFPs). The beacon period is used to distribute general information about the network, frame structure and so forth. During CAP nodes that do not have enough resources can compete for transmission opportunities using CSMA/CA and CFP is reserved for periodic messaging. The frame structure also allows inactive periods if there is nothing to be sent. While a node is idle it can turn its radio off and sleep to minimize energy consumption.

### 3.2 Multi-Channel MAC Approaches

Due to the challenging nature of radio channels and coexistence of various systems on unlicensed frequency bands, multi-channel communications can be utilized to enhance reliability of wireless networks. Since only a few multi-channel MACs have been designed especially for WSNs, we discuss the main approaches proposed for ad hoc networks in this subsection. In general, existing multi-channel MACs can be divided into four main classes, namely split phase, common hopping, parallel rendezvous and dedicated control channel.

Dedicated control channel schemes (Wu et al., 2000) tune one receiver on the chosen common control channel to avoid the *multi-channel hidden node problem*, which occurs if the channel usage of neighbor nodes is not known and nodes choose to transmit on a busy channel, and use a transceiver to carry out data transmission on different channels. In split phase based random access approaches the operation is divided into two parts. First, during the contention period nodes reserve resources on the chosen common control channel and afterwards, data transmissions will take place during the data period (So & Vaidya, 2004).

On the other hand, the basic idea behind common hopping approaches is to use periodic channel hopping on every channel in order to avoid availability and congestion problems of the common control channel (Tzamaloukas & Garcia-Luna-Aceves, 2000). Furthermore, the fundamental concept of parallel rendezvous approaches (So et al., 2007) is that all the nodes employ individual predetermined hopping patterns. If a node wants to transmit a packet, the node tunes onto the receiver's hopping pattern and the RTS/CTS message exchange and data transmission will be carried out on the receiver's current channel or alternatively by continuing the receiver's hopping pattern, depending on the protocol in question.

Since dedicated control channel schemes require one additional receiver, the approach is not suitable for simple, low-cost WSNs. Performance of different approaches was studied in (Mo et al., 2008) by performing theoretical analysis and simulations with respect to throughput and delay in a single collision domain. Results show that parallel rendezvous approaches outperform common hopping and split phase approaches in a single collision domain. However, parallel rendezvous approaches are unable to neither dynamically adjust to changes in radio environment since the hopping patterns are predetermined nor allow sleeping. The same applies to common hopping approaches as well. The difference in performance of common hopping and parallel rendezvous approaches is due to the fact that after a transmission the channel can be immediately reused in parallel rendezvous approaches while in common hopping approaches the channel cannot be reused until the hopping cycle reaches this particular channel again. The main problem with split phase based schemes is that a fixed part of the frame cycle is reserved for resource negotiations which causes throughput degradation and incurs additional delay. If a packet is generated during a data period, it has to wait at least until the beginning of next data period to be sent. Since delay is of significant importance in various wireless applications, we have designed a novel, delay efficient multi-channel MAC which will be presented next.

### 3.3 Generic Multi-Channel MAC Protocol

The proposed Generic Multi-channel MAC (G-McMAC) protocol is a hybrid CSMA/TDMA protocol for multi-channel systems which is scalable with respect to packet transmission delays and throughput. In G-McMAC, contention and data periods are merged to minimize delays. G-McMAC is presented in (Nethi et al., 2010) in detail along with a comprehensive set of simulation results and here we only summarize operations of the protocol and show some of the simulation results.

The operation of the protocol is divided into two segments: Beacon Period (BP) and Contention plus Data Period (CDP). Common Control Channel (CCC) can be used for data transmissions if the amount of available channels is otherwise small. If the CCC is used for data transmissions, delay constraints have to be relaxed since in that case secondary contentions can be performed rarely. G-McMAC uses the following messages: Beacons are sent periodically in order to keep time synchronization accuracies under control and routing information up to date, Resource Request (RsREQ) messages are used for making resource requests and Resource Acknowledgment (RsACK) messages are used for responding to the resource requests. Nodes have to sense the desired data channel before data transmissions to avoid the multi-channel hidden node problem. Fig. 2 shows the operation principles of G-McMAC for clarity.

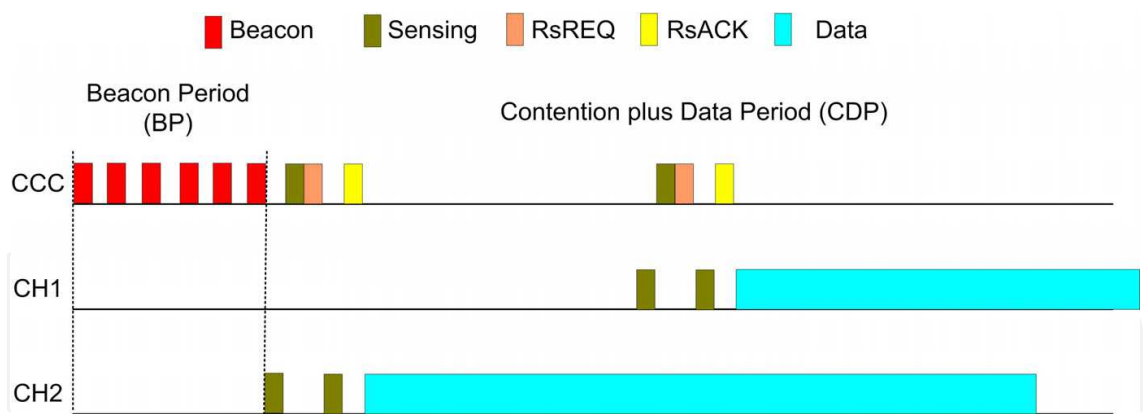


Fig. 2. Demonstration of G-McMAC functionalities.

We implemented G-McMAC on ns-2 (ns-2, 2010) and simulated a real-world industrial warehouse scenario. The scenario considers co-existence of three applications in an industrial environment: Crane Control System (Grey), Machine Health Monitoring System (Red) and Cooling system (Green), as indicated in Fig. 3. Typical communication constraints for Crane Control System (CCS) include a 500ms upper bound for delay and the Gateway (GW) should receive packets from all its sensors within this time limit. Failing to do so results in noticeable delay by the crane operator and the crane will shutdown. If the GW receives a response from all the sensors within 500ms after the polling is initialized, the attempt is considered as successful. In our scenario CCS is the primary network because of the strict delay requirements while Machine Health Monitoring System (MHS) and Cooling System (CS) have lower priority, i.e. they will compete for the rest of the resources. MHS monitors vibrations of the machine structure and in case of MHS, a successful attempt corresponds to MHS gateway node receiving current data sets from all the nodes on the Lathe machine in time. In addition, we also have sensors reporting the measured temperature values to the cooling system. The cooling unit controls temperature in the warehouse through air conditioning system. IEEE 802.15.4 radios are used for wireless communications. Fig. 3 illustrates the scenario.

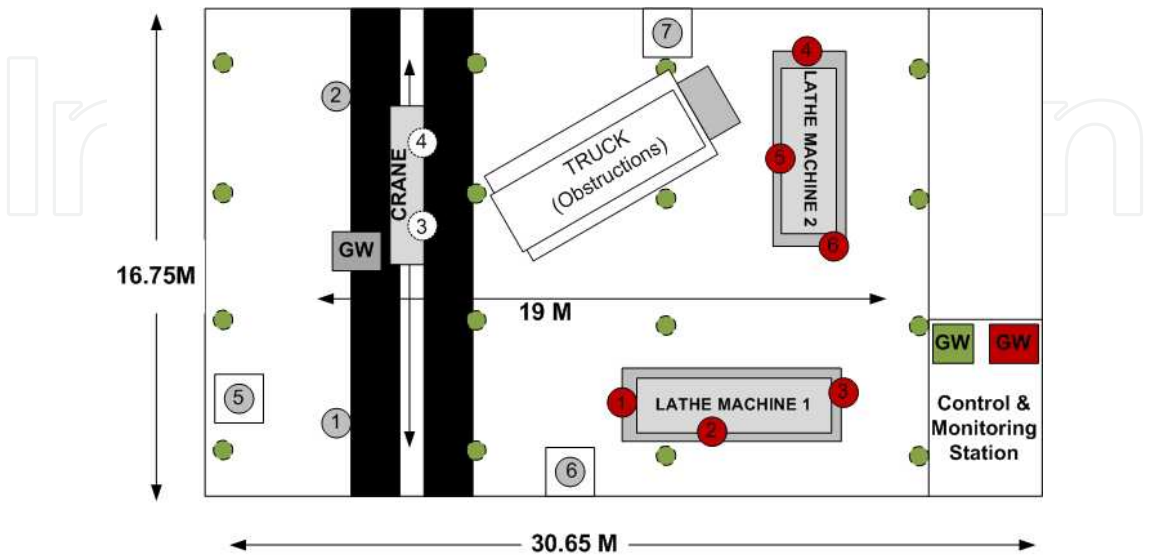


Fig. 3. Demonstration of the simulated industrial warehouse scenario.

The corresponding results for G-McMAC are presented in Fig. 4. CCS maintains high success rate for low channel resources and the performance improves as the number of available channels increases. On the contrary, since MHS is a low priority application, scarcity of channel resources leads to low performance. While the performance of MHS improves as the number of available channels grows, the performance of the cooling system deteriorates since MHS throttles the throughput of the cooling system.

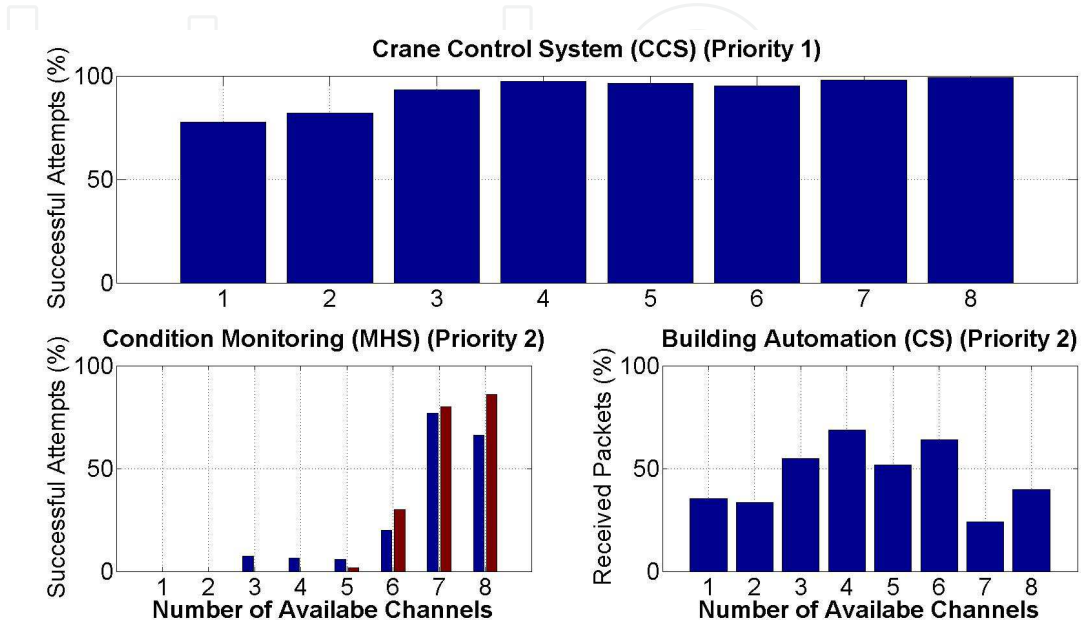


Fig. 4. Simulation Results using G-McMAC.

We have also compared the performance of different multi-channel protocols in case of Poisson arrivals in (Nieminen & Jäntti, 2010). In the paper we studied delay-throughput characteristics of various approaches and derived closed-form equations for different schemes by assuming fixed packet sizes. Time was divided into small time slots for the analysis and we verified the correctness of theoretical results by simulations using Matlab. Some of the results are depicted in Fig. 5. We denote the number of available channels by  $N$  and  $T$  is the packet size (in time slots). The results in Fig. 5(a) undoubtedly prove that G-McMAC outperforms other approaches in terms of delay regardless of the number of available channels, packet arrival rate or packet size. In case of Poisson arrivals, the delay of parallel rendezvous approaches is equal to the delay of common hopping approaches. Since the delay of split phase approaches is very high in case of Poisson arrivals, we only compare the throughput of G-McMAC to common hopping approaches in Fig 5(b). As we can see, G-McMAC achieves the highest throughput in many cases. However, in some cases other approaches may offer higher throughput. The performance of the different approaches is discussed in the paper more in depth. Nevertheless, since access delay is the most important parameter for many WSN applications, we conclude that utilization of G-McMAC is feasible in multi-channel WSNs.

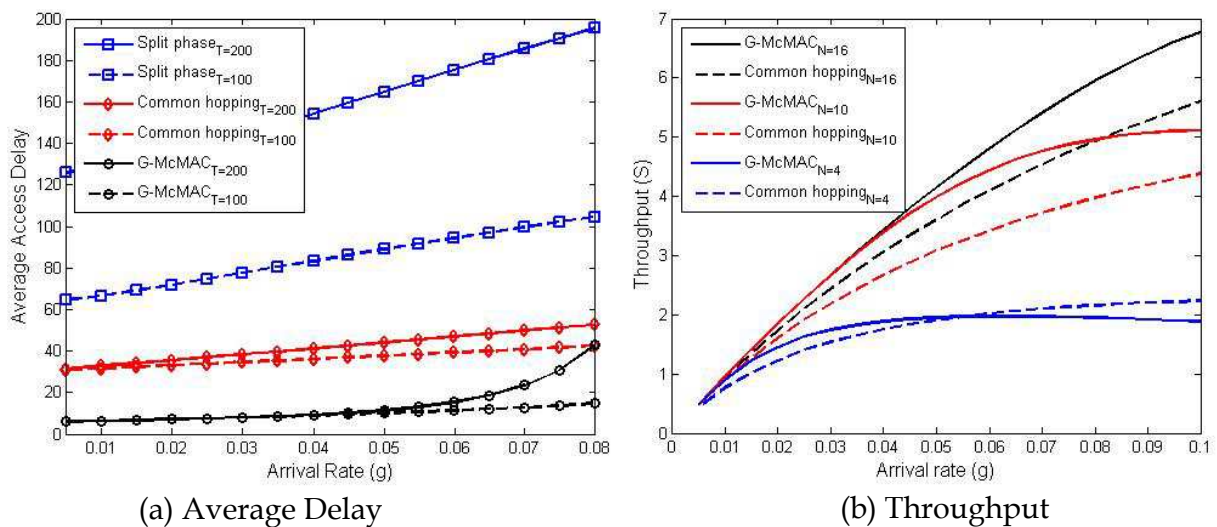


Fig. 5. Performance comparison of different multi-channel approaches.

### 3.4 Channel Ranking

A sensor network can experience interference in temporal and spatial domains on all the available channels which causes performance degradation. The solutions posed for such situations must efficiently incorporate interference avoidance schemes which are suitable for resource constrained wireless sensor networks (Stabellini & Zander, 2010). For interference avoidance, a single-/multi-channel sensor network must be able to identify the channel(s) offering relatively higher temporal and spatial gaps. This task requires designing the interference characterizing estimator algorithms that can evaluate the impact of temporal occupancy and signal level of a channel and combine the two estimates in a smart way to find an accurate relative channel ranking.

Channel ranking can be performed in an active or passive manner. The active approach, link level interference characterizing model PDR-SINR (Sha et.al., 2009), correlates the PDR with SINR by using the active measurement packets. It is an accurate approach in capturing any link dynamics in the presence of interference, however, it incurs high convergence time and overhead. Moreover, this model is not available during network initialization. A passive scheme to identify the spectrum access opportunities is spectrum sensing. Spectrum sensing allows exploiting the degrees-of-freedom in spatial separation and temporal gap of available channels and achieving orthogonality against the interference (Geirhofer, 2008).

In (Mahmood & Jäntti, 2010), we propose a channel ranking scheme based on spectrum sensing in the presence of WLAN interference. It estimates the interference estimators, activity factor and strength from a receiver centric perspective. Since during network initialization the link qualities are not known, the impact of interference estimators on a sensor location cannot be identified. Therefore, a design of generic consensus is required to weight and combine the two interference estimators according to their impact. Assuming  $p(c_i)$  and  $P(c_i, s_i)$  the channel occupancy and the signal strength of interference respectively on a channel  $c_i$  as perceived by a sensor at location  $s_i$ , the interference vector can be written as a function of the interference estimators as

$$\psi(c_i, s_i) = f(w_p \rho(c_i), w_p P(c_i, s_i)) \quad (1)$$

where  $w_p$  and  $w_p$  are the desired weights of the temporal occupancy and strength level. In order to find the channel ranking based on the influence the two estimators have on the suitability of the channels, a decision theoretic approach (Saaty, 1980) can be used which allows defining the impact of the interference estimators on the fitness of a channel to establish channel ranks. We found that two distinct decision rules for weighting the interference estimates can be derived by using theoretical PDR-SINR performance model. The rules are independent from the PDR-SINR model and a transition boundary governs the transition between the rules depending on the spread of the strength level estimator of the interfered channels. The rules are applicable without loss of generality to any modulation type employed by the sensors which makes the proposed method unique.

The decision rules on weighting the interference estimators are set according to the strength level estimator of the channels. Provided the strength level at a location for candidate channels is less than 1.4 dB, the two interference estimators must be weighted equally to minimize the ranking error. These channels are called as Type-I channels. Otherwise, strength estimator must be weighted 6-7 times more than the activity estimator. We call these channels as type-II channels. The ranking error determined for these channel types with respect to different scaling factors of interference estimators is shown in Fig. 6(a). The trend line shows the average ranking error for each channel type and the vertical bars along each the line indicates the confidence interval of ranking error. The possibility to find a single best channel by assigning these scales is shown in Fig. 6(b) where check mark (✓) indicates the best channel is found independent of the weight preference to any estimator otherwise it is crossed (x). The results are based on a real-world measurement campaign performed in the university campus area at Aalto University.

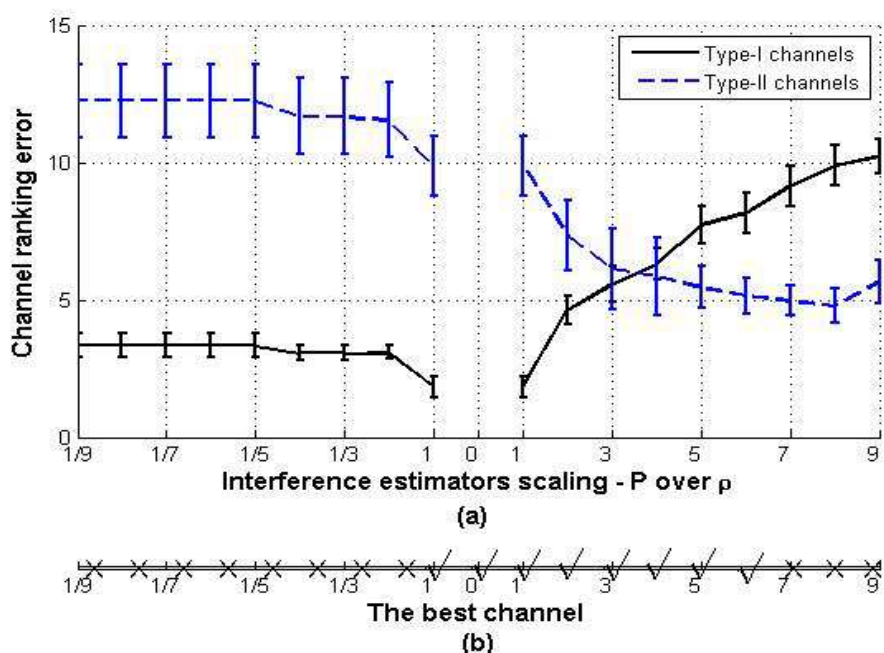


Fig. 6. Channel ranking error for two channel types with respect to the preference scale of interference estimators.

### 3.5 Summary

In the beginning of this section general aspects of MAC layer design were discussed. Then, we reviewed the most common single- and multi-channel approaches and concluded that for guaranteed medium access, multi-channel communications are required. After this, our proposed multi-channel MAC protocol designed especially for WSNs, named Generic Multi-channel MAC (G-McMAC), was introduced along with theoretical and simulation results to demonstrate the performance. Finally, we considered the importance of channel ranking in WSNs. In this case a novel algorithm was presented along with measurement results.

## 4. Network Layer and Reliable Routing

Routing in WSNs has specific requirements which means that routing protocols have to take into account such factors as limited bandwidth, variable capacity of radio links and energy-efficiency. Therefore, it is not a trivial task to find a path from one node to a possibly distant destination node if the network topology is dynamic, individual nodes are unreliable and only the nearest neighbors can be reached directly. Since wireless sensor nodes can communicate only with their nearest neighbors because of power limitations, a connection between two nodes often uses several intermediate nodes as relays (multi-hop connection). In general, the main objective of WSN routing protocols is to enable reliable communications between nodes while minimizing power consumption in order to prolong network lifetime. Supporting real-time communications with given delay bounds is also extremely important since some applications need to rapidly respond to sensor inputs. Added to this, practical algorithms should provide robustness against link failures, e.g. by performing multi-path routing, and track changes in the network topology in case of mobile nodes to ensure connectivity.

Routing solutions for other types of networks (e.g. wireline, MANET) cannot be employed directly since they have limitations regarding the WSNs. Nevertheless, due to the importance of routing, the topic has been widely studied and countless protocols have been proposed (Al-Karaki & Kamal, 2004). In this section we will overview some of the proposed solutions for WSNs by focusing on the main routing classes: hierarchical, multipath and flat routing. We also introduce a novel routing protocol which is designed particularly for WSNs. The main benefits of the proposed protocol are that it can be easily implemented on ZigBee and it outperforms the currently used protocol which is shown by simulations.

### 4.1 Classification of Routing Protocols in WSNs

Hierarchical routing is based on the creation of clusters and the assignment of different tasks to cluster heads and other nodes. Hierarchical approach allows more complicated data processing operations to be carried out by cluster heads. Due to data aggregation and fusion in the cluster heads, the number of transmitted messages in the WSN can be significantly reduced and hence, the energy efficiency increased. As a representative of hierarchical routing methods in WSNs, we consider the Ripple-Zone (RZ) routing scheme (Hu et al., 2005) where sensors are assigned to different ripples based on their distances in number of hops from the actuator. In each ripple, some sensors are chosen as masters based on the Topology Discovery Algorithm (TDA) previously proposed by the authors. Each master

collects data from the sensors in its zone and then transmits data to a master in the next ripple that is closer to the actuator. In the paper, authors show that the protocol is energy efficient, reliable and scalable. Moreover, it can adapt to changing network topology by employing the local link failure repair method. However, the cases where several actuators are interested in the same sensed data and coordination issues among actuators were not taken into account. The performance of the scheme in terms of latency, which is a crucial issue in real-time WSN applications, was neglected in the study as well.

An example of the flat routing approach is the Delay-Energy Aware Routing Protocol (DEAP) (Durrezi et al., 2005) which is designed for heterogeneous sensor and actuator networks. The major components of DEAP are loose geographic routing protocol based on Forwarding sets, which in each hop distributes the load among a group of neighbor nodes and the Random Wakeup Scheme (RAW) that controls the wake up cycle of sensors based on experienced packet delay. DEAP combines routing and sensor wake-up schemes and finds a trade-off between transmission delays and energy consumption. It is also capable of adapting to changes of network topology and takes advantage of actor nodes by using their resources when possible. Furthermore, Scalable Source Routing (SSR) proposed in (Fuhrmann, 2005) is a fully self-organizing protocol for efficient routing in large random networks. In the paper, the authors also point out disadvantages of routing schemes based on source routing bridges and shortest path routing (link state or distance vector) and come to the conclusion that these techniques must be avoided to obtain the desired efficiency.

As the name indicates, multipath routing protocols use multiple paths instead of a single path in order to enhance network performance and reliability. Successful delivery of data is ensured by exploiting optional paths if primary paths fail. By transmitting the same packet over several different paths, the probability of successful packet delivery can be increased at the cost of increased energy consumption and traffic overhead (Al-Karaki & Kamal, 2004). Another advantage of multipath routing is load-balancing, where traffic between a source and destination is split across multiple (partially or completely) disjoint paths. Load balancing spreads energy utilization across nodes in a network and this way prolongs its lifetime. Multipath routing is a promising approach for WSNs since high node densities allow utilization of multiple paths with similar costs. Most of the up-to-date multipath routing schemes are either targeted to find a number of disjoint routes or energy efficient routes (Ganesan et al. 2001; Li & Cuthbert, 2004; Popa et al., 2006). In these schemes, load is either distributed or sent on the best (e.g., most energy-efficient, best in QoS, etc.) path. In the first case, i.e. distributing load over multiple paths, the destination node has to cope with synchronization of arrival packets. Choosing the best path could avoid synchronization issues but the process easily drains out batteries of the participating nodes because the source node continuously uses the particular path until the link breaks. Because of these issues we propose a novel routing algorithm which gives the source and intermediate nodes freedom to choose from multiple local paths to the destination based on a cost function.

#### **4.2 Localized Multiple Next-hop Routing (LMNR) protocol**

The design of the ZigBee routing scheme is based on the Ad-hoc On-demand Distance Vector (AODV) (Perkins & Royer, 2001). AODV is an on-demand routing algorithm, meaning that the routes are established only when there is information to be sent and

maintained as long as they are needed for communication. Route freshness is ensured by using sequence numbers. AODV is loop-free, self-starting, and scalable. In AODV, if a source node does not have information about a destination node in its routing table, it initiates the Route Discovery procedure. The procedure starts by broadcasting a Route Request (RREQ) packet to the neighbor nodes. The RREQ automatically sets up a reverse path to the source from all intermediate nodes lying on the path from the source to the destination. The destination node sends a Route Reply (RREP) after receiving the first RREQ. Each intermediate node forwards the RREP to its predecessor until the RREP arrives at the source node. Meanwhile, each node (including the source node) having received the RREP establishes a route entry in its route table.

In Localized Multiple Next-hop Routing (LMNR) (Nethi et al., 2007c) we classify all the paths between a source-destination pair into two types: I) node disjoint paths and II) local paths. Instead of sending packets parallel using solely disjoint paths, the used paths can be selected locally. The novelty is that the source and intermediate nodes are given freedom to choose from multiple local paths based on a cost function. This will reduce delay and routing overhead which improves the network performance. HELLO messages of AODV are used to update the cost of each individual node. Since LMNR uses existing information in AODV and does not require any change in routing packets, the protocol is able to co-exist with AODV and easy to implement on ZigBee based systems. Our algorithm also adapts to topology changes by monitoring the activity of the neighbors. If the next hop on the path is unreachable, an unsolicited RREP with a new sequence number is propagated through the upstream of the break. Moreover, if the source node still requires a route to the destination, it can restart the discovery procedure. Since AODV restricts intermediate nodes to have a single route to the destination, link stability becomes a problem. Consequently, the delivery performance is degraded and reliability is compromised. We modify the route discovery process to incorporate multiple routes such that when a node receives another copy of RREQ from the same source, it will check the routing table as follows

1. If the new RREQ has a smaller hop count (i.e., shorter distance to the source node), it updates the route entry as original AODV does.
2. If it equals to the one(s) in route table, the node simply adds a new route (multipath to source).

By this mechanism, alternate (and equal hop count) paths at each intermediate nodes for one source-destination communication pair will be found. Furthermore, dynamic adjustment should be considered so that the intermediate nodes either shall not drain out all their energy or alleviate and balance the routing load. For this purpose we modify the AODV neighbor table, and introduce a new metric *Node Cost* (NC), which is put into the neighbor table. Actually the node cost function can be chosen from the following metrics (or a combination of them): outgoing queue buffer occupation ratio, congestion measurement which is proportional to the MAC layer contention (backoff) window size, measure of routing table size and freshness of route entries and/or packet leaving rate at the network layer outgoing queue. For more detailed information about the operations see (Nethi et al., 2007c).

With the knowledge of the routes each intermediate node can now avoid using (next-hop) nodes which have higher cost function, without increasing the number of hops to the destination. However, it is possible that for a given intermediate node all of its next-hop nodes may have very high cost. To cope with this problem, a back-propagation mechanism is introduced. The back-propagation logic can be described as follows. If a node sees that all its next hop nodes' costs are greater than the given threshold, the node will back propagate this update to its preceder so that the preceder is able to give up using this path. Once the RREQ-RREP procedure is completed, the source-destination pair and intermediate nodes involved will select a single path amongst all the available (local) paths.

4.3 Simulation Results

We implemented LMNR on ns-2 (ns-2, 2010) and carried out simulations to see how much gain LMNR achieves compared to AODV in practice. In the simulation scenario 50 nodes, which use IEEE 802.11 radios for communications, were randomly positioned on a grid. 10 source-destination pairs are randomly selected and each source generates Constant Bit Rate (CBR) traffic flows with the given packet rate (packets/second). The used NC metric was based on the size of routing tables and freshness of routes. Simulation setup is explained in (Nethi et al., 2007c) in detail and some of the results are depicted in Fig. 7. Fig. 7(a) compares the performance of the protocols with respect to end to end delay and as we can see, our scheme outperforms AODV clearly as traffic loads increase. The reason behind this is that LMNR can always find an optimal path due to the dynamic local next-hop selection mechanism. On the contrary, in AODV only one route is established which means that a new route-finding procedure is initiated in case of congestion. This can be also verified by Fig. 7(b), which shows the packet delivery ratios of the two routing protocols. LMNR is better than AODV at medium traffic loads whereas the performance is similar with low and high traffic volumes. This is because of the fact that LMNR tries to find a better next-hop path instead of initiating a Route Error (RERR) as AODV does. As traffic load increases, the entire network becomes saturated and hence, the performance of both protocols decreases.

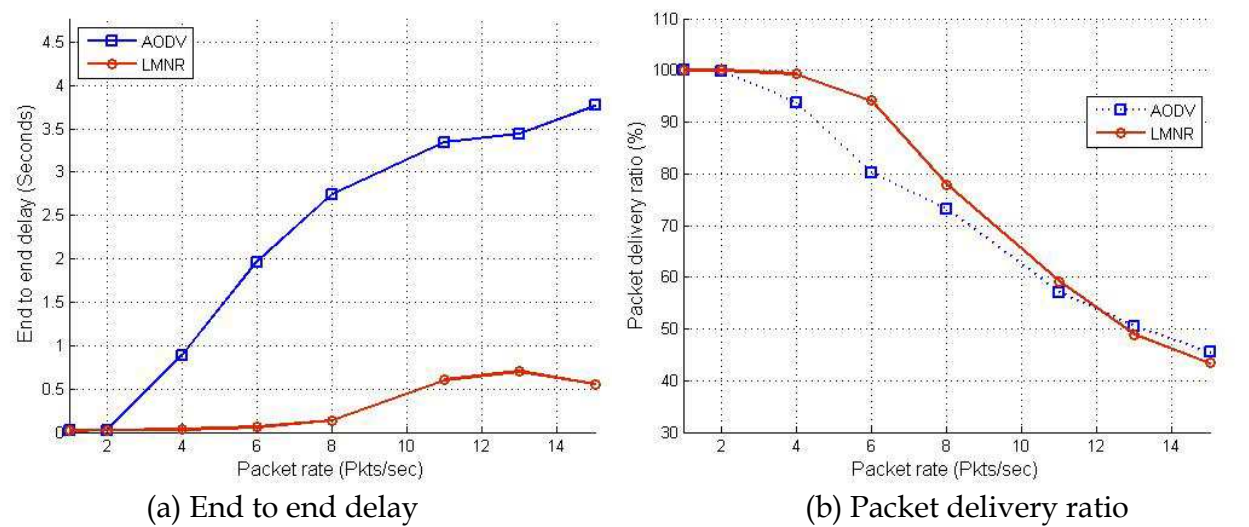


Fig. 7. Performance comparison between LMNR and AODV.

The simulation results show that LMNR outperforms AODV in terms of end to end delay. Furthermore, the results also indicate that the link failure resilience of LMNR is higher compared to the conventional AODV routing protocol since less packet drops are experienced with moderate traffic loads. LMNR requires only minor modifications on AODV and thus, the proposed protocol can be used, for example, in legacy ZigBee systems.

#### 4.4 Summary

In this section, we focused on network layer operations and considered the main problems related to routing in WSNs. We categorized routing approaches into three categories: hierarchical, multipath and flat routing. Pros and cons of each approach were analyzed and an example algorithm was given for each class. We drew a conclusion that the use of multipath routing is feasible in WSNs because of high node densities due to which there exists many paths with similar cost. Multipath routing enables transmission of multiple packet copies over multiple paths and load-balancing. Finally, we presented a novel routing algorithm which can be easily implemented on ZigBee, called Localized Multiple Next-hop Routing (LMNR), and demonstrated the achievable benefits by simulations.

### 5. Performance of Various Applications with Communication Co-Simulation

In addition to the theoretical results, co-simulation of the communication and application is important and necessary for several reasons. Simulations are a feasible way to test and evaluate wireless applications, such as sensor networks, distributed data processing algorithms, and wireless control systems. With simulations, the critical properties and behaviour of the network, and the impact on the application can be analyzed. Problems occurring in the network and the reaction and resulting performance of the algorithms to these issues can be studied. These issues, in particular the protocol specific ones, are hard to be approached analytically. Especially the study of wireless networked control systems (WiNCSs) benefit from co-simulation, where the real-time requirement of control is affected by the unreliability of wireless communication.

Simulation of wireless applications with a specific network protocol is thus needed. Therefore, the network and control co-simulator PiccSIM (Nethi et al., 2007a) has been developed. PiccSIM is aimed at communication and control co-simulation, especially for the study of WiNCSs. In PiccSIM, specific network protocols and control algorithms can be studied. The strength of PiccSIM is to enable one to quickly test several control algorithms in realistic WiNCS scenarios. In the following sections PiccSIM is described in more detail and some simulation cases are presented that show the benefits of co-simulation for WiNCSs design. The simulation cases involve multiple networked control loops, which cannot be studied without co-simulation.

#### 5.1 PiccSIM

PiccSIM integrates two simulators to achieve an accurate and versatile simulation system at both the communication and control level for WiNCSs. PiccSIM stands for *Platform for integrated communications and control design, simulation, implementation and modeling*. It has the unique feature of delivering a whole chain of tools for network and control modeling and

design, integrated into one package with communication and control co-simulation capabilities. The PiccSIM simulator is an integration of Matlab/Simulink where the dynamic system is simulated, including the control system, and ns-2, where the network simulation is done. The PiccSIM Toolchain is a graphical user interface for network and control design, realized in Matlab. It is a front-end for the PiccSIM simulator and delivers the user access to all the PiccSIM modeling, simulation and implementation tools (Kohtamäki et al., 2009).

There are already some suitable simulators for WiNCSs, such as TrueTime (Cervin et al., 2003) and Modelica - ns-2 (Al-Hammouri et al., 2007). Modelica/ns-2 is a very similar platform to PiccSIM. As in PiccSIM, the network simulation is done in ns-2, but the plant dynamics and the control simulation are done in Modelica. The simulation is controlled by ns-2 and the traffic is defined beforehand, so event-driven communication is not possible, contrary to PiccSIM where Simulink controls the communication based on the outcome of the dynamic simulation model. Perhaps the most well-known Simulink network blockset is TrueTime, which is actively developed at the Lund University, Sweden. It supports many network types (Wired: Ethernet, CAN, TDMA, FDMA, Round Robin, and switched Ethernet, and wireless networks: 802.11b WLAN and IEEE 802.15.4) and it is widely used to simulate wireless NCSs (Andersson et al., 2005). Besides the dynamic system simulation offered by Simulink, network node simulation includes simulation of real-time kernels. The user can write Matlab m-file functions that are scheduled and executed on a simulated CPU.

Two wireless node operating system simulators, TOSSIM (Levis et al., 2003) and COOJA (Österling et al., 2006), are worth mentioning. Both are sensor node operating system simulators, which simulate the code execution on the wireless nodes. They have simple range-based network propagation models to allow simulation of many nodes communicating with each other. They do not specifically support control system simulation, but complete wireless applications can be simulated with these tools, including input/output for sensing and actuation.

## 5.2 PiccSIM Architecture

The PiccSIM simulator consists basically of two computers on a local area network (LAN): the Simulink computer for system simulation, including plant dynamics, signal processing and control algorithms, and the ns-2 computer for network simulation. For further details see (Nethi et al., 2007a), where the integration of ns-2 and Simulink is reported, and (Kohtamäki et al., 2009) for the description of the PiccSIM Toolchain. The network is simulated in PiccSIM by the ns-2 computer. Packets sent over the simulated network are routed through the ns-2 computer, which simulates the network in ns-2 according to any TCL script specification generated automatically by a network configuration tool based on the user-defined settings. Simulation time-synchronization is performed between the computers.

Since PiccSIM is an integration of two simulators, they are by definition separated. To close the gap between the simulators, a data exchange mechanism is implemented, which can pass information from one simulator to the other. This enables the simulation of cross-layer protocols that take advantage of information from the other application layers. An example where the data exchange mechanism can be used is with mobile scenarios. Ns-2 supports

node mobility, but natively only with predetermined or random movement. There exist, however, many applications, such as search-and-rescue, exploration, tracking and control, or collaborating robots, where the control system or application determines the node movement in run-time. In these cases the controlled node positions must be updated from the dynamic simulation to the network simulator. The updated node positions are then used in the network simulation, and they affect, for instance, the received signal strength at the nodes. Moving nodes will eventually cause changes in the network topology, which requires re-routing.

### 5.3 Simulation cases

With PiccSIM, simulation of systems involving many interacting wireless protocols and algorithms, for example multiple control loops, can be studied. The intricate interaction between the network, such as routing and traffic pattern, and the control system, including mobility, can only be assessed by simulation. The application generated traffic and network performance affect the outage lengths, packet drops, and delays, which affect the whole application in some particular way. The capabilities of the PiccSIM simulator are demonstrated here in three different scenarios to show how the application performance can be assessed with co-simulation.

The first case is a building automation application where the temperature and ventilation of an office is controlled using wireless measurements. This case focuses on the throughput, packet drops, and structure of the network. The second case is a robot squad, which moves in various formations. This case is more demanding for the wireless network, as the formation changes alter the topology of the network and re-routing must be done continuously to maintain the communication between the robots. These example cases have previously been presented in (Nethi et al., 2007b), and (Pohjola et al, 2009). It is notable that the performance of these control systems cannot be determined analytically beforehand.

An office with wireless control of the heating, ventilation and air conditioning is simulated. The layout of the office is shown in Fig. 8 with a total of 39 rooms. The temperature and CO<sub>2</sub> of the office rooms, which depend on the occupancy of the room, are modeled using first principles (Nethi et al., 2007b). The network is a wireless IEEE 802.15.4 network using the AODV routing protocol. Wireless sensors in each room measure the temperature and CO<sub>2</sub> concentration and additionally presence event messages are sent to the central command when people enter or exit a room. The central control system coordinates the heating and ventilation of the individual rooms based on the wirelessly communicated measurements. The local heating/cooling and ventilation commands are transmitted back to the rooms. The wireless network deals with both time and event-triggered messaging. Because of the quantity of nodes, multiple hops, radio environment, and random access MAC, there are packet drops, which impair the control result.

The temperature variation in each room depends on the movement of people in and out of the room and the compensation done by the control system. The case is simulated and compared to the control performance with perfect communication. Generally, the fewer measurements are dropped by the network the better the control result is. Fig. 8 shows the increase of the maximum deviation from the desired temperature when using the wireless

network for delivering the measurements. The results with one access-point are not satisfactory, so another access-point is added near room number 19. The access-points are connected with a high-speed backbone network. With two access points the communication quality is so good that no difference in the control performance from the case with a wired system is discernible. Thus, by designing the network to be reliable enough, the control application works equally well to perfect communication.

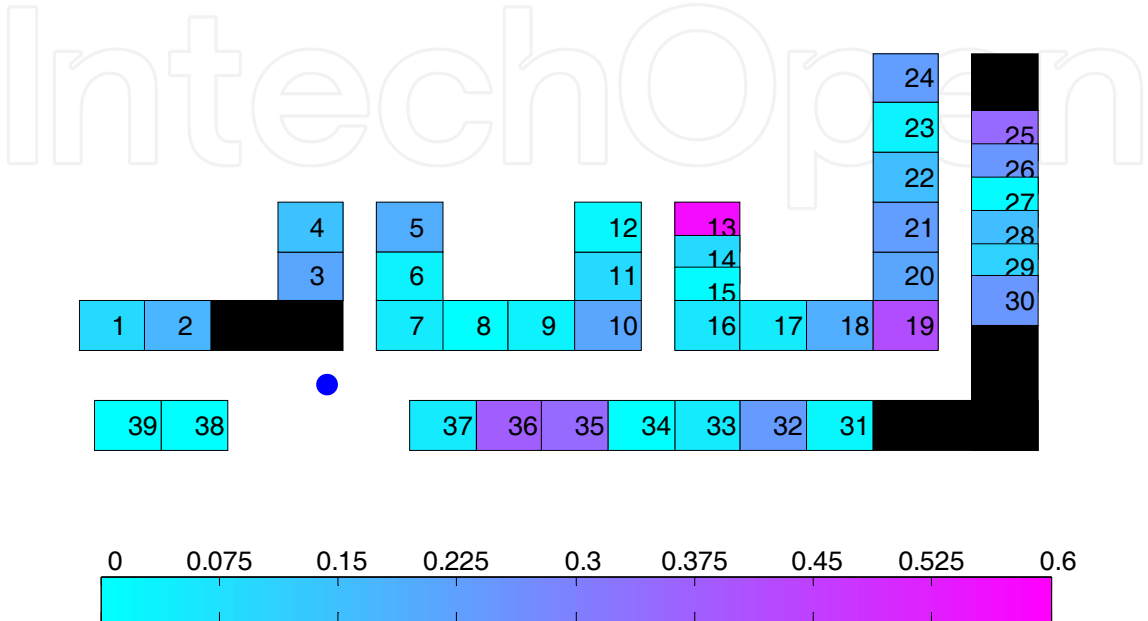


Fig. 8. Increase in maximum temperature error for wireless temperature control with one access point (blue dot) compared to perfect communication.

The second scenario considers a target tracking and control case with grid of nodes forming a static sensor network and a mobile wireless robot. The sensor network serves as an infrastructure network for transmitting measurement and control signals from/to the mobile node and providing a localization service. The objective for a centralized controller located at an edge of the infrastructure grid, is to control the mobile node according to a predefined track. On the control side a Kalman filter is used for filtering the mobile node position and predicting the position if the information is not available, due to packet drops. A PID controller is then used to control the mobile node. The control signal is routed to the mobile robot, which applies the acceleration command.

Nearby infrastructure nodes can measure their distance to the mobile node, for example by using ultrasound. The distances are transmitted to the controller. Using at least three distance measurements, the controller can determine the position of the mobile node by triangulation. By simulation it is noted that the requirement to receive three measurements from the same sampling interval is not always fulfilled. Hence the controller has to use data from older sampling instants for which more measurements have arrived, which causes trouble to the control application. A comparison between a singlepath routing protocol, specifically AODV and the LMNR multipath routing protocol is done in simulations. The simulation results listed in Table 1 show that the multipath routing protocol has better communication and control performance measures. The control performance is evaluated by

the integral of squared error (ISE) between the robot desired and actual position. This simulation shows that multipath is advantageous in some mobile scenarios, since at a link break it can quickly switch to a backup route (a counter-example is given next). Moreover, by combining these results (IEEE 802.15.4) with the results in Section 4.3 (IEEE 802.11 radios) we infer that LMNR performs well regardless of the used radio technology.

	Average delay [s]	Routing overhead [%]	Packet loss [% ]	Control cost (ISE)
AODV	0.08	8.1	23	18
LMNR	0.001	0.5	10	8.6

Table 1. Network and control performance metrics from the target tracking case

The third scenario is similar to the previous case and considers a squad of mobile wireless robots moving in various formations. A possible application is a search and rescue or exploration scenario. A leader robot controls the positions of the other robots. The assumption is that the robots can localize themselves based on GPS, odometer or inertia measurements. The robots transmit their positions to the leader robot. The leader then calculates the control signals for the locomotion, taking into account collisions and the final formation, and transmits, at every sampling time, the control message to the other moving robots. The communication is done over an IEEE 802.15.4 radio with a maximum communication range of 15 m. The communication conditions are modeled in ns-2 with Ricean fading, which results in individual packet losses because of fading links. Furthermore, the links may break due to mobility as well.

In this scenario, the speeds of the control system dynamics and the network are of the same magnitude. This means that the network delays are significant for the control system performance. Both the network and the control system need to be simulated at the same time to get accurate results of the whole networked system. As the robots change formation, the communication links might break, and a new route must be established. The speed at which the path is re-established depends on the routing protocol. The network performance, and ultimately the control performance, depends on the formation of the robots and how the packets are routed through the network. The communication outages naturally degrade the control performance. More generally, instead of mobility, the outages can be caused by a changing environment, such as moving machinery in a factory.

Simulations of three formation changes of a squad of 25 robots are done (Pohjola et al., 2009). The differences between using the AODV and LMNR routing protocols are evaluated. The results are compared to the case without network, i.e., control with perfect communication, and with no mobility, i.e. no topology changes. Some network and control results are in Table 2. The control cost is significantly higher than for the case without a network, and slightly higher with a network but without mobility. Thus, the network has a considerable impact on the control system. According to the performance metrics, singlepath routing has, contrary to the previous case, an advantage over multipath. This advantage is because in the high mobility case, there are more link breaks when using multipath routing, which generate more routing overhead.

	Average delay [s]	Routing overhead [%]	Packet loss [% ]	Control cost (ISE)
No network				0.1
No mobility	0.009	0.8	0.1	2.3
AODV	0.015	3.2	30	2.7
LMNR	0.09	11.2	20	3.3

Table 2. Network and control performance metrics from the robot squad case

5.4 Summary

The communication and control co-simulator PiccSIM was introduced. With PiccSIM, wireless applications can be simulated and studied. The application performance, which partly depends on the network design, can be measured. The presented simulation cases show the benefit of communication and control co-simulation of WiNCS. With simulation, the effect of the network on the application and the resulting performance can be assessed. The optimal network design depends on the application and is determined by the specific application operation and needs. This guides the protocol design to improve the essential network problems experienced by the application. More efficient design is obtained as the issues affecting the application the most can be identified and improved

6. Conclusions

Rapid development of small, low-cost sensors has opened the way for implementation of wireless sensor network technology in countless applications. Although research has been comprehensive in various important fields in the context of WSNs, such as energy efficiency and security, reliability of the underlying communication system has received less attention. Hence, in this chapter we considered robustness of existing protocols and discussed advanced communication solutions for reliable wireless sensor systems by considering physical, medium access and network layers. On the physical layer antenna diversity should be exploited to further enhance WSNs resiliency. Collision-free medium access enables reliable delivery of packets and by using efficient channel ranking algorithms and multi-channel communications the performance of the system can be improved, especially under interference. Furthermore, multipath routing provides several trails between transmitters and receivers with similar costs which can be utilized to ensure trustworthy communications in systems where links are relatively stable. Finally, we introduced the network and control co-simulator PiccSIM and studied the performance of some real-world applications by simulations.

7. References

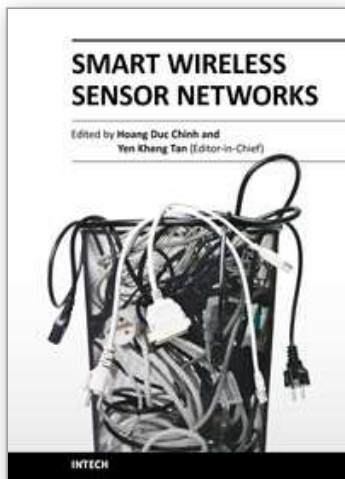
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## Smart Wireless Sensor Networks

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The recent development of communication and sensor technology results in the growth of a new attractive and challenging area – wireless sensor networks (WSNs). A wireless sensor network which consists of a large number of sensor nodes is deployed in environmental fields to serve various applications. Facilitated with the ability of wireless communication and intelligent computation, these nodes become smart sensors which do not only perceive ambient physical parameters but also be able to process information, cooperate with each other and self-organize into the network. These new features assist the sensor nodes as well as the network to operate more efficiently in terms of both data acquisition and energy consumption. Special purposes of the applications require design and operation of WSNs different from conventional networks such as the internet. The network design must take into account of the objectives of specific applications. The nature of deployed environment must be considered. The limited of sensor nodes’ resources such as memory, computational ability, communication bandwidth and energy source are the challenges in network design. A smart wireless sensor network must be able to deal with these constraints as well as to guarantee the connectivity, coverage, reliability and security of network’s operation for a maximized lifetime. This book discusses various aspects of designing such smart wireless sensor networks. Main topics includes: design methodologies, network protocols and algorithms, quality of service management, coverage optimization, time synchronization and security techniques for sensor networks.

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