Abstract

The interest in wireless technology for industrial applications has increased dramatically over the last few years. Wireless communication can reduce cost and complexity, enable mobility and provide much higher flexibility than its wired counterparts. However, to be considered for use in practice, wireless systems must provide sufficient levels of timeliness and reliability as required by industrial applications, while keeping reasonable levels of complexity as well as interoperability with existing wired networks. Wireless channels, characterized by pathloss, noise, multipath fading and shadowing, imply a particular challenge to fulfill the requirements on timely and reliable communication. To this end, this thesis work proposes and evaluates a number of techniques able to increase the reliability of wireless communication systems without causing excessive or unpredictable delays. In addition, all proposed solutions are implementable on top of commercially available devices, i.e., they require no large alteration of the standard IEEE 802.15.4 and minimal changes to the current infrastructure to be compatible with existing industrial communication systems. First, the characteristics of industrial communication environments are determined. Then, suitable models to approximate them are selected, since the effectiveness of different error control schemes able to increase reliability depends on the type of wireless channel encountered. Next, different possibilities for reliability improvements in wireless industrial networks, while subject to strict timing constraints, are evaluated. Based on this, relaying that has been proven to be beneficial for traditional wireless networks is evaluated for applicability in industrial systems. Finally, several different relaying strategies that are implementable at the link layer on top of existing chipsets are developed and evaluated. Depending on the specific type of industrial application and its corresponding performance metrics, relaying is combined with network coding, forward error control codes, packet aggregation and packet combining techniques – all of which support increased reliability with maintained delay, at reasonable complexity investments. To complete the framework, scheduling schemes tailored to various relaying protocols are also developed.

Sammanfattning

Intresset för trådlös kommunikation för industriella tillämpningar har ökat dramatiskt under de senaste åren. Införandet av trådlösa nätverk kan innebära stora kostnadsbesparingar, öppna möjligheter för rörlighet och ge större flexibilitet än dess trådbundna motsvarigheter. För att trådlös kommunikation ska kunna användas i industriella nätverk måste dock de särskilda krav på tillförlitlighet och fördröjning som ställs på industriella tillämpningar uppfyllas, samtidigt som komplexiteten bör hållas nere och lösningarna bör vara interoperabla med befintliga trådbundna nätverk. Signaler som skickas trådlöst påverkas i högre grad av dämpning, brus, fädning och skuggning, vilket innebär en särskild utmaning att uppfylla kraven på tillförlitlig kommunikation. Avhandlingen presenterar och utvärderar flera olika tekniker som gör trådlös kommunikation i industriella nätverk mer tillförlitlig utan att orsaka stora eller oförutsägbara fördröjningar. Dessutom är alla föreslagna lösningar implementerbara i kommersiellt tillgängliga enheter. De kräver inga stora ändringar av IEEE 802.15.4-standarden och endast mindre förändringar av den nuvarande infrastrukturen för att vara förenliga med gällande praxis avseende industriella kommunikationssystem. Först studeras egenskaperna hos industriella kommunikationsmiljöer. Därefter väljs lämpliga modeller för att approximera dessa, eftersom effektiviteten av olika felkontrollmetoder beror på vilken typ av trådlös kanal som påträffas. Härnäst utvärderas olika möjligheter för att förbättra tillförlitligheten i trådlösa industriella nätverk med strikta tidskrav. Baserat på detta utvärderas en teknik som har visat sig användbar i traditionella trådlösa nätverk, nämligen relaying. Slutligen har flera olika strategier för relaying, implementerbara i länkskiktet ovanpå existerade hårdvara, utvecklats och utvärderats. Beroende på den specifika typen av industriell tillämpning och dess tillhörande prestandakrav, kombineras relaying med tekniker för nätverkskodning, felrättande koder, paketaggregering och paketkombinering – tekniker som alla stödjer ökad tillförlitlighet med bibehållen fördröjning och rimlig komplexitet. För att komplettera arbetet har även olika schemaläggningsstrategier, speciellt anpassade till protokoll baserade på relaying, utvecklats.

To my family

Acknowledgements

First of all I would like to thank my supervisors Dr. Elisabeth Uhlemann, Prof. Mats Björkman, Dr. Johan Åkerberg and Prof. Maria Linden. Thank you for giving me the opportunity to become a PhD student and for all your guidance, encouragement and support during these years!

During my PhD studies I have spent 3 great months at university of Canterbury, Christchurch, New Zealand and would like to thank Dr. Andreas Willig for hosting me there and all the help and support I got from him. Next, I wish to thank Giuliana Alderisi and Prof. Lucia Lo Bello for the great collaborative work we have been doing after my Licentiate. Also, I would like to thank colleagues from my research group Mikael and Martin Ekström, Marcus Bergblomma, Kan Yu for all the interesting discussion and ideas!

I wish to thank lecturers, teachers and professors at MDH from whom I learned a lot during my studies. Thank you, Gordana Dodig-Crnkovic, Cristina Seceleanu, Dag Nyström, Thomas Nolte, Emma Nehrenheim, Hans Hansson, Paul Pettersson, Jan Gustafsson, Ivica Crnkovic, Lars Asplund, Jan Carlson, Radu Dobrin, Peter Funk, Damir Isovic, Björn Lisper, Kristina Lundqvist, Sasikumar Punnekkat, Guillermo Rodriguez-Navas, Mikael Sjödin, Giacomo Spampinato, Daniel Sundmark, and Ning Xiong!

Also, I would like to thank all the IDT administrative staff and especially Carola Ryttersson, Sofia Jäderen, Malin Åshuvud and Susanne Fronnå for their help with practical issues.

Moreover, many thanks go to all my friends and colleagues at IDT. It was a great pleasure to be here with all of you! Thank you for the fun we had during conference trips, “fikas”, barbeques and parties, while playing badminton and table tennis, watching movies.

Finally, I'm very thankful to my family for always being positive and supporting!

Svetlana Girs
Västerås, December 2015

The work in this thesis has been supported by the Swedish Knowledge Foundation (KKS) within the projects GAUSS and WIRE, and by the Swedish Governmental Agency for Innovation Systems (VINNOVA) within the TESLA project.

List of Publications

Publications Included in the Doctoral Thesis

Paper A: S. Girs, E. Uhlemann, and M. Björkman, “The effects of relay behavior and position in wireless industrial networks,” *Procideengs of IEEE International Workshop on Factory Communication Systems (WFCS)*, Lemgo, Germany, May 2012, pp. 183-190.

Paper B: S. Girs, E. Uhlemann, and M. Björkman, “Increased reliability or reduced delay in wireless industrial networks using relaying and Luby codes,” *Procideengs of IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)*, Cagliari, Italy, Sept. 2013, pp. 1-9.

Paper C: S. Girs, A. Willig, E. Uhlemann, and M. Björkman, “On the role of feedback for industrial wireless networks using relaying and packet aggregation,” *Procideengs of IEEE International Conference on Industrial Technologies (ICIT)*, Busan, South Korea, Feb. 2014, pp. 743-748.

Paper D: S. Girs, E. Uhlemann, and M. Björkman, “Adopting FEC and packet combining to increase the performance of IWSNs using relaying,” *Procideengs of International Conference on Computing and Network Communications (CoCoNet)*, Trivandrum, India, Dec. 2015.

Paper E: S. Girs, A. Willig, E. Uhlemann, and M. Björkman, “Scheduling for source relaying with packet aggregation in industrial wireless networks,” submitted to *Special Section on IEEE Transactions on Industrial Informatics*, June 2015.

Paper F: G. Alderisi, S. Girs, L. Lo Bello, E. Uhlemann, and M. Björkman, “Probabilistic scheduling and adaptive relaying for WirelessHART networks,” *Procideengs of IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)*, Luxembourg, Sept. 2015, pp. 1-4.

The included articles have been reformatted to comply with the doctoral thesis layout.

Additional Publications, not Included in the Thesis

- S. Girs, M. Bergblomma, E. Uhlemann, B. Štimac, and M. Björkman, "Design of channel measurement guidelines for characterization of wireless industrial environments", MRTC Report, urn:nbn:se:mdh:diva-20346, Mälardalen Real-Time Research Centre, Mälardalen University, July 2013, pp. 1-5.
- S. Girs, A. Willig, E. Uhlemann, and M. Björkman, "Scheduling transmissions in industrial networks using source relaying and packet aggregation," *Proceedings of World Conference on Factory Communication Systems (WFCS)*, Palma de Mallorca, Spain, May 2015, pp. 1-4.

Contents

I

Thesis

Chapter 1
Introduction

Significant benefits brought by wireless communication such as higher flexibility and availability, lower installation and maintenance costs and the possibility for new application areas, have sparked a lot of interest in adapting wireless technology to fit industrial applications. With small, wirelessly connected devices, it is much easier to temporary access a machine for diagnostics or testing, or even start controlling processes which were impossible to control before, such as processes involving moving machinery or mobile robots. However, to be adopted in practice for use in industrial systems, wireless networks must provide at least the same reliability and timeliness as the currently used wired systems do. This is due to the fact that in industrial environments erroneously received packets or missed deadlines can lead to stop in processes and economical losses or, in some critical applications, even danger to human lives. Wireless channels, introducing noise, fading, multipath, shadowing and path-loss with bit and packet errors as a result, imply a significant challenge to fulfill these requirements. Thus, *the main goal of this thesis work is to increase the reliability of industrial wireless communication systems while maintaining the timeliness*.

Extensive research efforts are currently focused on developing error control schemes that are able to tackle bit and packet errors introduced in wireless channels. However not all error control schemes developed for other types of wireless networks can be applied in industrial systems. The techniques intended for use in industrial systems should introduce only minimal additional delays and complexity. Moreover, it is typically required to use commercially available of-the-shelf devices and thus the error control schemes should be implementable on top of these simple devices and only minor alterations of the standard IEEE 802.15.4 and the current infrastructure are allowed. Fig. 1.1 shows the tools and techniques that can theoretically be used to increase reliability of industrial wireless systems and the additional complexity and delays introduced when they are applied. Two techniques traditionally used for improving the communication reliability of wireless systems are automatic-repeat-request (ARQ) and forward error correction (FEC). In ARQ schemes the originator of the data repeats lost or corrupted packets. ARQ schemes are easy to implement, but require additional time for retransmissions. In contrast, FEC coding, where redundant bits are introduced into transmitted packets and later used at the destination to recover erroneous bits, increases the reliability without introducing much additional delay. However, effectiveness of both techniques depends on the channel characteristics, i.e., FEC coding is useful only when the number of introduced errors is lower than the correcting capability of the code, while ARQ helps for the channels introducing bursts of errors but can lead to multiple retransmissions in the environments with evenly distributed errors. Hybrid ARQ (HARQ) techniques combine the benefits of FEC coding with retransmissions thus increasing the reliability for several types of wireless systems while introducing only a moderate delay, since fewer retransmissions are required when FEC is used. However, HARQ should be used with care in industrial communication systems since limitations on the device complexity prevent the usage of some types of FEC codes and the number of allowed retransmissions is limited by the deadline.

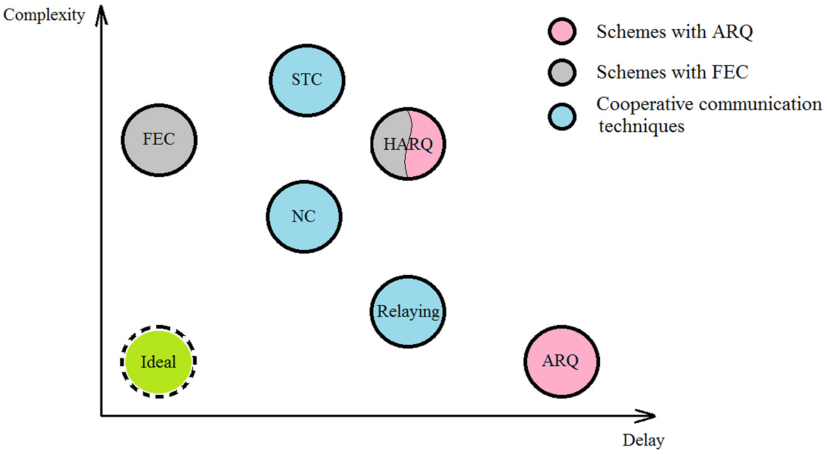

Fig. 1.1. Error control schemes

A new opportunity to deal with unreliability is provided by the multicast nature of wireless links. When a node sends a packet, there is a high probability that one or several neighboring nodes can overhear the transmission and later help by forwarding the data to the final destination. Apart from time diversity, spatial diversity is also provided when intermediate nodes perform retransmissions. Since the channel characteristics between various nodes are different, the chances for a retransmission to be successful are higher when it is performed by a relay node instead of the source node.

1.1. Problem Formulation

The first research question to be answered in this thesis work is:

RQ 1: Which techniques can be used to increase reliability in industrial wireless networks?

ARQ is traditionally used to increase reliability of wireless communication systems, but in industrial applications it cannot play out its benefits fully due to the limited number of time slots available for retransmissions. Relaying, on the other hand, might be able to increase communication reliability without introducing excessive delays. Thus, hypothesis 1 is proposed and studied.

Hypothesis 1: Relaying can be used to increase reliability also in deadline-constrained industrial wireless networks.

Various spatial diversity techniques such as relaying have been successfully used to increase performance in other types of wireless networks and thus, to answer the first research question and evaluate the validity of the first hypothesis, the suitability of using relaying in industrial wireless systems is studied. Many different spatial diversity and cooperative communication techniques exist, e.g., relaying, network coding (NC), fountain coding, distributed space-time coding (STC) and multiple-input multiple-output (MIMO) schemes. However not all of them can be used in industrial networks due to limitations on hardware complexity and the preferred use of simple, off-the-shelf components. Given these requirements, cooperative diversity using relaying or network coding is the most promising.

However, even if these techniques have been successfully applied to increase performance in other types of wireless networks, they were not designed and evaluated with industrial channel conditions and application requirements in mind. Industrial environments are characterized by the presence of highly reflective surfaces, multiple moving and vibrating objects, as well as electromagnetic radiation from working machinery, and therefore imply an additional challenge to provide the required reliability levels. To design effective error-correction schemes, it is vital to tailor the schemes to the characteristics of the targeted wireless channel. Thus, the second question to be answered in this research work is:

RQ 2: When, how and to what extent can relaying aid in increasing the reliability of industrial wireless networks?

Based on the studies of the channel characteristics describing industrial environments and specific requirements imposed by industrial applications together with the research done while answering the first question, hypothesis 2 is formulated.

Hypothesis 2: It is possible to find operational areas where each of the cooperative communication techniques listed above can help in improving reliability of industrial communication systems.

To test the second hypothesis, the achievable performance gain of introducing relaying into industrial networks, given the industrial application requirements and the corresponding channel model, is assessed. The adopted relaying schemes should be tailored to fit the particular constraints on timing and reliability of industrial applications so that guidelines on how e.g., to select the relay node with the best position, given a set of available candidates, can be formulated. Different acting strategies of the relay node, like the choice of which packet to relay, together with which additional error-correction techniques applied at the sources, like FEC, and at the destination, like packet combining, can be determined. Further, as it is not always cost-effective to have many relay nodes in industrial systems, it is crucial to choose the best behavior strategy for relay nodes aiding several sources simultaneously or alternatively, when no additional relay nodes are present, behavior strategies for source nodes acting as relay nodes must be evaluated. Additionally, the potential performance gain achieved by relaying depends on the scheduling scheme since a relay node must receive at least one source packet, before it is able to relay. Thus, scheduling schemes taking relaying into consideration must be developed to maximize the achievable gain.

1.2. Thesis Contributions

To answer the first research question, various spatial diversity techniques are studied for applicability in industrial communication systems and relaying is proposed as a promising technique to increase reliability in industrial networks. With relaying, erroneous packets are retransmitted by intermediate nodes, which have different channel conditions to the destination compared to the source node and potentially also are located closer to the destination than the source. The benefits of relaying have been evaluated previously for other types of wireless networks and it was shown that relaying increases communication reliability without causing the same amount of delay as introduced by traditional retransmissions. However, for relaying to take place, a carefully selected set of nodes, the relay nodes, must be allowed to overhear source packets and forward them to their destinations. Further, these relay nodes require additional energy for relaying, since they need to listen in time slots when they are not set as the final destinations and also forward packets that are not their own. Moreover, the scheduling scheme must be adjusted when relaying is used, so that e.g., relaying time slots are scheduled after source transmissions but still before packet deadlines, such that the reliability can be increased before a specific instance in time. Industrial systems also imply some additional constraints on the intended error control schemes. First, commercially available off-the-shelf devices must be used implying that low complexity solutions are needed. The proposed solutions should ideally be implementable on top of existing standards and infrastructure, and should require minimum changes to standards and already installed equipment and protocols. This also implies that the installation of several additional nodes for the sole purpose of relaying is not tractable. In contrast, the problem of additional energy required for relaying is not so critical for industrial applications, compared to e.g. traditional sensor networks, since factories and industrial plants typically have fixed energy supplies. Moreover, since reliability and availability are the main requirements in industrial applications, additional energy can be accepted to reach the required performance levels. However, even if energy supplies are present in industrial environments, energy consumption may still be important. Thus, this thesis work takes this into account and proposes that mainly actuators and only some sensors, having permanent power supply, perform relaying. The solutions concerning relay nodes as a sparse resource are therefore also relevant for this case. Additionally, industrial channels are often characterized by strong fading and shadowing, great time variance and thus imply an additional challenge for wireless systems working in industrial environments.

Given the industrial constrains described above, the first contribution of the current thesis is a thorough evaluation of relaying itself (Paper A). Various positions of the relay node together with two relay behavior strategies are studied for two different types of wireless channel models. The results show that relaying is beneficial even in cases where the relay node only receives some of the source packets correctly. Recommendations of the best relay node position depending on the wireless channel together with the best acting strategy depending on the application requirements are given. Next, once relaying was found to be beneficial even for harsh industrial channels, the work towards answering the second research question is conducted and the possibilities for performance improvements are studied further. Studies of relaying together with packet aggregation, packet combining, FEC and Luby coding are made (Papers B-E). Relaying was studied for the cases with one relay node per source as well as for networks with limited relay resources. A set of recommendations of the best relaying schemes given the specific channel conditions, the type of feedback available, the available relay positions, the number of relay and source nodes respectively, and specific application requirements is formulated. Additionally, for relaying to be the most beneficial it is important that the schedule allows relay nodes to overhear source transmissions and schedules relaying time slots accordingly. Thus, scheduling schemes exploiting the benefits of relaying are also proposed and evaluated (Papers E-F). The thesis contributions can be summarized as follows:

1. A thorough evaluation of the benefits of relaying, given a specific relay position, a time limit in terms of a deadline and various types of wireless channels which were found suitable to describe industrial environments (Paper A).
2. Development of design guidelines for the specific acting strategy of the relay nodes in the network, given the application requirements and the positions of the relay node, the source and the destination respectively (Papers A and D).
3. Development of two different protocols combining the benefits or relaying, Luby coding and packet aggregation such that the reliability of wireless industrial networks is increased, while maintaining a fixed delay, or, alternatively, that the delay is decreased, while keeping a certain reliability level (Papers B and C). The protocols are beneficial also in networks where relaying resources are sparse, i.e., where one relay node is required to aid several sources. Both scenarios where feedback is available and protocols in which no feedback is available are considered.
4. Identification of the number of consecutive errors from a particular node as one more key performance indicator for industrial wireless networks, apart from individual packet error rates and success probability, and evaluation of most of the developed protocols using it as well (Papers C, E and F).
5. Development and evaluation of scheduling schemes for networks allowing relaying which is either performed by the source (Paper E) or the relay (Paper F) nodes.

Note that all developed protocols can be implemented using existing lower-layer standards like IEEE 802.15.4, i.e. no changes to the physical layer are required.

1.3. Thesis Outline

The thesis consists of two parts: a comprehensive summary and a set of appended research papers. The reminder of the summary constituting the first part is structured as follows: in Chapter 2, the specifics of wireless communication for industrial applications are discussed, while Chapter 3 presents the error control strategies capable to improve the performance of wireless communication in industrial environments. Thereafter, Chapter 4 describes the method and assumptions used throughout the work, while Chapter 5 presents an overview of the included papers. Finally, in Chapter 6 the conclusions and possibilities for future work are presented. The second part of the thesis consists of the appended papers, i.e., Chapters 7 through 12 contain selected research publications included in this thesis.

Chapter 2

Wireless Communication for Industrial Applications

2.1. Industrial Applications

Two main areas in industrial networks where wireless communication would have many advantages are process automation and discrete manufacturing. In process automation the products are produced in a continuous manner, for example oil, steel or paper are produced in a continuous flow. In discrete manufacturing, on the other hand, products are produced and assembled in discrete steps. Typical examples of discrete manufacturing are automotive, medical and food industries. These industries heavily rely on robotics and belt conveyers and thus, reliability, latency and real-time requirements are very strict. Applications relying on communications in industrial automation can be divided into three subcategories [1]: monitoring and supervision, where many sensor nodes send their sensor readings to a control node; closed loop control, where sensors and actuators are connected to control a process; and finally interlocking and control, responsible for starting or stopping a machine. Depending on the application, industrial systems can be very sensitive to timing constraints and deadline misses. Packet losses and jitter are for example not so crucial for monitoring systems since the information is used for supervision and condition monitoring, but essential for closed loop control, where a process should be controlled based on the actual sensor readings. Interlocking and control is an area which is very sensitive to delays, where based on the received data, a machine has to start, stop or safety-interlock.

Thus, two main requirements in industrial communication systems are reliability and timeliness. In contrast to traditional wireless sensor networks (WSNs), deployed in e.g. volcanos, forests or deserts, where it is impossible to frequently change batteries in the sensor nodes, power consumption is not one of the main concerns in industrial wireless networks. Reliability, availability and timeliness have much higher priority and thus, additional resources can be used to provide them. It is crucial in industrial systems that packets are delivered correctly so that the received data accurately reflects the controlled processes. In addition, since sensor data is typically time-sensitive, e.g., alarm notifications, it is important that packets are delivered before their corresponding deadlines. Data with long latency due to processing or communication may be outdated and lead to wrong decisions in the monitoring system. Moreover, industrial networks must be available 24 hours per day and seven days per week. Some errors can be tolerated by industrial systems, but the number of consecutive errors should not exceed the values specified by the application. For example, often industrial systems can tolerate two consecutive erroneous packets from a particular node, although the machines must be turned into a safe state. However, when three consecutive errors occur, the machines have to be switched off. Wireless networks must fulfill all the industrial requirements to be allowed for use in industrial systems.

2.2. Industrial Networks

Typical industrial wireless networks, Fig. 2.1, consist of *Sensor nodes* (*S*), measuring temperature, pressure, humidity etc. and sending their readings through one or several *Access points (AP),* which act as radio interfaces between the wired and wireless parts of the network, to one or more gateways; *Gateways* (*GW*), collecting sensor data on a bus, typically based on HART, and transferring these sensor readings to another type of bus, e.g., a PROFIBUS, to which one or more *Control nodes* (*PLC*) are connected. The control node executes a control application and sets output values for actuators; *Actuators* (*A*), which receive information from a control node, are responsible for e.g., turning a machine into a safe mode in case of an emergency situation. In addition, there is also a *Network manager* (*NM*), that configures the network, schedules communication between devices, manages message routes and monitors network health; and a *Security manager (SM)*, managing and distributing security encryption keys and holding the list of devices authorized to join the network. Typically network and security managers, as well as access points, are parts of the gateway and thus, the rightmost bus shown in the figure may also be internal.

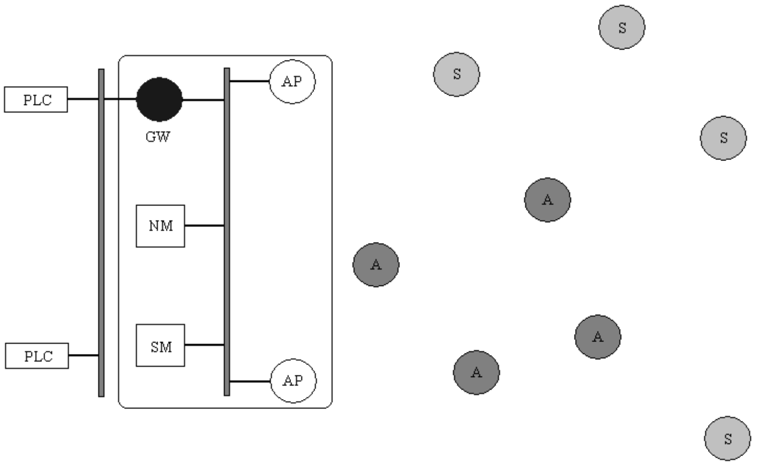

Fig. 2.1. Example of an industrial wireless network structure

Most of the currently used industrial networks are wired, where nodes are interconnected according to some topology. Thus, when wireless networks are introduced into industrial systems, the same types of topologies are generally preferred. Three common topology structures are star, mesh and cluster tree, Fig. 2.2. The star network topology fits point-to-point communication systems where all devices are placed one hop away from a single central coordinator, gateway or access point. The coordinator is responsible for initiating and maintaining the communication, collecting the data from sensor nodes and sending control information to actuators, via wired or wireless links. The end devices cannot communicate directly with each other but only through the coordinator. In wired networks this property can be ensured through absence of wires, while in wireless networks this is managed through fixed tables of addresses that the device is allowed to communicate with. Mesh network configurations, on the other hand, use multihop connections between devices and allow path formation from any source device to any destination device, using tree or table-driven routing algorithms [2]. Compared to star networks, mesh topologies extend the network range, but at the cost of increased complexity. The communication ranges between devices can vary from a few meters up to some hundred meters depending on the application [3], e.g. in the process automation domain the required range of wireless sensor networks is 100 m [1]. A cluster-tree topology is a hybrid topology, where wireless devices in a star topology are clustered around coordinators, which are able to communicate with each other and connected to a gateway in a mesh topology. This combines the advantages of several topologies: potentially low power consumption in the network arranged according to the star topology, and extended range and fault tolerance of the parts of the cluster-tree arranged according to a mesh topology.

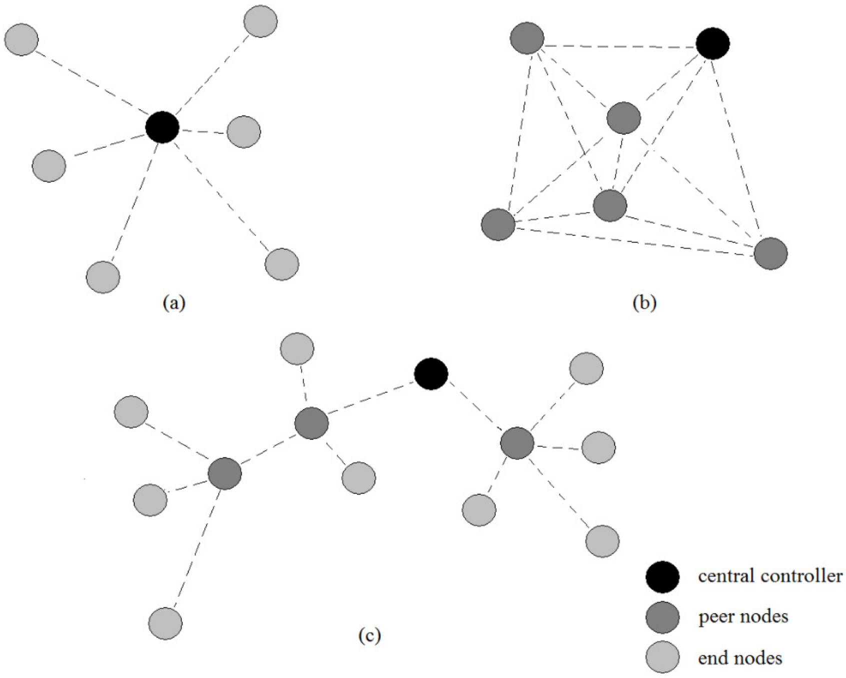

Fig. 2.2. Star (a), mesh (b) and cluster tree (c) network topologies

Typical packets transmitted in industrial networks are sensor readings sent from several sensor nodes to a common controller or gateway, actuator commands generated based on the received sensor data and transmitted from the controller, and service messages distributed in the network. These messages are transmitted periodically and should be delivered before specific deadlines, e.g. the next data update. Thus, the deadline for each packet often equals to its period and periods differ depending on the application: in e.g., interlocking and control systems they are in the range of 10-250 ms, while monitoring and supervision systems have the lowest update frequencies of around 1-5 s [1].

Due to periodic nature of the transmitted data and to provide predictable channel access delays, TDMA is often used in industrial systems. Thus, time is divided into superframes, each of which consists of a number of time slots assigned for sensor nodes to transmit their readings and the controller to send its commands to the actuators. Additionally, some of the time slots are assigned to send keep-alive messages and control commands required for correct operation of the system. To increase reliability every sensor node is often given several time slots to send each packet. For example, WirelessHART, which is a common wireless standard used in industrial communication systems, does not specify a scheduling scheme, but it gives a set of recommendations which should be fulfilled and one of them is that time slots for three transmission attempts must be assigned to each packet before its corresponding deadline [4]. Depending on the network topology used, the time slots available before a packet deadline are typically divided between direct transmissions, retransmissions and packet forwarding through alternative routes using intermediate nodes. Different routing algorithms and packet forwarding techniques exist and specific scheduling schemes ensuring deterministic end-to-end delay must be used to allocate the time slots for retransmissions and forwarding [5]. An example of a time slot allocation in one superframe for the star and mesh topologies is shown in Fig. 2.3. In a star scheme, only source retransmissions can be used to increase the reliability of the system. In case of lost or corrupted packets at the controller, the corresponding sensors repeat their transmissions. The time diversity, introduced by packet retransmissions, might result in the correct reception of the retransmitted packet even though it is sent from the same source and through the same physical channel. Several retransmissions, e.g. two as it is shown in the figure, are often allowed for each packet before the deadline. Retransmission time slots can be located consecutively for each source or interlaced, such that all retransmission slots occur after the original transmissions, depending on the chosen scheduling strategy [6]. If a packet retransmission is not needed, the time slots allocated for it stay empty, as the sender-receiver pair is fixed in advance for each time slot. Mesh schemes, on the other hand, use both time and space diversity. In case both the initial transmission and its retransmission have failed, an alternative route through one or more intermediate nodes is chosen and the following retransmission is made through this route, Fig. 2.3, much like relaying. Similar to star network, some of these preallocated retransmission time slots might stay empty if e.g. a packet was delivered correctly at the first attempt and retransmissions are not needed. These unutilized slots imply a longer superframe and bandwidth wastage. For this reason, protocols with shared retransmission time slots were proposed in e.g., [7] and [8]. The time slot allocation schemes for cluster tree networks depend on the schedule used. One time cycle typically consists of superframes allocated for communication within different clusters. Cluster superframes can be separated by only a time division scheme, when no simultaneous transmissions are allowed, or, alternatively, frequency together with time separation can be used, allowing parallel transmissions and leading to an increased number of schedulable clusters [9].

Fig. 2.3. Example of time slot allocation for the star (upper) and mesh (lower) networks

2.3. Industrial Wireless Channels

Industrial environments are very harsh for wireless communication compared to other wireless environments and thus imply an additional challenge to fulfill industrial requirements on reliability and timeliness. The often discussed issue of coexistence of different wireless networks operating on the same frequency band, e.g. [10, 11] and [12], is not so pronounced for industrial communication, as usually the factory owner can control all wireless equipment used in the factory and thereby avoid unintentional interference. However, disturbances from high reflective facilities and working electromagnetic machinery in industrial environments together with pathloss, noise, fading and shadowing in wireless channels affect the received signal. It is shown in e.g., [13] how different the industrial environments affect the propagating signals compared to office environments and how this influence diverges depending on a particular industrial site. Pathloss is a loss in signal strength depending on the distance between the source and the destination. Pathloss depends on the propagation environment, but in general it is a deterministic value. Thermal noise is present in all electronic devices and is caused by electron movement. When wireless environments are characterized by presence of many objects located within the communicating area, waveforms can be a subject to reflection, scattering and diffraction and thus many copies of the same packets but with different delay arrive at the destination. Since the copies traveled through different routes they also arrive at the destination with different attenuation and phase. Interference between them can be constructive or destructive and the signal is said to experience multipath fading. In case of destructive interference, the channel is usually said to be in a deep fade. Such a deep fade can also occur because of shadowing, e.g., if something suddenly blocks the line-of-sight (LOS), i.e., the direct path between the source and the destination. Measurements in a heating and power production plant conducted in [14] show that during deep fades, the signal strength can drop as much as 20-30 dB and sometimes signals can even be completely lost in case of shadowing.

As all the phenomena described above contribute to packet losses and deadline misses, a precise model describing the behavior of industrial channels is needed to effectively design error control schemes. Usually three main modeling methods are discussed in the literature [15]: channel impulse responses, deterministic channel models and stochastic channel models. Stored impulse responses are realistic and are easily reused, but the drawback is that they characterize only a certain area which might not be typical for the whole wireless propagation environment in industrial settings. The tap-delay channel model is an example of a deterministic channel model [15], where each path in the wireless propagation environment is modeled with its own delay, attenuation and phase shift. Deterministic channel models, such as the tap-delay model require exact geographical and morphological information about the area of system deployment, which is not always available at the time of designing the error control schemes. Moreover, industrial environments are often not stable; machines and people move in and out of the area, and thus, deterministic models may not be accurate enough. Stochastic channel modeling methods on the other hand, do not aim to correctly predict the full impulse response (or equivalent functions), but rather to characterize the probability density function (pdf) of the random process that affect the signals transmitted over a larger area. Stochastic channel models provide fairly simple, yet quite accurate models and are often considered to be the best choice for design and comparison of error control techniques. Therefore, this group of models is selected for further evaluation in the remainder of the thesis.

Thermal noise is usually modeled as additive white Gaussian noise (AWGN). For certain space communication channels, where there are no objects close to the communicating devices, AWGN can be a good channel approximation. However in most other channels, especially in industrial environments, there are many objects and people close or even in-between the source and the destination. To construct a stochastic channel model for a particular wireless channel, distance-dependent pathloss, large- and small-scale fading are usually factored out. For a given frequency, the received power at a certain distance, *d*, can be modeled as

$$P_r(d) = P_0 - 10\gamma\log_{10}\left[\frac{d}{d_0}\right] + X_\sigma + Y, \tag{2.1}$$

where P_0 is the power at the reference distance d_0, γ is the pathloss exponent, X_σ and Y are the large- and small-scale fading contributions respectively [16]. The pathloss exponent indicates how fast the signal power reduces with distance. The value of γ depends on the propagation environment: it is usually in the 2-4 range for indoor environments and typically more than 4 outdoors.

Currently, the most frequently used models to mathematically describe fading are: Rayleigh, Rician and Nakagami. The Rayleigh model assumes that there is no LOS path between the communicating nodes and hence the signal travels only through multiple reflective paths. During Rician and Nakagami fading, on the other hand, the signal may or may not travel through a LOS path but always through multiple non-LOS paths of different lengths. It was shown that different wireless channels affect the travelling signals differently [17] and thus it is crucial to know the key parameters of the channel in the targeted environment and to use them in the correct channel model when designing error-control schemes.

To determine the best model for describing a specific type of wireless environment, channel measurements are needed. Research with the goal to characterize indoor industrial environments is mostly directed towards the following areas: investigating the influence of industrial disturbances on wireless communication; finding the best-fit mathematical model to characterize industrial environments; and studying temporal characteristics of the channel.

The effect of industrial disturbances on wireless communication systems was described in [18] and studied in detail in [19, 20]. The authors of [19] carry out a set of measurements on the premises of a paper mill. They also evaluate the impact of disturbances from transport mopeds and 4-wheel motorcycles, which are often used in industrial environments, as well as repair work where welding or similar processes are carried out. Results show that electrical and mechanical equipment produce low frequency high-impulsive disturbances. Transport mopeds and 4-wheel motorcycles generate disturbances up to 1 GHz, repair work up to 300 MHz. Consequently, there is almost no interference from industrial processes on the 2.4 GHz frequency band.

Many authors have tried to estimate the pathloss exponent in industrial environments. In [21], a log-normal pathloss model was adopted and it was found that in different electric power environments, the pathloss exponent varies from 1.45 to 2.42 for LOS measurements and from 2.38 to 3.51 for measurements without a LOS component. Similar distributions of estimated values were found in [22], while in [23] an exact number of 3.086 was obtained. Different approach was used in [24], where based on 3D model of a factory building, wireless links were divided into four groups according to the strength of the LOS path. Next, a separate pathloss model was constructed for each of the groups.

Much previous work has been focused on determining the best model for approximating fading in wireless industrial channels. Different authors suggested various mathematical models, such as Rayleigh, Nakagami and Rician with different K-factors. The K-factor determines how strong the LOS is (i.e., a distribution with K-factor equal to zero models a channel with no LOS path, while a channel with K-factor going to infinity has only one strong LOS path, like an AWGN channel). For example, in [25] the authors concluded that the Rician distribution with K-factor 20 is the best-fit fading model for short range wireless sensor networks. Measurements in an engineering building and a retail store were conducted in [23]. In both buildings, the received values were aggregated into separate data pools for LOS and cluttered sites. Rician distributions with K-factors 5 and 2 were concluded to be the best-fit of the measured data for LOS and cluttered sites respectively. The authors of [26] concluded, after carrying out a set of measurements at various industrial locations, that it is unclear if a single distribution can be used to characterize the industrial wireless channel. Most of their results exhibited Nakagami-m characteristics, while some exhibited log-normal and Rayleigh characteristics. Shadowing was studied in [22] and found to follow a log-normal distribution with standard deviation changing depending on how strong the LOS component is.

Temporal properties of industrial propagation channels were investigated in [22, 27, 28]. A sequence of measurements in a machine shop over 24 h with 5 min averages was conducted in [27]. Radio link qualities exhibited minimal variations over time, which can be expected as no mobile obstacles were present. In contrary, 17-20 hours long measurements conducted in a rolling and a paper mill as described in [28] showed that channel properties change over time. Rayleigh and Rician fading models were found to overestimate the occurrences of deep fades, while lognormal distribution was found to underestimate these occurrences. Nakagami, composed Nakagami and lognormal distributions fitted the measured data the best. In [22] temporal fading, measured during 5 min intervals in different types of industrial environments, was found to correspond to a Rician distribution. The estimated Rician K-factors varied depending on the type of industrial environment: the highest K-factor (18.6 or 17.6 depending on the type of estimator) was found for automated production lines due to the lower presence of motion and the lowest (12.0 or 11.1) for manual production lines.

Thus, no final decision has yet been made on the best model for approximating industrial environments and therefore several mathematical models are studied in this thesis such that their influence on communication reliability can be compared. In particular, basically all papers consider at least both an AWGN channel and a Rayleigh channel to cover the situations where a strong LOS exists, as well as no LOS at all.

2.4. Wireless Technologies in Industrial Networks

Traditionally, the use of wireless techniques in industrial applications has been quite limited due to the harsh wireless conditions encountered in industrial environments and the strict requirements set by industrial applications. However, replacing currently used wired networks with wireless solutions can lead to a significant reduction of cost, and it can increase flexibility and availability of the communication systems. Wireless networks are much easier to install, test and maintain; with them it is possible to control many secondary processes, gathering information from where it previously was economically unfeasible. Wireless communication systems can easily and fast be deployed for temporary measurements or in emergency cases. Moreover wireless industrial networks can offer built-in redundancy and capabilities for failure recovery [29]. However to play out all these advantages and to be accepted for implementation in industrial applications, wireless networks should fulfill all important industrial requirements. Additionally, to keep costs down, it is preferably to use commercially available chipsets for factory communication. In short, to be competitive and cost efficient, wireless industrial networks must meet all requirements that are met today using wired fieldbuses. Moreover, it is important to note that the requirements mentioned above distinguish industrial communication systems from most other wireless systems. For the consumer industry bandwidth, speed and range are more important than reliability and timeliness, while for industrial communication the opposite is true. Thus, standards specifically targeting industrial requirements are needed.

Wireless sensor networks, and also their application in industrial systems, have been attracting a lot of interest over the last years [1-3, 29-36]. A variety of standards exist, which are currently used or planned for usage in industrial wireless communication systems, e.g. Bluetooth [37], WISA [38], WLAN IEEE 802.11 [39], and IEEE 802.15.4-based standards, such as ZigBee [40], WIA-PA [41], ISA100.11a [42, 43], WirelessHART [4, 44], and IEEE 802.15.4e [45]. Most of them operate in the unlicensed ISM band of 2.4 GHz.

Bluetooth / IEEE 802.15.1

Bluetooth is largely used in mobile phones, laptops, headsets and other personal devices. Bluetooth networks are able to provide deterministic transmissions once the network has been set up due to the use of TDMA. However, the number of nodes a Bluetooth network can support is typically rather low. Additionally, since the operation of different collocated piconets is not coordinated, packet collision may occur.

WISA

WISA is a wireless standard based on Bluetooth and developed for factory communication systems. WISA provides both wireless communication and wireless power supply. Raw data rates of up to 1 Mb/s can be provided by WISA, but it supports only networks with star topology.

IEEE 802.11

WLANs have always been interesting for use in industrial systems as they are commonly available and largely tested [46-49]. For example in [50], IEEE 802.11 was shown suitable for cell level communication. Cell level lies immediately above the field level; nodes communicating on the cell level are usually controllers, responsible for a group of sensor nodes grouped according to a common application they belong to, e.g., a robot. The main drawbacks of IEEE 802.11 when considered for industrial use are high energy consumption and no support for mesh networks. However, these limitations start to disappear as a recent study showed that even working with output power decreased to the levels used by the IEEE 802.15.4 standard, IEEE 802.11 can achieve a good performance [51] and a new IEEE 802.11s standard supporting mesh topologies has been published.

IEEE 802.15.4

Many standards considered for use in industrial systems are based on the IEEE 802.15.4 standard. IEEE 802.15.4 specifies physical (PHY) and media access control (MAC) layers. On the PHY layer direct sequence spread spectrum (DSSS) is adopted, allowing operation in two frequency bands (868/915 MHz and 2.4 GHz) and with a data rate of 250 kb/s. On the MAC layer two operational modes are defined: unbeaconed mode with unslotted CSMA/CA and beaconed mode with slotted CSMA/CA. For reliability improvement, acknowledgments and retransmissions are provided by the standard. The main reasons for basing many wireless standards for industrial systems on IEEE 802.15.4 are that it has comparably low energy consumption and further that there are low-cost chipsets available from several different vendors.

IEEE 802.15.4-based Standards

ZigBee is based on IEEE 802.15.4 and is currently largely used in e.g. home automation applications. It was developed for short range communication and is targeting applications requiring low data rate, low power consumption and low costs. ZigBee has no frequency or path diversity and therefore its use for industrial applications is limited since it cannot fulfill industrial requirements on robustness and security [52, 53].

WirelessHART is an extension of the HART protocol [54] and was designed for use in process automation and control systems. Due to this, WirelessHART is mainly focused on reliable, time synchronized and secure mesh networking. In 2008-2009 two new standards; WIA-PA and ISA 100.11a were announced. WIA-PA is a standard intended for use in industrial wireless sensor networks (IWSNs), developed by the Chinese industrial wireless alliance. Contrary to WirelessHART and ISA 100.11a, WIA-PA adopts both the PHY layer and the superframe structure from IEEE 802.15.4. The ISA 100 group of standards is proposed to accommodate all of the processes on a plant as a single integrated wireless platform, and assimilate devices communicating using different protocols. All three standards were designed specifically for reliable industrial communication and therefore some additional features were added compared to IEEE 802.15.4. The standards support channel hopping and generate redundant routes to reliably deliver the data. Furthermore, TDMA is used by all three standards for deterministic channel access. Compared to ISA 100.11a, WirelessHART and WIA-PA are less flexible as they have e.g., fixed time slot duration and support for less other industrial standards. However, the flexibility of ISA 100.11a has the disadvantage of increased complexity.

IEEE 802.15.4 Amendments

After the standards described above were released, the work on improving the communication quality of the standards towards support of new application areas continued [45, 55, 56]. Two amendments to the IEEE 802.15.4 standard were designed, approved and published.

The first amendment, IEEE 802.15.4a [56], approved in 2007, was designed to propose an alternative PHY. The new standard adopts UWB impulse radio PHY, operates in three frequency bands and supports higher data rates, extended range, improved robustness against interference, and mobility, while enabling new applications based on high precision location capability. It supports applications such as e.g., connecting laptops to projectors or music distribution between a mobile phone and wireless headsets, demanding higher range and relatively high data rates. At the same time, for applications requiring longer ranges and communication between devices moving at high speeds, as e.g., moving vehicles monitoring and vehicle-to-vehicle communication, the chirp spread spectrum (CSS) PHY operating in the unlicensed 2450 MHz band was added. Additionally, two sets of transmission rates are supported – 1 Mb/s and optionally 250 kb/s, provided by CSS PHY, while the UWB PHY supports the rate of 851 kb/s with optional data rates of 110 kb/s, 6.81 Mb/s, and 27.24 Mb/s for its three bands [57]. IEEE 802.15.4a supports all types of devices and topologies defined by the original IEEE 802.15.4 standard.

The second amendment to the IEEE 802.15.4 standard, IEEE 802.15.4e [45], was approved in 2012. It was developed to better support industrial markets and permit compatibility with modifications being proposed within the Chinese WPAN. The new standard overcomes the main limitations of IEEE 802.15.4, such as MAC unreliability, unbounded delay and absence of channel access guaranties due to adoption of CSMA; vulnerability to interferences and multi-path fading due to absence of frequency hopping in IEEE 802.15.4 [58, 59]. Among others, IEEE 802.15.4e introduces new features like deterministic and synchronous multi-channel extension (DSME), low latency deterministic network (LLDN) and time slotted channel hopping (TSCH), which specifically target industrial applications. DSME enhances GTS by grouping multiple superframes to form a multi-superframe and using multi-channel operation. Like GTS, DSME runs in beacon-enabled mode. The LLDN mode is mainly targeting applications using short packets and requiring low and deterministic latency, such as e.g., robots, overhead cranes, portable machine tools, automated packaging and conveyors. To guarantee the latency requirements of the targeted applications, LLDN only supports the star topology, and uses a superframe consisting of a fixed number of time slots. Dedicated and shared group time slots can be scheduled, and CSMA/CA is used in the shared group time slots. Finally, the standard adopts TSCH. Combining time slotted access, multi-channel communication and channel hopping, this new standard is particularly suitable for multi-hop networks. It guarantees predictable and bounded latency, allows more nodes to communicate simultaneously thus increasing network capacity and mitigates the effects of interference and multi-path fading thus improving reliability.

All of the results obtained by this thesis work can be applied to several of the wireless standards intended for use in industrial environments, but the main standards in focus for the thesis work are IEEE 802.15.4 and WirelessHART. However, given the new strategies for reliability improvements adopted in IEEE 802.15.4e, this standard is also likely to have a major impact on industrial wireless networks.

Chapter 3

Relaying as an Error Control Strategy

All the standards listed in Chapter 2 support ARQ mechanisms to improve the reliability on the MAC layer. In ARQ schemes, the-originator of the packets performs retransmissions of lost or corrupted packets. To request the retransmission of packets a feedback channel is needed, through which the receiver can send retransmission request for lost or corrupted packets or, alternatively, send acknowledgments for correctly received packets. ARQ schemes perform well until the probability of packet errors becomes too large. In this case, numerous retransmissions will cause high communication latency and since industrial systems have strict timing constraints they limit the number of allowed retransmissions by a deadline. Additionally, in ARQ schemes packets are retransmitted through the same physical channel and will likely not be successful unless the instantaneous channel conditions have changed. For instance, measurements performed in an industrial storage hall in [60] showed that in approximately 59% of the cases, one packet error is followed by another one and thus simple retransmissions are not able to improve reliability. The single-channel restriction between the source and the destination is removed when spatial diversity techniques are used to increase communication reliability [61]. In this class of mechanisms, information is transmitted over multiple spatial channels. These channels should be far enough apart so that they are stochastically independent and thus the probability of them being in a deep fade at the same time is very small. Mesh topology, used in many of the standards described in Chapter 2, already exploits spatial diversity by assigning an alternative route for some transmissions. However, these alternative routes are used only after a number of retransmissions, e.g. for the third and last retransmission in WirelessHART, and require the source to repeat the packet once more when sending it to the next hop. Thus, new techniques leading to the decrease of bit and packet errors as well as time required for retransmissions are needed.

There are several spatial diversity techniques which can be used to increase network reliability: MIMO schemes, relaying or cooperative communication, network coding and distributed space-time coding. In industrial networks, devices are limited by size and hardware complexity to one antenna, and therefore MIMO techniques can typically not be used. In addition, the use of low complexity, off-the-shelf components in industry generally prevents the use of sophisticated space-time codes. However, the idea of cooperative diversity using relaying or network coding is promising.

Exploiting spatial diversity of wireless channels by e.g. introducing relaying can noticeable improve communication performance in wireless networks [61-67]. The concept of relaying is not new, and the first theoretical work was done already in the seventies [68]. One of the first examples of practical cooperative diversity protocols was proposed by Laneman, Tse and Wornell in [69]. In relaying schemes, e.g., [70], intermediate nodes are allowed to overhear their neighbors' transmissions and forward the overheard packets to their final destinations, Fig. 3.1. Compared to traditionally used ARQ protocol, relaying decreases the number of required retransmissions since retransmissions are performed through alternative channels which are likely to affect the signal differently, compared to the original source channel. Additionally, similar to ARQ, relaying can help recovering corrupted packets in environments with large bursts of errors, where e.g. FEC might not be able to improve the performance.

To apply relaying in single-hop networks, some of the nodes must be instructed to overhear transmissions done by neighboring nodes and be assigned time slots to perform relaying. In multi-hop networks relaying can be performed by intermediate nodes forwarding the packets. When relaying is applied, the same routing protocols as for mesh schemes can be used. In traditional mesh networks, intermediate nodes already relay packets, but all the transmissions are prescheduled and intermediate nodes listen only to the packets directed to them. On the contrary, in relaying schemes, relay nodes are allowed to overhear packets not originally directed to them. This thesis work shows that in a designed accordingly network with relaying, a relay node can have several overheard packets from different sources. Thus, compared to forwarding nodes in traditional multi-hop communication schemes, relay nodes can have more overheard source packets and if a relay node does not have a specific packet, it can be given flexibility to dynamically choose to send another missing at the destination one, thus not leaving any time slots empty. Furthermore, relaying can react to changing topologies and channel conditions much faster than multi-hop, as new routes do not need to be explicitly calculated [71].

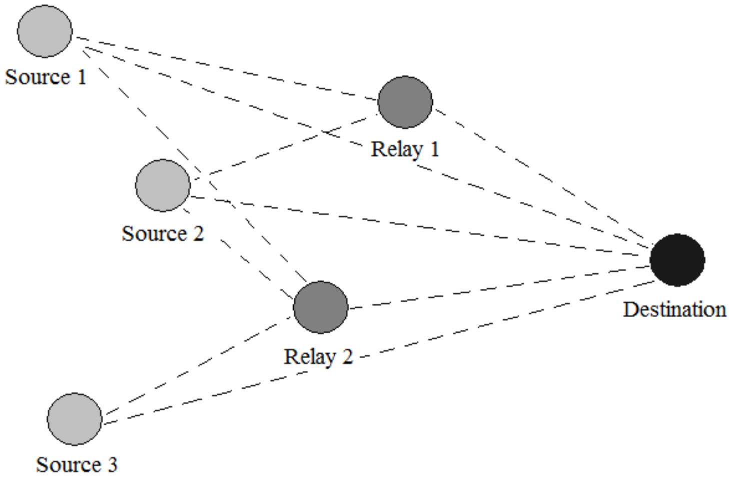

Fig. 3.1. Relaying

In industrial settings, a node acting as a relay node, can be a sensor node, an actuator or even an extra node introduced in the network purely for relaying. Additional energy is required to overhear transmissions done by neighboring nodes and forward the data. However, as reliability is the top priority in industrial systems, additional energy can be spent on relaying, resulting in performance improvements. When it is not cost efficient to introduce multiple redundant nodes only for the purpose of relaying and sensor nodes are too simple and battery powered, actuators, being allowed more complexity than sensors and usually having permanent power supply, can play the role of relay nodes when various spatial diversity techniques are added to industrial applications.

In the last few years, a great deal of information-theoretical research as well as research on practical integration of relaying has been carried out. When deploying a relaying protocol intended for use in industrial wireless networks, some significant questions should be answered [64, 72]. First of all, it is important to decide if relaying is desired (i.e. if timing constrains allow a relaying attempt) and required (if there are packets not yet delivered correctly to the destination). Given that relaying is desired and required, the third question is how to choose the position of the relay node and its behavior strategy. Some research on the best relay node placement was done in, e.g., [73-80]. In [73] the authors present a wireless relay placement algorithm for wireless sensor networks, which attempts to reduce the sensor-average probability of error. The results from [75] show that the choice of pathloss model and fading distribution model affects the optimal amount of relay nodes as well as their positions. However, even though the results from [73] and [75] are relevant also for industrial settings, they cannot be directly applied as [73] only evaluates the average probability of error, while in the case of industrial communications, the worst case error probability is of essence, and [75] considers only one specific kind of environment – underground tunnels. A relay selection algorithm adapting to channel quality between the communicating nodes was presented in [78]. The scheme is adaptive and new relay nodes are chosen in case of link quality decrease. The drawbacks of the scheme are the necessity of route and schedule changes during the operational time and additional overhead brought by the selection algorithm. Two other relay selection schemes were proposed in [66, 79]. In [66] the relay nodes are chosen based on the instantaneous channel assessment, the number of packets in the queue of every potential relay node and the chances of interference with other transmissions if a particular relay is selected. The scheme shows good results in improving network reliability and energy consumption. However, the scheme was proposed for networks with a CSMA/CA channel access scheme, while in industrial systems TDMA is prevailing to insure deterministic channel access. The authors of [79] first develop a simulation tool which takes as input a CAD file from the site under analysis and the possible positions of the nodes and computes the link quality between all the nodes. The relay nodes are chosen to cover the parts of the network connected by weak or broken links, which are discovered from the developed site-specific connectivity map.

3.1. Relaying in Networks with Sparse Resources

Although relaying was proven to increase reliability in wireless networks, it is often not possible to have a separate relay node for every source. Moreover, it can happen that there are not enough time slots available before the packet deadlines to forward all source packets. In such cases, the relay nodes present should try to aid several source nodes simultaneously. This can be done by using e.g. network coding [81-83], or fountain codes [84]. Due to the broadcast nature of wireless networks, relay nodes, located in between other communicating devices, can have overheard several different packets. Network coding suggests that intermediate nodes instead of forwarding packets one-by-one, encode them into one, by e.g. applying linear transformation, and send this new combined packet instead. The destination nodes need to receive a subset of the original and the encoded packets to recover all original data. Thus, network coding helps decreasing the number of time slots needed to deliver information from one or several nodes to multiple receivers. Network coding for networks with sparse resources was considered e.g. in [85], where the authors look at a network with two sources and a relay node which should either help one of the sources or alternatively try to be helpful for both of them by using network coded packets. Unfortunately the results from this paper are not directly applicable to industrial communications as the network parameters assumed are based on mobile communications and the main performance measure is capacity, and not packet delays and error rates.

Fountain codes were originally designed to transfer data from one source to many receivers. Traditional file transfer protocols divide a file into a set of packets and transmit each packet until it is successfully received. A feedback channel is required for these protocols to figure out which packet should be retransmitted together with time slots available for retransmissions. Fountain codes, in contrast, transfer packets that are random functions of the original file. These codes are rateless, meaning that any amount of encoded packets can be generated from the source packets much like retransmissions. The transmitter sends packets without any knowledge of which packets are received. Once a receiver obtains the same number of correct packets as the size of the original file, all original packets can be decoded. One example of fountain or rateless codes [84] is Luby codes, introduced by Michael Luby in [86], where a set of k packets is encoded into a set of $k+m$ packets which can be sent through different routes in the network. To decode the original packets, it is enough to correctly receive any k packets of the $k+m$ sent ones. The codes were designed especially for channels with erasures, but also proven to have good performance in fading channels [87].

Research work on the topic of fountain codes is still ongoing and is concentrated on e.g., designing more efficient codes for different types of applications [88], [89], or aiming to evaluate the benefits of using fountain coding in cooperative communication schemes for wireless systems. Many authors look at the possibilities to use rateless coding in various application areas, such as e.g. satellite communication [90], content distribution [91] or underwater networking [92], and for different network types, e.g., line networks [93], tree networks [94], networks with several parallel chains of relay nodes between the source and the destination [95], [96], decentralized networks for transmission and storage of the source readings [97], etc. Most of these works mainly focus on helping one source to send large quantities of data either to one or more than one destination. However, in industrial networks, short data packets are typically transmitted from several sensor nodes to one single gateway and thus, the problem of coding and relaying packets not from one, but from several different sources is more interesting. Moreover, some authors consider the choice of selecting the best relay node from a group of possible relayers, e.g., [85], or the most suitable deployment strategy for source and relay nodes, e.g., [98]. In industrial networks, sensor nodes are typically placed in strategic positions dictated by the application and can therefore not be moved. Furthermore, it is mainly actuators, having a permanent energy supply that can become relay nodes, and consequently the problem of choosing the best positions for relay and source nodes is often not applicable for industrial applications. However, given a specific position, proper selection of the best relaying technique is crucial for this type of networks. Some relay behavior strategies, combining fountain coding at the source node and XOR operations at the relay node, are discussed in [93], [99].

Another interesting and potentially beneficial technique for spatial diversity schemes is packet aggregation. Industrial packets are typically short, while the allocated time slots are usually large enough to accommodate the transmission of one packet of the maximum size, as allowed by the standard, and an immediate acknowledgment. Thus, when a relay node has several short packets it has overheard, it can concatenate some of them into one longer packet and send this instead of forwarding each packet separately [100]. By doing that, the relay node saves time slots which can be used either to provide additional reliability or to schedule more source transmissions in a superframe. Packet aggregation was shown to increase network capacity and decrease delays in various types of wireless networks in e.g., [101-103], but not much previous work have considered industrial wireless networks.

3.2. Relaying with FEC and Packet Combining

Luby and network coding combined with relaying promise to increase reliability in industrial wireless networks. However these schemes should be designed with care since a specific number of packets must be received by the destination to be able to decode all source packets. For example, with Luby coding, if less than k correct packets are received at the destination, all packets are undecodable and simple ARQ would have been better. This thesis work has shown that it often happens that the relay node does not receive the required number of source packets or that the destination does not have enough packets to perform network decoding. FEC coding then emerges as a possible way to increase the number of correctly received packets without increasing the delay.

However, FEC works the best when the number of bit errors is moderate, and for very challenging wireless channels, where errors appear in bursts that are longer than the error correction capability of the code, FEC is less useful. A lot of research work has been concentrated on introducing FEC into wireless sensor networks over the last years. Most of it was focused on energy efficiency of FEC coding schemes and FEC protocols developed to adapt to the channel conditions. However, industrial networks introduce additional requirements. To be used in industrial systems, FEC codes should be implementable on top of the often very simple chipsets used in industrial setting. In addition, they should be able to play out their advantages also for rather short industrial packets. Further, coding and decoding must be performed within the limited time specified in a superframe. Thus, adoption of some codes in industrial networks is prevented due to the short packets and timing limitations on the slot duration and thus basically only light-weight codes can be used in industrial networks [104, 105]. Preferably, the selected error control technique should also be tailored to the specific channel characteristics encountered in industrial environments. It is shown in e.g. [106] how the results achieved by the same FEC coding scheme, can vary for different wireless channels.

Additional reliability gains can be achieved by packet combining, where the nodes take advantage of multiple copies of the same packet travelling in the network [74, 107]. In schemes using retransmissions, relaying or network coding, it often happens that destination receives several copies of the same packet. In case all these copies contain errors, the destination node can perform packet combining to avoid additional retransmissions and thus not to increase latency. Packet combining stands for combining several erroneous copies of the same packet in an attempt to recover the original packet [107]. To perform combining, the destination node needs to work in promiscuous mode, where the hardware allows accepting erroneous packets. Several packet combining techniques exist, such as e.g., bitwise majority voting (MV), which can be applied for any odd number of copies of a packet; combinatorial testing, where different allocations of zeroes and ones are tested for the bits differing between packets and thus suspected to be in error and a checksum test is performed after each iteration; and maximal ratio combining, where perfect channel knowledge is assumed and packets are weighted accordingly.

An HARQ scheme with packet combining at the destination and where relay and source nodes collaboratively create a space-time-block-code was studied in [108]. Moreover, a cooperative network with FEC protected packets and a relay node performing network coding was considered in [109]. Finally, a scenario with one source node sending its HARQ packets to the destination and a relay node overhearing source transmissions and helping by relaying the packets was studied in [110]. In that work HARQ was used together with turbocoding and packet combining. However, none of these papers consider deadline-constrained applications, which is vital to the functionality of industrial wireless networks. In addition, to be adopted by industry, it is vital that all solutions are implementable on top of existing wireless standards, without requiring hardware changes [104, 105].

In this thesis work the applicability of the above techniques in industrial networks is studied and relaying is chosen as the most promising technique. Next, the benefits of relaying, Luby coding, packet aggregation, FEC and packet combining are merged together to improve reliability in wireless industrial networks.

3.3. Scheduling in Networks with Relaying

Apart from reliability improvements due to utilization of both time and space diversity, relaying can bring additional gain in terms of timeliness. Fig. 3.2 shows the comparison of a superframe structure of a traditional network with mesh topology and a mesh network where relaying is used. In both cases additional time slots for two retransmissions are allocated. The first retransmission is performed through the same route as the original transmission, while the other one is done through an alternative path. In a traditional mesh network, shown in Fig. 2.3 and Fig. 3.2, this requirement is fulfilled by scheduling one retransmission from the source node and one retransmission though an intermediate node. In the case of a retransmission using an intermediate node, the source first transmits its data to the intermediate node (orange colored slots in Fig. 3.2) and then, in the next time slot, the intermediate node forwards the data to the controller, if the packet was correctly received. When relaying is introduced into the network, each relay node is allowed to overhear packets from source nodes even if it is not stated as the final destination. Consequently, as the results of this thesis work show, the time slots, which would in a traditional mesh scheme be allocated to source nodes to send their data to the intermediate node (orange colored time slots in the Fig. 3.2), can be saved. These time slots may either be assigned for additional relay retransmissions for increased reliability, used to schedule more sources in a superframe, or alternatively, they can be dropped to reduce the jitter.

Additionally, this thesis work shows that by carefully scheduling source and relay time slots and by giving the relay nodes flexibility in the choice of which packets to send in case the originally planned transmission is not possible, the gain can be increased even further. For example, in case of a traditional mesh scheme, if a packet sent during an orange time slot in Fig. 3.2 is corrupted at the relay node, the corresponding blue time slot stays empty. In the proposed relaying protocols, where relay nodes are allowed to overhear packets sent by different sources, the relay node does not have to keep quiet in the blue slot in case it did not receive a particular source packet (as it would do in a traditional mesh scheme), but can instead retransmit another packet, thus increasing the overall reliability level. Consequently, it is especially important to carefully schedule the time slots to give the relay node as much choice as possible and thereby maximize the gain. WirelessHART requires that the scheduling starts with the sources having the shortest update rates, i.e. shortest deadlines [4]. Thus, often the schedule is made assigning slots to one source after another in accordance with e.g., earliest deadline first or rate monotonic scheduling. However, with this approach it often happens that the relay nodes have very few chances to overhear source packets before their transmission time slots are scheduled and thus they do not have much flexibility in the choice of which packet to transmit. Instead, when relaying is used it is important to schedule transmissions so that several sources transmit first, and thus relay nodes have the opportunity to overhear several source packets and have a set of packets to choose from when their transmission time slots come. If only one frequency channel is available, this requirement means that a superframe should start with source transmissions and retransmissions following one after another before any relay nodes are given any time slots, Fig. 3.2.

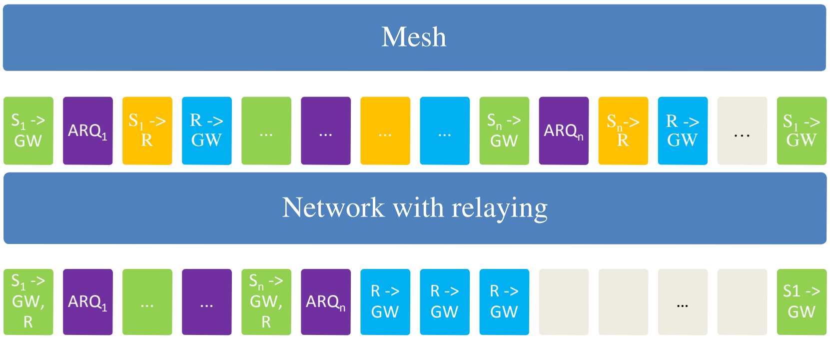

Fig. 3.2. Time slot allocation example for networks with and without relaying

Scheduling for wireless networks with relaying was addressed in [111], where the authors constructed several TDMA-based deadline-aware schedules, which were shown to reduce the average number of packets not meeting their deadlines. However, more work towards that direction is required.

Chapter 4
Methodology

The research methodology includes literature studies, interaction with industry in several industrial collaboration projects, numerical evaluations and, above all, extensive computer simulations, which were conducted to evaluate the proposed protocols. The research process adopted in this thesis is shown in Fig. 4.1. First, an initial literature study is made, a motivation is identified and the general research problem is formulated. The motivation is the insufficient reliability and timeliness provided by wireless networks when used in industrial applications. The main research question then becomes how can the reliability in industrial wireless networks be increased? Consequently, the first general goal of the research work is to increase the performance of industrial wireless networks. To narrow down the problem and to formulate concrete research questions, a new round of literature investigations is done. This revealed that industrial environments are harsh and thereby imply an additional challenge for wireless communication and thus known error-correction schemes must be adjusted to the specific environments in industrial settings. Thus, to answer the first research question, a literature study with the goal of finding tools and techniques which can be used to increase the performance of industrial wireless networks is performed. Once the study is completed, the process moves to the next step where a hypothesis that relaying can be successfully applied in industrial networks is formulated based on the application requirements from industrial automation. Next, an initial protocol, introducing relaying into industrial networks, is proposed and tested (Paper A). Performance is assessed through numerical evaluations and computer simulations. The process is hereafter iterative since new problems, challenges and ideas are found during the results collection and analysis stages. The feedback received during the results analysis and conclusions made after validation are used to formulate new research sub-goals and hypotheses and to propose new solutions. The new solutions (Papers B – F) are also investigated and tested following the steps in Fig. 4.1.

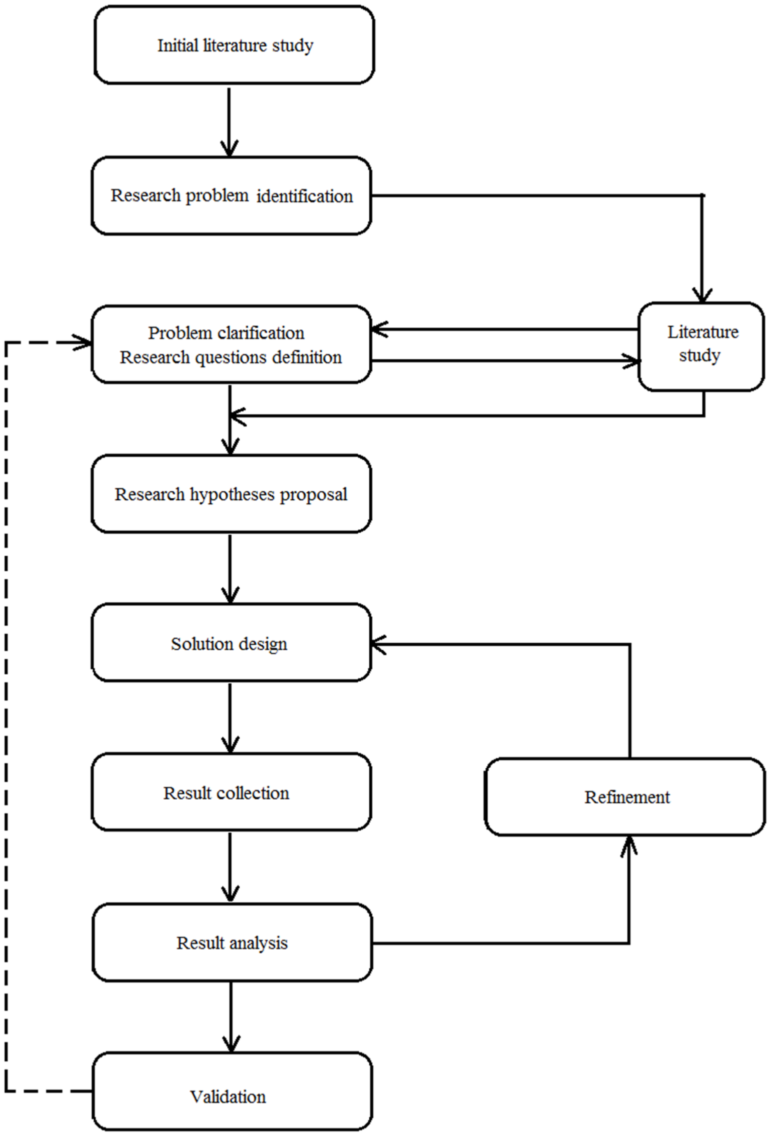

Fig. 4.1. Research process steps

Simulations in this work were performed in Matlab, although NS2 and OMNET++ are the most popular among the existing simulation environments. Matlab was chosen as the main simulation tool because of its mathematical models and its comparably low complexity. Using as few pre-programmed blocks as possible, the models of the wireless channel and its characteristics can be fully understood, such that errors resulting from incorrect use of built-in functions can be minimized.

Some of the important assumptions and simplifications made in the simulations are:

1. General assumptions:
    a. *The use of Rayleigh or Rician distributions to describe fading in industrial wireless environments.* No final conclusion has been drawn yet about the most suitable (fading) model describing industrial environments. However, most of the available research publications aiming to find models for approximating the effects of fading in harsh wireless environments, select Rayleigh or Rician models. To compensate for potential inaccuracies in the choice of fading model, most of the protocols described in this thesis have been evaluated with fading as well as without, and, in the case of fading, both with the presence of a LOS path and without.
    b. *The use of BPSK modulation instead of OQPSK, as adopted in IEEE 802.15.4, upon which most industrial standards are based.* The choice of BPSK decreases the complexity of the simulation programs without introducing notable performance differences. BPSK and QPSK with Gray mapping both have the same bit error probability for Gaussian channels, and the offset part in OQPSK is introduced to enable the use of simpler and thereby cheaper receivers. If we assume that receivers able to handle 180 degree phase shifts are available, the only major difference between BPSK and OQPSK that could occur is due to frequency selective fading over the frequencies used in the hopping sequence included in e.g., WirelessHART. However, since no final conclusions about the wireless environments encountered in industrial settings have yet been made, we assume frequency flat fading. This assumption can be revised later, when the dominating factors affecting channel quality in industrial environments have been established.
    c. *Assuming perfect error detection.* Assuming perfect cyclic redundancy check (CRC) codes provides an upper bound on performance. In the case of CRC check failure, possible consequences are decreased throughput, when correctly received packets are retransmitted, or reliability decrease, in the case when corrupted packets are not detected

and thereby not repeated as the protocol relies on a false positive outcome of the CRC check. However, given a good enough CRC code, the bound is tight. Instead of implementing a CRC code in the simulator, the number of errors in each received packet is checked. By doing this, simulations are simplified as the computation time decreases.

2. Assumptions in separate papers:
    a. *Transmission of keep-alive messages is not implemented in Paper B.* In Paper B, the presence of periodically transmitted keep-alive messages is assumed. Using these, the relay node can estimate the long-term packet error rates on the links between the sources and the controller. However as stated in the paper, instead of actually sending these messages in the simulator, the knowledge of pathloss and distances between nodes is used. Both fading and thermal noise change with time and affect signals differently during different superframes, while the pathloss is deterministic and thus contributing the most to the long-term error rate. Pathloss, affecting propagating signals, strictly depends on the distances between the nodes, decreasing the strength of the signal travelling to the nodes located furthest away the most.
    b. *Full Luby coding is not implemented in Paper B.* Instead of implementing an actual Luby encoder, a regular packet is sent by the relay node. Thereafter, all packets are considered successfully decoded only when the receiver is able to correctly receive at least k packets. This assumption does not affect the performance of the system, but significantly decreases the complexity of the simulator and its run time.
    c. *Reduced number of ARQ time slots in the simulator in Papers B, C and E.* In WirelessHART, each transmission would be followed by a retransmission attempt through the same path, before selecting an alternative route. However, in the simulators used in Papers B, C and E, the time slots allocated for retransmissions directly from the source nodes, denoted ARQ_1 – ARQ_n in Fig. 2.3 and Fig. 3.2 are omitted. As these time slots are present in all considered schemes, they do not significantly affect the comparison between the different approaches and simply prolong the simulation time. It is, however, likely that the extra retransmission slots from the source nodes would be beneficial for the relaying schemes proposed in the thesis, as they give the relaying nodes an additional opportunity to overhear the source packets. However, given that the number of consecutive packet errors is one of the performance indicators, these slots are excluded to reduce simulation time. Allowing excessive retransmissions would make the probability

of having three consecutive packet errors too small. It should, however, be noted that this feature can be introduced later to further improve the performance of relaying.

d. *Random assignment of source packets to retransmission time slots in Paper C.* In most practical cases, where a TDMA scheme is used, a certain transmitter-receiver pair is selected in advance for each time slot and thus, when the number of available before the deadline retransmission time slots is smaller than the number of sources, a specific subset of source nodes would always be assigned the retransmission slots. In this case, to get sufficient statistics about the evaluated protocols, simulations must be done for hundreds of different realizations of nodes positions. However, such simulations are excessively time and computational power consuming. Thus, in an attempt to constrain the simulation time, while still providing some average over different node positions, it was chosen in the paper to fix the positions of all nodes, and instead randomly select the sources assigned retransmission time in each superframe. In other words, when the protocol does not have any long-term feedback or knowledge of channel conditions between sources and destination, it randomly selects which source that is allowed to retransmit in cases when the number of time slots available for retransmissions is less than the number of sources.

e. *Equal channel PER for short source and long aggregated packets in Paper E.* Longer aggregated packets may have higher packet error rates, however for simulation simplicity we assume that all packets experience the same packet error rate. This is a reasonable assumption for packets with a relatively small maximum size (compared to other wireless technologies) of just 133 bytes in total. Additionally, with this assumption we thus consider the worst case scenario, where source packets are of the same length as longer aggregated packets and consequently experience higher channel PER than they might have experienced being of the original size.

Chapter 5

Overview of the Included Papers

There are six papers included in this thesis. Paper A treats the benefits of relaying itself and the differences in performance gain depending on the channel conditions, position and behavior strategy of the relay node. Once relaying was proven beneficial even in harsh industrial environments, it is studied further in combination with FEC coding, packet aggregation, packet combining and network coding (Papers B-E). Relaying for networks with sparse relay resources is evaluated (Papers C-D) as well as for a network where only source nodes perform relaying (Paper E). Additionally, for relaying to play out its full advantage the transmission order must be defined accordingly, and thus scheduling for networks with relaying is also considered in the thesis (Papers E-F).

The included papers together address both research questions. Paper A directly answers the first research question by considering spatial diversity techniques in detail and showing that relaying can be beneficial even when applied in harsh industrial environments. Next, Papers B and D evaluate relaying combined with Luby coding and FEC respectively and therefore also contribute to answering the first research question. All the papers included in the thesis look at the use cases of different relaying protocols and their benefits depending on various network and channel parameters and thus address the second research question regarding how, when and to which extend various techniques can be used.

5.1. Paper A

Title: The Effects of Relay Behavior and Position in Wireless Industrial Networks
Authors: Svetlana Girs, Elisabeth Uhlemann, and Mats Björkman
Status: published in the proceedings of IEEE International Workshop on Factory Communication Systems (WFCS), Lemgo, Germany, May 2012.

Short summary: The main goal of this paper is to evaluate how different types of communication channels encountered in industrial wireless environments affect the benefits of relaying. The modeled network consists of one sensor, sending data, one relay node and one destination. The positions of the sensor and the destination are fixed, while the position of the relay node is a parameter in the evaluation. The aim is to study the effects the relay node location has on performance, to find the most suitable acting strategy for the relay node given its position. Two types of relay acting strategies are studied: the relay node always retransmits whenever a retransmission is requested, or it only retransmits if it has obtained a correct copy of the packet – otherwise the source handles the retransmission. Three different scenarios are therefore evaluated: "ARQ but no relaying", "always relay" and "only relay when correct". The protocol performance is evaluated using computer simulations for different relaying scenarios and two types of channels: Rician and Rayleigh fading channels representing communication links with and without line of sight respectively. Also, theoretical expressions and bounds are derived, which are used to verify the correctness of the results from the simulations. The results clearly show that the benefits, the choice of the best position and behavior strategy of a relay node depend on the wireless channel, and whether or not the bit errors appear randomly or in bursts and also on the overall distance between the source and the final destination.

Paper contribution: Paper A extends the work in [73-75] by finding suitable behavior strategies for a relay node, given different locations and different types of wireless channels typically found in industrial environments. Interestingly, it can be concluded that the best position and behavior strategy for a relay node depends on the wireless channel, i.e., the type of fading, pathloss and overall distance between the source and the destination. For channels with a strong LOS, it is always best to select a relay node located midway between the source and the destination, while for channels with strong fading, this is not the case. For short distances between the source and the destination, coupled with strong fading and absence of LOS, the relay node should be located as close to the destination as possible, mimicking a multiple-antenna array, while for larger distances between the source and the destination, a relay midway in-between is better. Further, it can be concluded that the best behavior strategy for a relay node should be chosen depending on the particular performance requirements of the system; for applications sensitive to packet losses, it is better to only allow a relay node to relay if it has obtained a correct copy of the source packet. However, for systems that can handle some bit errors, possibly due to the presence of FEC coding, it is better to always allow the relay node to relay, i.e., forwarding even packets with bit errors.

Author's contribution: The author implemented the simulator for evaluation of the proposed relaying schemes, derived theoretical expressions and bounds, and analyzed the results. Furthermore, the author wrote the majority of the paper.

Knowledge gained after the paper was published: After the paper had been published it was discovered that an incorrect number for the pathloss at the reference distance $d_0 = 1$ m, was used in equation (7.3), i.e., $l(d_0) = -50$ dB should be changed to $l(d_0) = -40.2$ dB. This error affects the calculations in the paper and results in slightly worse values for the PER at a given distance or, alternatively, in shorter distances when requiring a specific PER value. Additionally, the thermal noise in the receiver circuitry, N_0, was erroneously assumed to be equal to -173 dBW instead of -173 dBmW, which made the results more optimistic. However, the errors discovered in the calculations affect only the absolute numbers presented in the paper, but do not affect the conclusions derived from the conducted work.

5.2. Paper B

Title: Increased Reliability or Reduced Delay in Wireless Industrial Networks Using Relaying and Luby Codes
Authors: Svetlana Girs, Elisabeth Uhlemann, and Mats Björkman
Status: published in the proceedings of IEEE International Conference on Emerging Technologies and Factory Automation (ETFA), Cagliari, Italy, Sept. 2013.

Short summary: Although relaying was proven to be beneficial, it is not always possible to install a separate relay node for every source and thus the main goal of this paper is to find the best behavior strategy for a relay node helping several, three in the considered case, sources to send their packets to a central controller before a common deadline. Luby coding at the relay node is proposed to increase the performance of the system, either in terms of increased reliability, given a fixed number of time slots allotted for retransmissions, or in terms of reduced delay, while maintaining a certain reliability level. To save time slots, the relay node is allowed to overhear the source packets transmitted from the sensors to the central controller. Following this, the relay node is assigned one or more time slots. Thus, based on the number of correct packets at the relay node and the number of available time slots for relaying, the relay node can either decide to forward one or more original source packets or to perform Luby coding and instead send one or more coded packets. However, to perform Luby coding, the relay node must have received all source packets correctly. Further, given that the relay node transmits Luby coded packets, the destination needs to receive at least the same amount of packets correctly as there are source nodes, otherwise none of the Luby coded packets can be decoded. Given that Luby coded packets can be constructed and decoded, all source nodes benefit from each Luby coded packet. In contrast, in case of relaying source data, the choice of which source to help must be made. Different relay node behavior algorithms are compared in order to find the one with the best performance. Simulations are conducted for different sizes of the deployment area, several values of the packet length and two types of fading channels. The performance of several relaying schemes, where one relay node helps three sources to send data to the destination node is evaluated. The results show that performance improvement can be achieved by combining Luby coding and relaying, and the gain is greatest when there are not enough available resources for all source nodes to retransmit, given that the wireless channel in between the sources and the relay is of sufficient quality, such that Luby coded packets can be constructed.

Paper contribution: In this paper an algorithm, combining the benefits of two spatial diversity techniques: relaying and Luby coding, is proposed and shown to improve performance in industrial wireless networks. Luby coding in combination with relaying significantly improves the performance of the system and also contributes to increased performance for all source nodes, even in cases when e.g., the deadline allows only a single retransmission slot. However, it can also be concluded that Luby coding is most advantageous when no feedback information is available at the relay or at the source nodes. This is due to the fact that erroneous or lost packets from any source node can be recovered from the Luby coded packets.

Author's contribution: The author implemented the proposed relaying scheme with Luby coding and analyzed the results. Moreover, most of the paper was written by the author.

Knowledge gained after the paper was published: Similar to Paper A, in Paper B the thermal noise in the receiver circuitry, N_0, was erroneously assumed equal to -173 dBW instead of -173 dBmW. However, this error affects the absolute numbers presented in the paper, but not the derived conclusions. All the trends and connections found in the paper are still the same regardless of the discovered error.

5.3. Paper C

Title: On the Role of Feedback for Industrial Wireless Networks Using Relaying and Packet Aggregation
Authors: Svetlana Girs, Andreas Willig, Elisabeth Uhlemann, and Mats Björkman
Status: published in the proceedings of IEEE International Conference on Industrial Technologies (ICIT), Busan, South Korea, Feb. 2014.

Short summary: Continuing the work started in Paper B, the main goal of this paper is to look further at the networks with one relay node serving several sources. In this paper the performance of relaying schemes with and without packet aggregation for systems with different types of available feedback information is evaluated. Rather than selecting only one source packet for forwarding, the relay node concatenates several source packets into one and instead relays such combined packets [101]. Obviously, all the source packets being aggregated must have the same final destination and be short enough to allow aggregation into one packet of a size smaller than what is maximally allowed by the standard. Such an aggregated packet structure was proposed in [100] for industrial systems. All the proposed algorithms are tested though simulations of a network with five sensor nodes, sending their data to a central controller and one relay node helping in the communication. The results show that the more freedom the relay node has in choosing its behaving strategy, the better the final results, i.e. the scheme combining aggregation and relaying works best for all considered feedback scenarios. When feedback information is available, the performance is improved even further.

Paper contribution: In this paper an algorithm combining the benefits of relaying and packet aggregation is proposed. Packet aggregation can either be used to reduce delay, as fewer time slots are needed to transmit the same number of packets, or, alternatively, increase the probability of correct packet reception, as time now allows retransmitting each packet several times. The simulations show that the more freedom the relay node has in choosing its behaving strategy, the better the final results are. However, packet aggregation schemes should also be designed with care, since longer packets have a higher probability of packet error. Given a carefully designed aggregation scheme, the evaluations show that performance is improved considerably for all types of available feedback.

Author's contribution: The author participated in the discussion of the initial problem formulation, implemented the proposed relaying and packet aggregation scheme, analyzed the results. Moreover, the author wrote most of the paper.

Knowledge gained after the paper was published: Similar to Papers A and B, in Paper C an incorrect value of -173 dBW instead of -173 dBmW was used to describe the thermal noise in the receiver circuitry, N_0. However, this error only affects the absolute numbers presented in the paper, not the derived conclusions. All the trends and connections found in the paper are unaffected.

5.4. Paper D

Title: Adopting FEC and Packet Combining to Increase the Performance of IWSNs Using Relaying
Authors: Svetlana Girs, Elisabeth Uhlemann, and Mats Björkman
Status: published in the proceedings of International Conference on Computing and Network Communications (CoCoNet), Trivandrum, India, Dec. 2015.

Paper summary: Previous work has shown that relaying improves the communication performance significantly, however, often relay nodes are not able to receive the source packets missing at the destination correctly and consequently they cannot assist by relaying. Thus, to benefit even further from relaying, additional measures should be taken both to increase the number of the correct packets at the relay node and to allow the destination to recover more correct packets. Consequently, the focus of this work is schemes enabling relaying, FEC and packet combining. Similar to Paper A, a network with one source node, one relay and one destination is considered and various relaying protocols are studied. Relaying is studied with and without FEC and packet combining. FEC is performed at both, the source node and the relay, while packet combining is done only at the destination for the packets received from the source and the relay. Three different FEC schemes are compared and the results show that the introduction of FEC and packet combining does improve performance by enabling relay nodes to help more often, however the exact performance gain depends on the specific FEC scheme used.

Paper contribution: A new FEC coding scheme is proposed in this paper and compared with two other previously investigated solutions. Additionally, the possibility of packet combining is considered for the cases when the destination node receives two erroneous copies of the same packet. The performance is evaluated for three wireless channel models. It was shown that introduction of FEC and packet combining does improve performance by giving the relay node an opportunity to help more often. However, the size of the preamble and other fields that must be left uncoded significantly affects the PER performance. Packet combining further improves the performance, although when FEC is applied, the improvement is not so large since packets with few errors are corrected by the FEC code and packets with many errors often exceed the capacity of the combinatorial testing algorithm used for combining. Packet combining is therefore likely more efficient if more retransmissions are allowed, as then more erroneous copies are available for combining.

Author's contribution: The author participated in the discussion of the initial problem formulation. The author implemented the studied relaying schemes with FEC coding and packet combining, analyzed the results. Furthermore, most of the paper writing was done by the author.

5.5. Paper E

Title: Scheduling for Source Relaying with Packet Aggregation in Industrial Wireless Networks
Authors: Svetlana Girs, Andreas Willig, Elisabeth Uhlemann, and Mats Björkman
Status: A shorter version of the paper is published in Proc. WFCS, whereas the included paper is submitted to a Special Section on IEEE Transactions on Industrial Informatics in June 2015 and is currently undergoing the third round of reviews.

Paper summary: Since it is not always possible or cost-efficient to deploy additional relay nodes in industrial systems, this paper evaluates the performance gain achieved from relaying and packet aggregation implemented at source nodes. Every source node is allowed to listen to the transmissions performed by other nodes and to aggregate one of the overheard packets with its own one. The more source nodes use the opportunity to aggregate, the better performance can be achieved and thus, it is important to set the order in which the sources transmit their data in a way so that the probability that all nodes, except the first one, have overheard at least one other packet to aggregate is maximized. Several source scheduling schemes both with and without channel adaptation were studied in this work as well as several different packet aggregation strategies. The results show that packet aggregation by itself leads to significant performance improvements. When the source transmission schedule is adjusted to the channel conditions, the gain grows and even further improvement can be achieved by making the choice of packet to aggregate, in case a source node has overheard several packets, aware of current source transmission schedule as well as the actions of other sources.

Paper contribution: In this paper, we propose to use a combination of relaying and packet aggregation at the source nodes to improve the overall network reliability. The proposed protocol enables each source to overhear packets transmitted by other sources, aggregate one of the overheard packets with its own one and transmit this aggregated packet in the time-slot assigned to this particular node. Additionally, a new adaptive scheduling scheme ordering the source transmissions based on the channel estimations is proposed. The results show that the schedule adapting to the varying channel conditions improves the performance substantially. By carefully choosing which packet to aggregate, even further improvements can be achieved.

Author's contribution: The author participated in the discussion of the initial problem formulation and implemented the simulation program for source relaying and adaptive scheduling protocols presented in the paper. Moreover, results analysis and most of the paper writing were done by the author.

5.6. Paper F

Title: Probabilistic Scheduling and Adaptive Relaying for WirelessHART Networks
Authors: Giuliana Alderisi, Svetlana Girs, Lucia Lo Bello, Elisabeth Uhlemann, and Mats Björkman
Status: published in proceedings of IEEE International Conference on Emerging Technologies and Factory Automation (ETFA), Luxembourg, Sept. 2015.

Paper summary: It was shown in the previous work that introduction of relaying significantly improves the performance of industrial wireless networks. However for relaying to be the most beneficial, the schedule used in the network should be built taking relaying into account. In this work a new scheduling approach taking channel characteristics between the nodes into consideration and adapted to maximize the performance gain from relaying is proposed. Initial results show that the schedule adapted to channel conditions and relaying performs better than a typical static schedule and allows to either save time slots maintaining the same reliability level or alternatively, to increase the reliability using the same number of time slots. In planned continuation of the work, scheduling for larger networks where relaying is allowed to be combined with FEC and packet aggregation will be considered.

Paper contribution: A new scheduling scheme, called Iterative Probabilistic Scheduling with Adaptive Relaying (IPS-AR), consisting of a static part (IPS) and a dynamic part (AR), is proposed in this work. IPS takes into account the channel characteristics and exploits relaying to achieve a minimum reliability threshold as requested by the supported industrial application. In the AR part, each relay node decides on the packet to be sent based on online assessment of both the number of consecutive errors experienced by previous packets belonging to the same flow, as well as the number of copies of the packet currently available at the other relay nodes. This enables IPS-AR to achieve the desired reliability level while using the available resources in terms of time and bandwidth more efficiently.

Author's contribution: The author participated in the discussion of the initial problem formulation, conducted a big part of the literature study, and wrote a large part of the paper. Also the author participated in the design of scheduling schemes and their analysis.

Chapter 6

Conclusions

The main goal of the current thesis is to increase the reliability of wireless communication systems applied in industrial environments. Wireless systems have many advantages compared to the currently used wired ones, but also some shortcomings which have to be resolved. Bit and packet error rates are much higher in wireless networks due to pathloss, fading and shadowing; working machinery, reflective surfaces and multiple moving objects typical for industrial environments imply additional challenges. Further, the reliability requirements in industrial applications are much higher than in traditional sensor networks since lost or delayed packets can lead to e.g. factory stop and thus significant economic losses.

Spatial diversity techniques have been shown to improve the communication performance of wireless systems and in this thesis their potential use in industrial networks is studied. Industrial systems put additional constraints on the techniques by requiring the use of of-the-shelf devices and allowing only minimum changes to existing standards. On the other hand, the usual constraint on energy consumption for most sensor networks is not so strict in industrial wireless networks since permanent energy supply is often present in industrial plants and this energy is allowed to be used to provide the required reliability levels since reliability and availability have higher priority.

Based on the requirements and constrains analysis, relaying was chosen as a good candidate technique to be used in industrial environments. In this thesis work relaying was studied both by itself and applied together with packet aggregation, packet combining, Luby and FEC coding. Various channel conditions, relay node positions and behavior strategies were also evaluated together with different types of networks, i.e. networks with sparse relay resources and networks where source nodes perform relaying. It was found that relaying significantly increases reliability, while introducing Luby coding and packet aggregation in cases when relay resources are sparse, improves performance even further. Additional gains can be achieved when FEC and packet combining are added. At the same time, the results show that the benefits of the proposed mechanisms depend on the assumed channel models and thus, a model that accurately describes the targeted industrial environments is essential. Given an appropriate channel model, the proposed relaying schemes can be tailored to the specific wireless environment, such that the reliability in industrial applications can be increased, with maintained delay – or alternatively, that the delay can be reduced, with maintained reliability levels, paving the way for reliable wireless industrial communications. Additionally, the performance evaluations showed that maximum gain from relaying is achieved when the scheduling scheme is adapted accordingly. Thus, scheduling protocols for the studied relaying schemes were also considered. The results conclude that relaying can be applied in industrial networks to acquire the desired levels of reliability and timeliness while introducing a minimum of additional complexity by implementing the solutions on top of existing wireless standards.

A few things were left out of the scope of the thesis and can be addressed in future work. Industrial channel characterization was done in the thesis based on literature studies only. Additional channel measurements to investigate and characterize industrial channels and confirm the conclusions from the literature study could be done. Additionally, the proposed relaying and scheduling schemes were studied through computer simulations and numerical evaluations only. Network coding together with relaying was proven to be implementable on industrial devices in [83], but similar tests could be done for the other schemes.

Bibliography

[1] J. Åkerberg, M. Gidlund, and M. Björkman, "Future research challenges of industrial wireless sensor networks," *Proc. Int. Conf. Ind. Inf.*, Lisbon, Portugal, July 2011, pp. 410-415.

[2] K. Sohraby, D. Minoli, and T. Znati, *Wireless Sensor Networks: Technology, Protocols, and Applications*: John Wiley & Sons, 2007.

[3] V. Ç. Güngör, and G. P. Hancke, *Industrial Wireless Sensor Networks: Applications, Protocols, and Standards*, Boca Raton: CRC Press Taylor&Francis Group, 2013.

[4] D. Chen, M. Nixon, and A. M. Mok, *Wireless HART: Real-Time Mesh Network for Industrial Automation*: Springer Science+Business Media, 2010.

[5] M. Baldi, R. Giacomelli, and G. Marchetto, "Time-Driven Access and Forwarding for Industrial Wireless Multihop Networks," *IEEE Trans. Ind. Inf.,* vol. 5, no. 2, pp. 99 - 112, 2009.

[6] G. Gamba, F. Tramarin, and A. Willig, "Retransmission Strategies for Cyclic Polling Over Wireles Channels in the Presence of Interference," *IEEE Trans. Ind. Inf.,* vol. 6, no. 3, pp. 405 - 415, 2010.

[7] H. Zhang, M. Albert, and A. Willig, "Combining TDMA with slotted Aloha for delay constrained traffic over lossy links," *Proc. 12th Int. conf. on Control, Automation, Robotics and Vision*, Guangzhou, China, Dec. 2012, pp. 701-706.

[8] D. Yang, Y. Xu, H. Wang *et al.*, "Assignment of Segmented Slots Enabling Reliable Real-Time Transmission in Industrial Wireless Sensor Networks," *IEEE Trans. on Ind. Electronics,* vol. 62, no. 6, pp. 3966-3977, 2015.

[9] E. Toscano, and L. Lo Bello, "Multichannel Superframe Scheduling for IEEE 802.15.4 Industrial Wireless Sensor Networks," *IEEE Trans. Ind. Inf.,* vol. 8, no. 2, pp. 337-350, 2012.

[10] A. Sikora, and V. F. Groza, "Coexistence of IEEE802.15.4 with other systems in the 2.4 GHz-ISM-band," *Proc. IMTC 2005 - Instrum. and Meas. Techn. Conf.*, Ottawa, Canada, 2005, pp. 1786-1791.

[11] D. Yang, Y. Xu, and M. Gidlund, "Wireless Coexistence Between IEEE 802.11-and IEEE 802.15. 4-based Networks: A Survey," *Int. Journal of Distributed Sensor Networks,* vol. 11, pp. 1-17, 2011.

[12] L. Lo Bello, and E. Toscano, "Coexistence Issues of Multiple Co-Located IEEE 802.15.4/ZigBee Networks Running on Adjacent Radio

Channels in Industrial Environments," *IEEE Trans. on Ind. Inf.,* vol. 5, no. 2, pp. 157-167, 2009.

[13] J. Ferrer-Coll, P. Ängskog, J. Chilo *et al.*, "Characterisation of Highly Absorbent and Highly Reflective Radio Wave Propagation Environments in Industrial Applications," *IET Commun.,* vol. 6, no. 15, pp. 2404-2412, 2012.

[14] J. Åkerberg, F. Reichenbach, M. Gidlund *et al.*, "Measurements on an Industrial Wireless HART Network Supporting PROFIsafe: A Case Study," *Proc. IEEE Conf. on Emerging Tech. and Factory Automation*, Toulouse, France, September 2011.

[15] A. Molish, *Wireless Communications*: John Wiley & Sons Ltd., 2005.

[16] C. F. Mecklenbräuker, A. F. Molish, J. Karedar *et al.*, "Vehicular Channel Characterization and its Implications for Wireless Systems Design and Perfomance," *Proceedings of The IEEE* vol. 99, no. 7, pp. 1189-1212, 2011.

[17] P. Di Marco, C. Fischione, F. Santucci *et al.*, "Effects of Rayleigh-lognormal fading on IEEE 802.15.4 networks," *Proc. IEEE Int. Conf. on Communic.*, Budapest, Hungary, June 2013, pp. 1666-1671.

[18] ZVEI, "Coexistence of Wireless Systems in Automation Technology," 2009.

[19] C. Ängskog, K. Karlsson, C. F. Coll *et al.*, "Sources of disturbances on wireless communication in industrial and factory environments," *Proc. Asia-Pacific Symp. on Electromag. Compatib.*, Bejing, China, April 2010, pp. 281-284.

[20] O. Staub, J. Zurcher, P. Morel *et al.*, "Indoor propagation and electromagnetic pollution in an industrial plant," *Proc. Int. conf. on Ind. Electr., Control and Instrum.* 1997, pp. 1198-1203.

[21] V. C. Gungor, B. Lu, and G. P. Hancke, "Opportunities and Challenges of Wireless Sensor Networks in Smart Grid," *IEEE Trans. Ind. Electr.,* vol. 57, no. 10, pp. 3557-3564, 2010.

[22] E. Tanghe, W. Joseph, L. Verloock *et al.*, "The Industrial Indoor Channel: Large-Scale and Temporal Fading at 900, 2400, and 5200 MHz," *IEEE Trans. on Wireless Communic.,* vol. 7, no. 7, pp. 2740-2751, 2008.

[23] S.-C. Kim, H. L. Bertoni, and M. Stern, "Pulse Propagation Characteristics at 2.4 GHz Inside Buildings," *IEEE Trans. Vehicular Tech.,* vol. 45, no. 3, pp. 579-592, 1996.

[24] S. Savazzi, S. Guardiano, and U. Spagnolini, "Wireless channel characterization and modeling in oil and gas refinery plants," *Proc. IEEE Int. Conf. on Ind. Tech.*, Cape town, South Africa, Feb. 2013, pp. 1546-1551.

[25] F. Darbari, I. A. Glover, and R. W. Stewart, “Channel and interference analysis for wireless sensor networks,” *Proc. IEEE Int. Conf. on Communic.*, Glasgow, UK, June 2007, pp. 3289-3294.

[26] D. Sexton, M. Mahony, Lapinski, M., and J. Werb, “Radio channel quality in industrial wireless sensor networks,” *Proc. Sensors for Ind. Conf.*, Houston, TX, Feb. 2005, pp. 88–94.

[27] L. Tang, K. Wang, Y. Huang *et al.*, “Channel Characterization and Link Quality Assessment of IEEE 802.15.4-Compliant Radio for Factory Environments,” *IEEE Trans. on Ind. Inf.,* vol. 3, no. 2, pp. 99-110, 2007.

[28] P. Agrawal, A. Ahlén, T. Olofsson *et al.*, “Long Term Channel Characterization for Energy Efficient Transmission in Industrial Environments,” *IEEE Trans. on Communic.,* vol. 62, no. 2, pp. 3004-3014, 2014.

[29] A. Willig, K. Matheus, and A. Wolisz, “Wireless Technology in Industrial Networks,” *Proceedings of the IEEE,* vol. 93, no. 6, pp. 1130-1151, 2005.

[30] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam *et al.*, “A Survey on Sensor Networks,” *IEEE Commun. Mag.*, pp. 102-114, 2002.

[31] G. P. Hancke, and G. P. Hancke, “Industrial wireless sensor networks: a selection of challenging applications,” *Proc. Conf. on Antennas and Propagation*, Prague, Czech Republic March 2012, pp. 64-68.

[32] L. Hou, and N. W. Bergmann, “System Requirments for Industrial Wireless Sensor Networks,” *IEEE*, 2010.

[33] K. S. Low, W. N. Win, and M. J. Er, “Wireless sensor networks for industrial environments,” *Proc. Int. conf. on comput. intelligence for modelling, control and automation* 2005.

[34] F. Pellegrini, D. Miorandi, S. Vitturi *et al.*, “On the Use of Wireless Networks at Low level of Factory Automation Systems,” *IEEE Trans. Ind. Inf.,* vol. 2, no. 2, pp. 129-143, 2006.

[35] A. Willig, “Recent and Emerging Topics in Wireless Industrial Communications: A Selection,” *IEEE Trans. Ind. Inf.,* vol. 4, no. 2, pp. 102-124, 2008.

[36] L. Doherty, J. Simon, and T. Watteyne, “Wireless Sensor Network Challenges and Solutions,” *MICROWAVE*, pp. 22-34, 2012.

[37] "802.15.1-2005 - IEEE Standard for Information technology - Local and metropolitan area networks - Specific requirements - Part 15.1a: Wireless Medium Access Control (MAC) and Physical Layer (PHY) specifications for Wireless Personal Area Networks (WPAN)," Reaffirmed Sept. 2010.

[38] D. Dzung, C. Apneseth, J. Endresen *et al.*, “Design and Implementation of a Real-Time Wireless Sensor/Actuator Communication System,” *IEEE,* vol. 2, pp. 433-442, 2005.

[39] "802.11-2012 - IEEE Standard for Information technology - Telecommunications and information exchange between systems Local and metropolitan area networks -Specific requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications."

[40] "http://www.zigbee.org," ZigBee Alliance.

[41] Chinese Industrial Wireless Alliance, http://www.industrialwireless.cn/en/index.asp.

[42] American National Standards Institute, Washington DC., *ANSI/ISA100.11a-2011 - Wireless systems for industrial automation: Process control and related applications*, 2011.

[43] S. Petersen, and S. Carlsen, “WirelessHart versus ISA100.11a: The Format War Hits the Factory Floor ” *IEEE Ind. Elec. Mag.,* vol. 5, no. 4, pp. 23-34, 2011.

[44] HART Communication Foundation, *TDMA Data Link Layer Specification, HCF SPEC 075 Revision 1.1*, 17 May, 2008.

[45] IEEE Standards Association, "IEEE Standard for local and metropolitan area networks," *PART 15.4: Low rate Wireless Personal Area Networks (LR-WPANs) Amendment 1: MAC sublayer*, IEEE, 2012.

[46] L. Seno, S. Vitturi, and F. Tramarin, “Tuning of IEEE 802.11 MAC for improving real-time in industrial wireless networks,” *Proc. IEEE Conf. on Emerging Tech. and Factory Automation*, Krakow, Poland, Sept. 2012, pp. 1-8.

[47] D. Koscielnik, “Simulation Study of IEEE 802.11e Wireless LAN - Enhancements for Real Time Applications,” *Proc. IEEE Int. Symp. on Ind. Electronics*, Montreal, Quebec, Canada, Jul. 2006, pp. 1875-1880.

[48] S. Cavalieri, and D. Panno, “On the integration of FieldBus traffic within IEEE 802.11 wireless LAN,” *Proc. IEEE Int. Workshop on Factory Communic. Systems*, Oct. 1997, pp. 131-138.

[49] N. Krommenacker, and V. Lecuire, “Building industrial communication systems based on IEEE 802.11g wireless technology,” *Proc. IEEE Conf. on Emerging Tech. and Factory Automation*, Catania, Italy, Sept. 2005, pp. 71-78.

[50] G. Cena, L. Seno, A. Valenzano *et al.*, “On the Performance of IEEE 802.11e Wireless Infrastructures for Soft-Real-Time Industrial Applications,” *IEEE Trans. on Ind. Inf.* , vol. 6, no. 3, pp. 425-437, 2010.

[51] K. S. Ting, G. K. Ee, C. K. Ng *et al.*, “The performance evaluation of IEEE 802.11 against IEEE 802.15.4 with low transmission power,” *Proc. Asia-Pacific Conf. on Communic.*, Kota Kinabalu Sabah, Malaysia, Oct. 2011, pp. 850-855.

[52] T. Lennvall, S. Svensson, and F. Hekland, “A comparison of WirelessHART and ZigBee for industrial applications,” *Proc. IEEE Int. Workshop on Factory Communic. Syst.*, Dresden, Germany 2008, pp. 85-88.

[53] J. Song, S. Han, A. M. Mok *et al.*, “WirelessHART: applying wireless technology in real-time industrial process control,” *Proc. IEEE Real-Time and Embedded Tech. and App. Symp.*, St. Louis, Missouri, USA Apr. 2008, pp. 377-386.

[54] HART Communication Foundation, *HART Communication Protocol Specification, HCF SPEC 013, Revision 7.5*, May, 2013.

[55] IETF 6TSCH mailing list, https://www.ietf.org/mailman/listinfo/6tsch.

[56] IEEE 802.15.4a-2007, "Part 15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (WPANs); Amendment 1: Add Alternate PHYs," 2007.

[57] E. Karapistoli, F.-N. Pavlidou, I. Gragopoulos *et al.*, “An Overview of the IEEE 802.15.4a Standard,” *IEEE Communic. Magazine,* vol. 48, no. 1, pp. 47-53, 2010.

[58] G. Anastasi, D. D. Guglielmo, and A. Seghetti, "From IEEE 802.15.4 to IEEE 802.15.4e: a Step towards the Internet of Things," pp. 135-152: Springer, 2014.

[59] D. Chen, M. Nixon, S. Han *et al.*, “WirelessHART and IEEE 802.15.4e,” *Proc. IEEE Int. Conf. on Ind. Tech.*, Busan, Korea, Feb. 2014, pp. 760-765.

[60] T. Andre, G. Brandner, N. Marchenko *et al.*, “Measurement-based analysis of cooperative relaying in an industrial wireless sensor network,” *Proc. IEEE Global Communic. Conf.*, Anaheim, California, Dec. 2012, pp. 549-554.

[61] S. N. Diggavi, N. Al-Dhahir, A. Stamoulis *et al.*, “Great Expectations: The Value of Spatial Diversity in Wireless Networks,” *Proc. of the IEEE,* vol. 92, no. 2, pp. 219-270, 2004.

[62] X. S. Shen, A. Hjrungnes, Q. Zhang *et al.*, “Special issue on cooperative networking – challenges and applications (part 1),” *IEEE Journal on Selected Areas in Communic.,* vol. 30, no. 2, pp. 241–244, 2012.

[63] N. Marchenko, T. Andre, G. Brandner *et al.*, “An Experimental Study of Selective Cooperative Relaying in Industrial Wireless Sensor

Networks," *IEEE Trans. on Ind. Inf.,* vol. 10, no. 3, pp. 1806-1816, 2014.

[64] A. Willig, "How to Exploit Spatial Diversity in Wireless Industrial Networks," *IFAC Annual Reviews in Control,* vol. 32, no. 1, pp. 49-57, 2008.

[65] Y. Li, "Distributed Coding for Cooperative Wireless Networks: And overview and Recent Advances," *IEEE Commun. Mag.,* vol. 47, no. 8, pp. 71-77, 2009.

[66] D. D. Tan, G.-Y. Lee, and D.-S. Kim, "Distributed relay assignment with interference limitation for industrial wireless networks," *Proc. IEEE Int. Conf. on Ind. Inf.*, Bochum, Germany, July 2013, pp. 36-41.

[67] T. Andre, P. Arumugam, and C. Bettstetter, "Experimental evaluation of multihop-aware cooperative relaying," *Proc. Int. Symp. on Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks*, Mumbai, India, May 2015, pp. 96-101.

[68] T. M. Cover, and A. El Gamal, "Capacity Theorems for the Relay Channel," *IEEE Trans. on Information Theory,* vol. 25, no. 5, pp. 572-584, 1979.

[69] N. Laneman, D. Tse, and G. Wornell, "Cooperative Diversity in Wireless Networks: Efficient Protocols and Outage Behavior," *IEEE Trans. on Information Theory,* vol. 50, no. 12, pp. 3062-3080, 2004.

[70] A. Nosratinia, T. E. Hunter, and A. Hedayat, "Cooperative Communication in Wireless Networks," *IEEE Commun. Mag.,* vol. 42, no. 10, pp. 74-80, 2004.

[71] B. Zhao, and M. C. Valenti, "Practical Relay Networks: a Generalization of Hybrid-ARQ," *IEEE Journal on Selected Areas in Communic.,* vol. 23, no. 1, pp. 7-18, 2005.

[72] A. S. Ibrahim, A. K. Sadek, W. Su *et al.*, "Cooperative Communications with Relay-Selection: When to cooperate and Whom to Cooperate With?," *IEEE Transactions on Wireless Communications,* vol. 7, no. 7, pp. 2814-2827, 2008.

[73] J. Cannons, L. B. Milstein, and K. Zeger, "An Algorithm for Wireless Relay Placement," *IEEE Transactions on Wireless Communications,* vol. 8, no. 11, pp. 5564-5574, 2009.

[74] E. Uhlemann, and A. Willig, "Joint design of relay and packet combining schemes for wireless industrial networks," *Proc. IEEE Vehicular Tech. Conf.*, Singapore, May 2008, pp. 2441–2445.

[75] R. Liu, I. J. Wassell, and K. Soga, "Relay node placement for wireless sensor networks deployed in tunnels," *Proc. IEEE Int. Conf. Wireless and Mobile Computing, Networking and Commun.*, Niagara Falls, ON, Oct. 2010, pp. 144–150.

[76] A. Willig, and E. Uhlemann, “On relaying for wireless industrial communications: Is careful placement of relayers strictly necessary?,” *Proc. IEEE Int. Workshop Factory Commun. Syst.*, Lemgo, Germany, May 2012, pp. 191-200.

[77] A. Willig, “Placement of relayers in wireless industrial sensor networks: an approximation algorithm,” *Proc. IEEE Int. Conf. on Intelligent Sensors, Sensor Networks and Inf. Processing*, Singapore, Apr. 2014.

[78] T. Andre, N. Marchenko, G. Brandner *et al.*, “Measurement-based analysis of adaptive relay selection in industrial wireless sensor networks,” *Proc. Int. Symp. on Modeling and Optimization in Mobile, Ad Hoc and Wireless Networks*, Tsukuba Science City, Japan, May 2013, pp. 113-118.

[79] S. Savazzi, R. H. de Souza, and L. Buss Becker, “Wireless network planning and optimization in oil and gas refineries,” *Proc. Brazilian Symp. on Computing Systems Engineering*, Niterói/RJ, Brazil 2013, pp. 29-34.

[80] M. Younisa, and K. Akkayab, “Strategies and Techniques for Node Placement in Wireless Sensor Networks: A Survey,” *Ad Hoc Networks,* vol. 6, no. 4, pp. 621-655, 2007.

[81] S.-Y. R. Li, R. W. Yeung, and N. Cai, “Linear Network Coding,” *IEEE Trans. on Information Theory,* vol. 49, no. 2, pp. 371-381, 2003.

[82] C. Fragouli, D. Katabi, A. Markopoulou *et al.*, “Wireless network coding: opportunities & challenges,” *Proc. IEEE Military Communic. Conf.* , Orlando, Florida, Oct. 2007, pp. 1-8.

[83] O. Valle, C. Montez, G. Araujo *et al.*, “A WSN data retransmission mechanism based on network coding and cooperative relayers,” *Proc. World Conf. on Factory Communic. Systems*, Palma de Mallorca, Spain, May 2015.

[84] D. J. C. MacKay, “Fountain Codes,” *IEE Proc. Commun.,* vol. 152, no. 6, pp. 1062-1068, 2005.

[85] J. Manssour, A. Osseiran, and S. B. Slimane, “Opportunistic relay selection for wireless network coding,” *Proc. IEEE 9th Malaysia Int. Conf. on Commun.*, Kuala Lumpur, Malaysia, Dec. 2009, pp. 102-106.

[86] M. Luby, “LT Codes,” *Proc. 43rd Annual IEEE Symp. Foundations of Computer Science*, Nov. 2002, pp. 271-282.

[87] J. Castura, and Y. Mao, “Rateless Coding over Fading Channels,” *IEE Communic. Letters,* vol. 10, no. 1, pp. 46 - 48, 2006.

[88] Y. Ma, D. Yuan, and H. Zhang, “Fountain codes and applications to reliable wireless broadcast system ” *Proc. IEEE Inf. theory workshop* 2006, pp. 66-70.

[89] A. Hagedorn, S. Agarwal, D. Starobinski *et al.*, “Rateless coding with feedback,” *Proc. IEEE conf. on copmuter commun.*, Rio de Janeiro, Brazil, Apr. 2009, pp. 1791-1799.

[90] J. W. Byers, M. Luby, and M. Mitzenmacher, “Accessing multiple mirror sites in parallel: using tornado codes to speed up downloads,” *Proc. Joint Conf. of the IEEE Computer and Communic. Societies*, New York, NY, USA 1999, pp. 275–283.

[91] J. W. Byers, M. Luby, M. Mitzenmacher *et al.*, “A digital fountain approach to reliable distribution of bulk data,” *Proc. Conf. on Applic., Tech., Architectures, and Protocols for Computer Communic. (SIGCOMM)*, Vancouver, BC, Canada, Aug. 1998, pp. 56-67.

[92] P. Casari, M. Rossi, and M. Zorzi, “Fountain codes and their application to broadcasting in underwater networks: performance modeling and relevant tradeoffs,” *Proc. ACM int. workshop on Underwater Networks*, San Francisco, California, USA, Sept. 2008, pp. 11-18.

[93] P. Pakzad, C. Fragouli, and A. Shokrollahi, “Coding schemes for line networks,” *Proc. IEEE Int. Symp. on Inf. Theory*, Adelaide, Australia 2005, pp. 1853-1857.

[94] R. Gummadi, and R. S. Sreenivas, “Relaying a fountain code across multiple nodes ” *Proc. IEEE Inf. Theory Workshop*, Porto, Portugal, May 2008, pp. 149 - 153

[95] A. F. Molisch, N. B. Mehta, J. S. Yedidia *et al.*, “Performance of Fountain Codes in Collaborative Relay Networks ” *IEEE Trans. on Wireless Commun.,* vol. 6, no. 11, pp. 4108 - 4119 2007.

[96] H. Liu, W. Lei, and X. Xie, “Multi-hop Relay Pairs Transmission Scheme Based on Fountain Code,” *Proc. IEEE Int. Conf. on Wireless Communic. and Signal Proc.*, Nanjing, China, Nov. 2011, pp. 1-6.

[97] J. Liang, J. Wang, and J. Chen, “An overhearing-based scheme for improving data persistence in wireless sensor networks,” *Proc. IEEE Int. Conf. on Communic.*, Cape Town, South Africa, May 2010, pp. 1-5.

[98] R. R. Rout, S. K. Ghosh, and S. Chakrabarti, “Network coding-aware data aggregation for a distributed wireless sensor network,” *Proc. Int.Conf. on Ind. and Inf. Systems* Peradeniya, Sri Lanka, Dec. 2009, pp. 32-36.

[99] A. Apavatjrut, C. Goursaud, K. Jaffres-Runser *et al.*, “Towards Increasing Packet Delivery for Relaying LT Fountain Codes in Wireless Sensor Networks,” *IEEE Commun. Lett.,* vol. 15, no. 1, pp. 52-54, 2011.

[100] J. Neander, T. Lennvall, and M. Gidlund, “Prolonging wireless HART network lifetime using packet aggregation,” *Proc. IEEE Int. Symp. Ind. Elec.*, Gdansk, Poland Jun. 2011, pp. 1230 - 1236.

[101] E. Fasolo, M. Rossi, J. Widmer *et al.*, “In-Network Aggregation Techniques for Wireless Sensor Networks: a Survey,” *IEEE Wireless Comunic.,* vol. 14, no. 2, pp. 70-87, 2007.

[102] R. Raghavendra, A. P. Jardosh, E. M. Belding *et al.*, “IPAC: IP-based Adaptive Packet Concatenation for Multihop Wireless Networks,” *Proc. Fortieth Asilomar Conf. on Signals, Systems and Computers*, Pacific Grove, California, USA, Oct. 2006, pp. 2147-2153.

[103] D. Kliazovich, and F. Granelli, “On packet concatenation with QoS support for wireless local area networks,” *Proc. IEEE Int. Conf. on Communic.*, Seoul, South Korea, May 2005, pp. 1395-1399.

[104] K. Yu, M. Gidlund, J. Åkerberg *et al.*, “Reliable and Low Latency Transmission in Industrial Wireless Sensor Networks,” *Proc. Int. Workshop on Wireless Networked Control Systems* Ontario, Canada, Sept. 2011, pp. 866-873.

[105] Y. H. Yitbarek, K. Yu, J. Åkerberg *et al.*, “Implementation and evaluation of error control schemes in industrial wireless sensor networks,” *Proc. IEEE Int. Conf. on Ind. Tech.*, Busan, Korea, Feb. 2014, pp. 730-735.

[106] F. Barac, M. Gidlund, and T. Zhang, “Scrutinizing Bit- and Symbol-Errors of IEEE 802.15.4 Communication in Industrial Environments,” *IEEE Trans. on Instrumentation and Measurement,* vol. 63, no. 7, pp. 1783-1794, 2014.

[107] E. Uhlemann, and A. Willig, “Hard decision packet combining methods for industrial wireless relay networks ” *Proc. Int. Conf. on Communic. and Electr.*, Hoi An City, Vietnam Jun. 2008, pp. 104-108

[108] I. Stanojev, O. Simeone, Y. Bar-Nes *et al.*, “Performance of Multirelay Collaborative Hybrid-ARQ Protocols Over Fading Channels,” *IEEE Communic. Letters,* vol. 10, no. 7, pp. 522-524, 2006.

[109] T. X. Vu, P. Duhamel, and M. D. Renzo, “Performance Analysis of Network Coded Cooperation with Channel Coding and Adaptive DF-Based Relaying in Rayleigh Fading Channels,” *IEEE Signal Processing Letters,* vol. 22, no. 9, pp. 1354-1358, 2015.

[110] I. Khalil, A. A. Khan, and Zohaib-Ur-Rehman, “Turbo-coded HARQ with switchable relaying mechanism in single hop cooperative wireless system,” *Proc. Int. Conf. on Frontiers of Inf. Tech.*, Islamabad,Pakistan, Dec. 2011, pp. 253-257.

[111] A. Willig, and E. Uhlemann, “Deadline-Aware Scheduling of Cooperative Relayers in TDMA-Based Wireless Industrial Networks,” *Wireless Networks,* vol. 20, no. 1, pp. 73-88, 2014.