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Wireless Sensor Networks in Industrial Automation

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1. Introduction

Wireless sensor networks (WSN) are gaining the ground in all sectors of life; from homes to factories, from traffic control to environmental and habitat monitoring. Monitoring seems to be the key word. Wireless systems can take control actions, too and in this way they compete e.g. with existing process automation systems or with conventional home automation.

WSN consist of nodes. A node in the sensor network includes a microcontroller, data storage, sensor, analogue-to-digital converters (ADC), a data transceiver, controllers that tie the pieces together, and an energy source. The nodes connect to each other using different architectures depending on the applications and surrounding environment. Several architectures, usually called network topologies, are possible: star, cluster-tree and mesh. In different topologies, sensor nodes can act as simple data transmitters and receivers or routers working in a multi-hop fashion (Aakvaag et al., 2005).

Energy is the limiting resource in WSN. A simple microcontroller may operate at 1 mW/10 MHz. When most of the circuits are turned off (in standby/sleep mode), the power consumption is typically about 1 μ W. The amount of energy needed to communicate wirelessly increases rapidly with distance and obstructions further attenuate the signal. WSN radios' energy consumption is about 20 mW and their range is typically tens of meters. The network minimizes the energy consumption by eliminating communications or turning off the radio, when communications do not occur. There are several possibilities: local processing of data in nodes, communicating, only if something of interest occurs, data aggregation, compression and scheduling, assigning certain tasks for special nodes and turning off radio, when uninteresting packet is received (Culler et al., 2004).

Recently, the use of WSN in industrial automation has gained attention. The proposed and already employed technologies vary from short-range personal area networks to cellular networks, and in some cases, even global communications via satellite are applied. In industrial environments, the coverage area of WSN as well as the reliability of the data may suffer from noise, co-channel interferences, and other interferers (Low et al., 2005). For example, the signal strength may be severely affected by the reflections from the walls (multi-path propagation) (Werb & Sexton, 2005), interferences from other devices using ISM bands (Low et al, 2005), and by the noise generated from the equipments or heavy

machinery (Werb & Sexton, 2005). In these conditions, it is important to maintain data integrity for operation-critical data, for example alarms (Low et al., 2005). All these factors set a special emphasis on automation design and the fact that WSN are technically challenging systems, requiring expertise from several different disciplines, emphasizes this. Additionally, requirements for industrial applications are often stricter than in other domains, since the system failure may lead to loss of production or even loss of lives. (Low et al., 2005); (Werb & Sexton, 2005).

This Chapter discusses wireless sensor networks in industrial automation, focusing especially on performance issues, both in the design phase and during actual operation. The Chapter will proceed as follows: Section 2 introduces industrial applications. Moreover, a demo system, developed by Control Engineering Laboratory, University of Oulu, is presented as an example. Section 3 concerns the protocols and standards in the industrial WSN. In Section 4, the interferences in industrial environment are discussed briefly. Finally, networked control systems are addressed in Section 5, and a list of references given in Section 6.

2. WSN in Industrial Applications

From industrial point of view, ISA SP100 workgroup introduces six classes (Class 5 – Class 0) for wireless communications based on analysis of industrial, inter-device wireless communication applications (ISA SP100.11, 2006).

Class 5 defines items related to monitoring without immediate operational consequences. This class covers applications without strong timeliness requirements. The reliability requirements may vary. Class 4 defines monitoring with short-term operational consequences. This includes high-limit and low-limit alarms and other information that may require further checking or involvement of a maintenance technician. Timeliness of information in this class is typically low (slow). Class 3 covers open loop control applications, in which an operator, rather than a controller, “closes the loop” between input and output. For example, an operator could take a unit offline, if required. The time horizon for this class is in a human scale, measured in seconds and minutes. Class 2 consists of closed loop supervisory control, and applications usually have long time constants, with the time scale measured in seconds to minutes. Class 1, closed loop regulatory control, includes motor and axis control as well as primary flow and pressure control. The timeliness of information in this class is often critical. Class 0 defines emergency actions related to safety, which are always critical to both personnel and the plant. Most safety functions are, and will be, carried out by dedicated wired networks in order to limit both failure modes and vulnerability to external events or attacks. Examples in this category are safety interlock, emergency shutdown, and fire control. (ISA SP100.11, 2006)

According to survey results (Hoske, 2006), the leading application for industrial networks (both wired and wireless) is supervisory control and data acquisition (SCADA). Next are diagnostics, testing, maintenance; both continuous and batch processing; motion control, robotic equipment; and machine control. Furthermore, the applications include pump, fan, and blower applications; continuous processing; packaging machines; materials handling equipment (elevators, cranes, hoists); and discrete product manufacturing. The most used means of communication are Ethernet TCP/IP, RS232 and 4-20 mA. Ten most used networks, communications and protocols did not include wireless alternatives.

However, applications of wireless technologies will grow especially in following areas (Low et al., 2005):

- Rare event detection
- Periodic data collection
- Real-time data acquisition
- Control
- Industrial mobile robots
- Real-time inventory management

WSN applies for example to bearings of motors, oil pumps, engines, vibration sensors on packing crates, or to many inaccessible or hazardous environments. For these environments, the wired solution may be impractical due to e.g. isolation required for cables running near to high humidity, magnetic field or high vibration environment. Wireless solutions are feasible for mobile applications. (Low et al., 2005)

Compared to wired solutions in industrial applications, the wireless systems and WSN have several advantages. These include, for example (Aakvaag et al., 2005); (Low et al., 2005); Shen et al., 2004); (US Department of Energy, 2007) :

- Flexibility in installing/upgrading network
- Reduced deployment and maintenance costs
- Decentralization of automation functions
- Better coping with regulatory and safety obstacles in running cables in constricted or dangerous areas
- Applicable for moving and rotating equipment
- Improved fault localization and isolation: for example, critical tasks are often ensured with redundant wires, which may pose difficulties for fault location and isolation
- Incorporating short-range technologies to automation system (which has possible interfaces to wide area networks) forms a heterogeneous network, which may improve automation system efficiency
- Exploitation of micro-electromechanical systems (MEMS): integrated wireless sensors with built-in communication capabilities offer a more robust design than attaching wires to small-sized devices.

A small demo system was developed in Control Engineering Laboratory, University of Oulu for testing the performance of WSN in industrial environment. A steam boiler produces steam for a laboratory-scale chemical pulping process. The process uses fuel oil and includes the water storage tank, boiler, and pipelines. The feed water temperature is approximately 20 °C and after the boiler, the steam temperature is approximately 200 °C. There are four measurements implemented: three for the temperature and one for the steam pressure. Fig. 1 shows the measurement locations.

The temperature is measured from the flame in the combustion chamber (the required measuring range from the room temperature to approximately 1500 °C), from the combustion gas pipe (from the room temperature to over 300 °C) and from the surface of the steam pipe (from the room temperature to approximately 300 °C). The pressure, which normally is approximately 13 bar, is measured from the bypass manifold. During shutdowns and maintenance operations, however, the pressure may vary between 0-40 bars. The lower temperatures from the combustion gas pipe and from the surface of the steam pipe are measured by Pt100-sensors. Since the measurements are located closely to each

other, the sensors are attached into one two-channel wireless transceiver node. The higher temperature from the flame in the combustion chamber is measured with the S-type thermocouple and it has its own wireless transceiver node. For the thermocouple, the mains power is required for the transmitter head. Additionally, the pressure sensor has its own wireless transceiver node and requires the mains power. Altogether, the equipment has three nodes and one gateway (Fig. 2). The gateway uses the OPC interface, which passes the measurement information to the LabVIEW™ development system. The test environment has potential sources of disturbances such as thick cement walls, metal pipes, humidity, and varying temperatures.

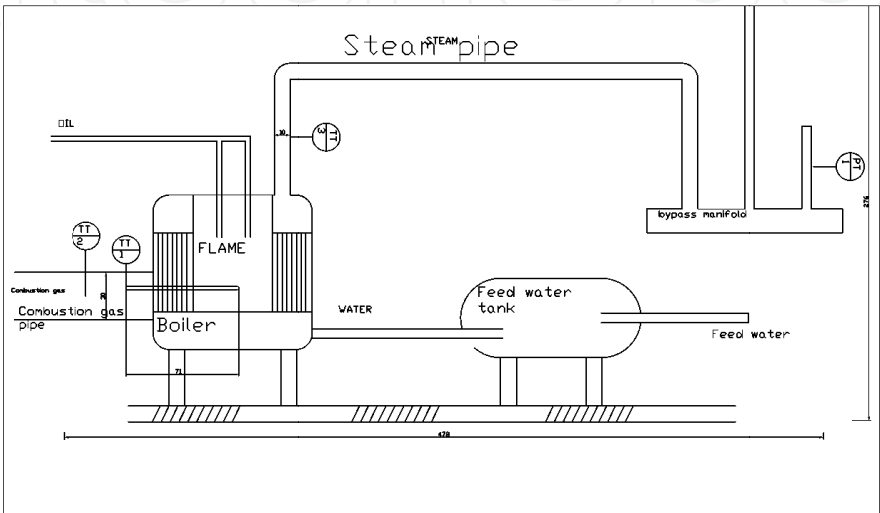


Fig. 1. The steam boiler process with measurements.

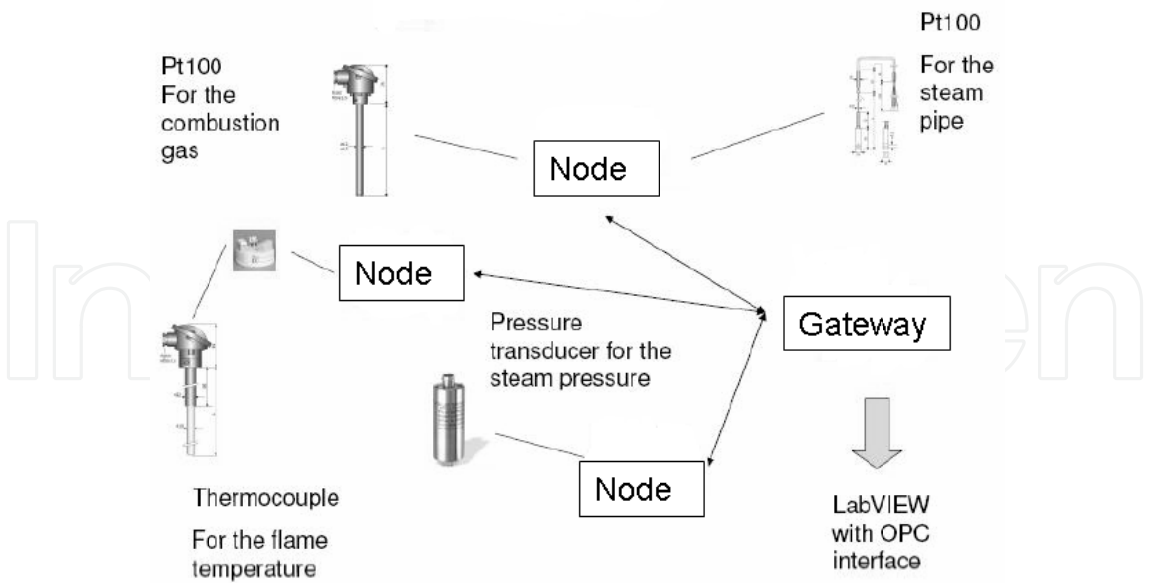


Fig. 2. The WSN and sensors applied for monitoring the temperatures and the pressure of the steam boiler.

Concerning the ISA classes, the steam boiler monitoring application belongs to class 4. For example, it could be used to inform operator about abnormal changes in pressure or temperature. Due to the slow process, the requirements for message timeliness are low, however. Typically, the measurement is expected to arrive within tens of seconds. The performance of the WSN in the presence of interferences is discussed briefly in Section 4 and more detailed in (Paavola & Ruusunen, 2008). More information about the application, for example requirements definition and lessons learned, can be found from (Paavola, 2007).

3. Protocols and standards in the industrial WSN

3.1 Protocols

As mentioned above, the application requirements for the wireless communications in the industrial environments may vary significantly. Taking the demo system presented in this Chapter as an example, the amount of data is little and the acceptable latency within tens of seconds. On the other hand, at the lowest level of the factory automation systems, also a limited amount of data is exchanged, but within very strict real-time constraints, typically 10 ms (Vitturi et al., 2007). These cases provide very different requirements for the WSN protocol stack (see Fig. 3).

In order to introduce radio-based technologies to the industrial automation systems, the automation domain specific requirements have to be fulfilled. These requirements include guarantees for the real-time (RT) behaviour, functional safety, and security (Neumann, 2007). However, the primary objective of the wireless sensor network design has been to maximise the lifetime of the network and nodes, leaving the other performance metrics as secondary objectives (Demirkol et al., 2006). Indeed, many schemes presented in the literature do not concentrate on the joint energy conservation and real-time (RT) performance (Pantazis et al., 2009). It should also be noted, that in some industrial applications, especially in the factory automation domain, the energy consumption may not be critical requirement since mains power is generally available (Flammini et al., 2009).

In this section, the protocols applied in the industrial WSN are discussed, excluding the proprietary protocols (a short introduction to several industrial communication systems as well as to some proprietary protocols can be found in (Neumann, 2007)).

Regarding to industrial WSN protocol development the following requirements can be found from the literature:

- RT, reliable communication, also in heterogeneous networks (Heo et al., 2009)
- Coping with transient interferences: guarantee deterministic and timely data delivery in case of temporary link failures (Song et al., 2006)
- Design, that takes the resource-constraints of the WSN (low processing power, limited energy and small memory) into account (Al-Karaki & Kamal, 2004); (Akyildiz et al., 2002)
- Energy-efficiency: operate at low duty cycles, maximising shutdown intervals between packet exchanges (Rowe et al., 2008))
- Deterministic node lifetime (Rowe et al., 2008)
- Scalability (Rowe et al., 2008)
- Capability for localisation, synchronization and energy management (Flammini et al., 2009)
- Safety and security (not discussed in this paper) (Neumann, 2007)

All these requirements have significant impact on the WSN protocols stack (Fig. 3). In the horizontal planes, the layers of the Open Systems Interconnection (OSI) Reference Model protocol stack, developed by International Organization for Standardization (ISO), are presented. The vertical planes illustrate the modifications required specifically by WSN. In some applications, knowledge of positions, provided by the localisation capability, is required (Flammini et al., 2009). The power manager handles on-board power sources or energy scavenging units (Yeatman, 2007). Finally, to support RT communication, synchronisation capability is needed (Rowe et al., 2008).

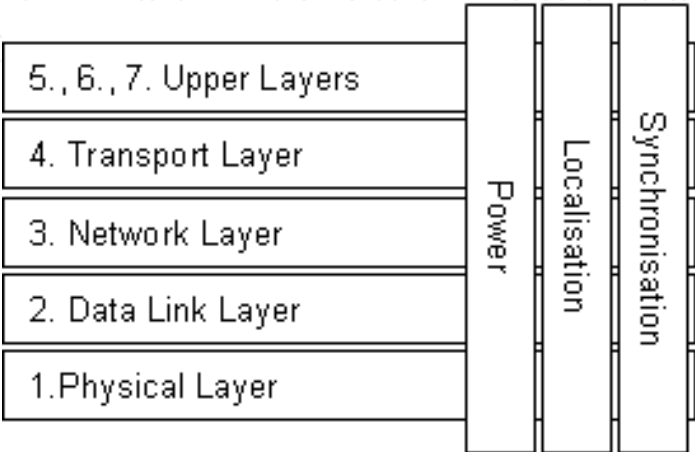


Fig. 3. They layers of the WSN protocol stack. (Flammini et al., 2009)

Concerning the horizontal planes, the tasks of the physical layer include frequency selection, modulation, and data encryption. Since the short-range transceivers are more efficient in terms of the energy consumption and the implementation complexity, their use is preferred. Most widespread commercial solutions available implement spread spectrum modulation techniques and are capable for data rates ranging from 0.1-1 Mbps (Flammini et al., 2009). The common IEEE 802.15.4-standard based radio uses industrial, scientific and medical (ISM) bands, whose selection is dependent on country-specific legislation (see Section 3.2). The most typical spread spectrum modulation techniques include direct sequence spread spectrum (DSSS) and frequency spread spectrum (FHSSS) (Hu et al., 2008). These have different physical characteristics, and therefore they react differently in industrial settings. In general, FHSS is more suitable for harsh environments due to frequency hopping (Low et al., 2005). Moreover, user can choose not to use certain frequencies, if there is known narrowband interference present (Low et al., 2005). On the other hand, the DSSS can remove the interference completely, if the interfering signal power is within the jamming margin (Low et al., 2005). For more discussion about the modulation regarding the industrial environment, refer to (Low et al. 2005); (Hu et al., 2008).

The data link layer incorporates multiplexing of data streams, data frame detection, medium access control (MAC), and error control. The MAC controls the radio and therefore, it has remarkable impact on the energy consumption and node lifetime (Flammini et al., 2009). The MAC also decides when the nodes access the shared medium and tries to ensure that the competing nodes do not interfere with each other's transmissions. The two main approaches to the sharing of the radio channel are the contention and schedule-based ones. In the former, nodes contend over the resource, and collisions are possible. In the latter, the

transmissions are based on a schedule. The contention-based MAC protocols, such as commonly used CSMA, suffer from overhearing, hidden terminal problem and performance degradation with high contention levels (Wang et al., 2006). In schedule-based protocols, such as commonly applied TDMA, the hidden terminal problem can be handled by scheduling. However the synchronization required, as well as the collisions presents a fundamental challenge (Rowe, et al. 2008). Moreover, the scalability of the network may be worse (Wang et al., 2008.). Additionally, hybrid approaches can be found in the literature (for an industrial example, applied in real-time temperature monitoring, refer to (Flammini et al., 2007)).

Several different MAC protocols have been proposed for the WSN in the literature. Discussion and comparisons can found from e.g. (Demirkol et al., 2006); (Rowe et al., 2008); (Pantazis et al., 2009); (Martinez et al., 2007). The focus in WSN MAC protocol development has been in the energy efficiency (Demirkol et al. 2006); (Pantazis et al., 2009). However, some studies (Phua et al., 2009); (Rowe et al., 2008); (Zhou et al., 2008) have addressed the reliability and RT performance of the MAC protocol regarding to the industrial automation domain. (Phua et al., 2006) presented a TDMA-based protocol that uses link state dependent scheduling. In the approach, the node gathers samples of the channel quality and generates prediction slots. The nodes wake up to transmit/receive only during the slots that are predicted to be clear. The proposed approach could improve the reliability of the transmission. (Zhou et al., 2008) proposed an approach of dividing 802.15.4 MAC layer into three services, each of which had additional sub-classes. The division was carried out to meet the RT communication needs of the industrial applications, as presented in ISA classification (see Section 2). The proposed approach could improve the real-time performance of the network. (Rowe et al., 2008) presents an interesting TDMA-based protocol which uses pluggable time-synchronization modules. The hardware-based globally synchronized link protocol could achieve sub-100 μ s network synchronization, being still cost-effective and energy efficient. Moreover, the end-to-end latency remained constant in the multi-hop networks.

The network layer is responsible for routing the data from the upper layers of the source nodes to the corresponding layers of the sink node. In case of a single-hop architecture, the source and sink nodes are directly connected. In the multi-hop network, the nodes can forward information not intended for them.

The possible topologies include star (single-hop), mesh (multi-hop) and hybrid (cluster-tree), presented in Fig. 4. The advantage of the star topology is energy efficiency and long lifetime, even if a node collapses. Namely, energy is not consumed on listening to network changes and relaying messages between the nodes, as in case of multi-hop architecture. As a disadvantage of the star topology, smaller number of nodes compared to the multi-hop network is allowed. However, this may not be a problem, if the coordinators use wired links. On the other hand, the multi-hop networks have a longer range and since all the nodes are identical, separate sink nodes are not necessarily needed. However, in addition to the aforementioned energy consumption, the network may suffer from increased latency. The hybrid architecture attempts to combine the low power and simplicity of the star topology as well as the longer range and self-healing of the mesh network. Also in this approach, nonetheless, the latency may still be a problem. (Flammini et al., 2009)

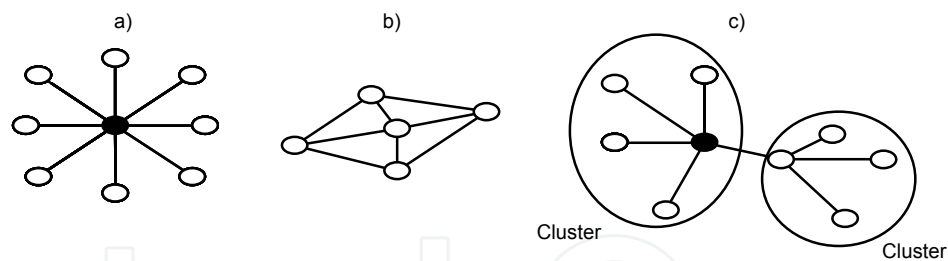


Fig. 4. WSN topologies. Star (a), mesh (b), and hybrid (c). (Flammini et al., 2009)

A comparison of several different network layer protocols from network performance point of view has been presented in (Martinez, et al., 2007). (Heo et al., 2009) discusses several RT routing protocols, concerning especially the industrial applications. They also propose an approach, EARQ that takes into account the RT, reliability and energy efficiency of the communications. EARQ can set the reliability of a packet to manage the trade-off between energy and reliability. Concerning energy awareness, lost packets or packets missing deadlines, the EARQ was reported outperforms other RT protocols discussed in the study. Moreover, it was concluded, that in the practical environments networks are often heterogeneous, comprising of several technologies. Therefore, a protocol ensuring RT also in these operating environments was considered necessary.

The transport layer is usually implemented to provide the end users with an access to WSN through the internet (Flammini et al., 2009). The upper layer is usually combined to a generic application layer, intended to hide the implementation details from the end-user (Flammini et al., 2009). (Vitturi et al., 2009) addresses the importance of the application layer from both the standardisation and performance point of view (Vitturi et al., 2007). In the study, an excellent analysis of the application layer implementation and performance issues using a prototype layer derived from wired fieldbus systems is carried out. It is concluded, that the performance of the implemented approach is worse than expected on the basis of the protocol analysis. According to the authors, the performance degradation is related to several factors: structure of the developed application layer, implementation of the communication standards and software execution times of the components. Moreover, (Vitturi et al., 2007) give a brief introduction to application layer in the industrial communication systems, as well as to the related literature. For more detailed description of the WSN protocol stack in general, refer to (Jiang et al., 2006); (Flammini et al., 2009).

In the classic layered architecture, each protocol layer acts as an independent module with dedicated functions, and handles data packets coming from layer above or below it. The layered architecture is proven to function well in the wired world, but has faced challenges in wireless networks, mainly due to typical characteristics of WSN, such as shared transmission medium, limited resources and lossy communication channels (Zhuang et al., 2007). To overcome these issues, cross-layer design approach (Goldsmith & Wicker, 2002) has been proposed. Cross-layer design allows communications between different protocol layers and the actual functions can be designed jointly. The benefits of the approach include improved efficiency, throughput, and better allocation of resources, lower delay, and more effective energy consumption (Goldsmith & Wicker, 2002). Practical examples of cross-layer design in a real industrial monitoring case can be found in (Franceschinis et al., 2008); (Lu et al., 2008).

In the next section, the industrial automation related standards are shortly discussed. Since some of the standards are already discussed extensively in the literature, only brief introductions with references are given. However, recently published WirelessHART-standard is discussed more closely.

3.2 Standards

The IEEE 802.15.4 (IEEE, 2006) standard defines the protocol and interconnection of devices via radio communication in a low data rate, low power consumption, and low cost personal area network (PAN). The media access is contention-based, applying carrier sensing multiple access with collision avoidance (CSMA/CA) in non-beacon enabled -mode. However, using the optional superframe structure, guaranteed time slots (GTS) can be allocated by the PAN coordinator to devices with time critical data in beacon enabled -mode. Connectivity to higher performance networks is provided through a PAN coordinator. The PHY is defined to for operation in three different ISM frequency bands: 868-868.6 MHz (Europe), 902-928 MHz (North America) and 2400-2483.5 (worldwide). The supported network topologies include star and peer-to-peer. For more detailed description of IEEE 802.15.4, refer to (IEEE, 2006); (Hameed et al., 2008); (Zhuang et al., 2007). (Hameed et al., 2008) also present a performance evaluation and optimisation of IEEE 802.15.4 beacon enabled -mode. Based on the simulation results, the GTS mechanism outperformed the CSMA/CA being able maintain constant MAC delay. Applying the proposed optimisation algorithm, the number of nodes with GTS could be improved.

ZigBee (ZigBee Alliance, Inc., 2008) consists of standard IEEE 802.15.4 (lower layers of the protocol stack) and specifications and profiles defined by the ZigBee specification. A recent study (Pinedo-Frausto & Garcia-Macias, 2008) provides a detailed introduction to ZigBee, as well as extensive performance analysis carried out with a real implementation. Based on the analysis, the authors conclude, that the technology is suitable for applications in ISA usage classes 3 to 5 (see Section 2), but it is not adequate for applications in classes 0 to 2 (emergency actions to closed loop control).

Two recent studies, (Körber & al., 2007); (Lill & Sikora, 2008) lend support to (Pinedo-Frausto & Garcia-Macias, 2008). Namely, they report the inapplicability of the current standard wireless solutions, such as IEEE 802.11, IEEE 802.15.1, IEEE 802.15.4 and ZigBee for hard real-time (5 ms trigger limit) applications. In (Lill & Sikora, 2008) a custom hardware and firmware for communication, synchronisation, and frequency hopping functionalities were designed. Based on the initial results presented, the proposed approach could meet the 5 ms limit. In (Körber et al., 2007), development of a hard real-time sensor actuator is presented extensively, starting from user requirements and ending to a prototype implementation. The proposed approach applies the star network topology, combines frequency division multiple access with TDMA (F/TDMA), and a low-power commercial radio transceiver. The initial results report the trigger limit performance between 6 ms and 11 ms (worst case). (Lill & Sikora, 2008), also mention a commercial alternative capable of meeting strict RT requirements, namely ABB WISA (Scheible et al., 2007). However, as a disadvantage in their case, (Lill & Sikora, 2008) report inapplicability to the battery-powered devices. Moreover, although WISA capable of reaching 10 ms trigger limit and thus suitable for several applications, it was considered unable to reach the extremely tight 5 ms limit.

WirelessHART, developed by HART Communication Foundation, is a wireless interface to widely-adopted HART standard. It aims to address the need for an open standard, which

fulfils the industrial requirements for wireless technology as well as ensures that the customers are not locked to a single supplier. In addition to supporting WirelessHART compatible products from different vendors, the specification is also intended for diverse array of applications, including process monitoring and control, asset management, health safety and environmental monitoring.

A Wireless HART network is formed by a group of network devices. The devices can be either field devices, connected directly to the process plant, or handheld devices. The network supports both star and mesh topology, and therefore, each network device must be able to work as a source, sink or router. A WirelessHART gateway connects the network to the plant. Moreover, a network manager is applied to maintain network status information. Together with the network manager, a security manager is utilised to prevent possible attacks and intrusions. (Kim et al., 2008)

The WirelessHART standard specifies the communication protocol stack using the OSI model, and supports also cross-layer design. The PHY layer of wireless HART is based on IEEE 802.15.4-2006, operating on 2.4 GHz unlicensed band, with maximum data rate of 250 kbps. The modulation applies combination of DSSS and FHSS to provide robust communications against both the broadband and the narrowband interferences. At MAC layer, TDMA is utilised to ensure contention free transmission. Data link layer takes care of sharing of the wireless medium, formatting the data packets as well as correcting bit errors. The responsibilities of the network layer include routing, topology control, end-to-end security and session management. The transport layer ensures end-to-end reliability and flow control. Additionally, block transfer of large data sets is supported. Moreover, a four-level priority classification is supported. (Kim et al, 2008)

The development of the WirelessHART specification is still in progress. For example, the current specification does not consider mobility, interference from time-varying wireless channels, localisation, and effective handover when operator moves from one network /device to another or constant change in topology. For more details about WirelessHART, refer to (Kim et al, 2008); (Lennvall & Svensson, 2008).

4. Interferences in industrial environment

As mentioned earlier, the reliable and real-time communications are required for industrial automation applications. The harsh industrial environment, however, may decrease the network performance due to e.g.:

- multipath propagation: the signal strength may be severely affected by the reflections from the walls (Werb & Sexton, 2007)
- interferences from other devices using ISM bands (Werb & Sexton, 2007)
- noise generated from the equipments or heavy machinery (Low et al., 2005)
- wide operating temperatures, strong vibrations, and airborne contaminants (Low et al., 2005)

It is important to understand the radio channel characteristics in order to predict the communications performance in industrial operating conditions (Low et al., 2005). In this section, the empirical studies on the effect of different interferences on wireless communication performance are surveyed. Especially, the focus is on the research performed in actual IEEE 802.15.4 environment, commonly applied in the WSN.

Based on the literature, the area that has gained the most attention (Bertocco et al., 2007); (Vanheel et al., 2008); (Bertocco et al., 2008a); (Bertocco et al., 2008b); (Toscano et al., 2008) is the co-existence of several wireless communication systems in the same ISM band. (Bertocco et al., 2007); (Bertocco et al., 2008a) and (Bertocco et al., 2008b) concentrate on the performance of the CSMA/CA without interferences and in the presence of interferences. In all these papers, the network under study is based on IEEE 802.15.4 and the performance is evaluated both in cyclic polling and in acyclic alarm task.

In (Bertocco, et al., 2007), a signal generator is applied to produce the interference specified for radiated immunity tests of electromagnetic compatibility (EMC). The interference varying between 300 MHz to 1000 MHz (out of the ISM band) did not cause any significant changes in the WSN behaviour. Moreover, the same apparatus is applied to emulate interference from IEEE 802.15.1 and IEEE 802.11 networks, both continuous and in bursts. In both cases, the performance of the polling task was degraded (in this study, the performance in alarm task was studied only without interference). Especially, when the continuous interference signal exceeds the clear channel assessment (CCA) threshold of the CSMA/CA, the polling task is hindered completely. (Bertocco et al., 2008a) extends the aforementioned study, proposing methods for industrial WSN performance evaluation, and assessing the effect of burst interference on alarm tasks. The interference increased the alarm latencies notably. (Bertocco et al., 2008b) investigates clear channel assessment (CCA) procedures in the presence of IEEE 802.15.1 (Bluetooth), IEEE 802.11g and IEEE 802.15.4 (ZigBee) interference. The network under study is based on IEEE 802.15.4 and the performance is evaluated both in cyclic polling and in acyclic alarm task. The applied metric is PER. The results show that the interference IEEE 802.11g and IEEE 802.15.4 are significant. The interference from Bluetooth, however, is equivalent to “no interference” –situation. Interestingly, best performing CCA procedure seems to be the “no-CCA” in which no channel assessment is carried out at all. Disabling CCA completely resulted to the best resistance against the interference as well as best performance in the cyclic and acyclic tasks. (Vanheel et al., 2008) study the distance of interference sources (IEEE 802.11b and IEEE 802.11g) on IEEE 802.15.4 (ZigBee) connection. For both the sources, minimum distance causing worst case packet error ratio (PER) of 0.1 on IEEE 802.15.4 link is examined. The measurements agree with the simulation results presented for IEEE 802.11b interferer in the standard IEEE 802.15.4, Annex E: large frequency offsets allow close-proximity co-existence. (Toscano et al., 2008) study the cross-channel interference in IEEE 802.15.4 –network. The results imply that if the powers of the interfering signal and source node are comparable at the receiver, the interference has only small effect (in this case 4.5% worst case PER). However, when either the power of the interfering signal is significantly stronger or the actual source node is considerably farther from the receiver, the packet loss ratio can increase significantly, especially if unacknowledged communication is used together with high duty-cycle transmissions. Moreover, (Toscano et al., 2008) also assess the sensitivity of the received signal strength indicator (RSSI) in detecting the interferences. Based on results, the RSSI seems to be incapable of detecting cross-channel interference. The performance measurements presented in (Paavola & Ruusunen, 2008)) are in good agreement with the aforementioned studies, concerning interference from the IEEE 802.15.1 and the IEEE 802.11 networks.

In addition to aforementioned studies about the influence of IEEE 802.15.1 and IEEE 802.15.4, (Paavola & Ruusunen, 2008) evaluated some network design parameters, and the

effect of frequency converter -originated interference in the monitoring environment described in Section 2. Especially, the focus was on clarifying, if the communications remained isochronous. For this, variability in latency, jitter, was investigated. Several statistical quantities were compared in analysing the jitter distributions, and a novel approach, entropy, was proposed. The entropy performed well in the jitter analysis, being able to point out statistically factors decreasing isochronous performance. The effect of frequency converter was equal to IEEE 802.11. Based on the study, both of these, however, have a smaller influence than the network design parameters, such as distance from nodes to gateway, number of nodes and sampling interval. Additional information and some references to interference studies can be found from (Paavola & Ruusunen, 2008).

5. Networked control

Networked Control Systems (NCS) are spatially distributed systems consisting of the process to be controlled together with its actuators, sensors, and controllers (Antsaklis & Baillieul, 2007); (Hespanha et al., 2007). The communication between system components takes place via a shared band-limited digital communication network. The systems may also operate in an asynchronous manner, but aim at desired overall objectives. The design of NCS must rely on both control and communication theories. The control theory assumes data transfer through “ideal channels”, whereas the communications theory takes the data transfer through “imperfect channels” into account (Hespanha et al., 2007). On the other hand, the communication theory is concerned with reliable transfer of data independent from its usage, where as the control theory is interested in using data in feedback control for some purpose requiring a certain performance (Nair et al., 2007).

Networked control, be it wired or wireless, set some new challenges for the design and performance of the control systems:

- real-time requirement
- band-limited channels
- network delay
- data consistency (packet dropout)
- network architectures
- multipath fading

Real-time behaviour:

Real-time operation is necessary for control functions. In this connection, “real-time” means that the system must be able to response to control requests timely, so that corrections still have their desired effect on process operation. This presumes both the real-time operation system and data transfer; deterministic operation is the most important requirement.

Real-time requirements depend on the application and they can be divided in four categories (Neumann, 2007):

- non-real-time applications in diagnosis, maintenance, commissioning, slow mobile applications
- soft real-time applications: in process and factory automation, mainly in data acquisition and monitoring
- hard real-time applications in process and factory control, fast mobile applications, machine tools
- isochronous hard real-time applications especially motion control.

According to (Neumann, 2007) industrial control problems belong to hard real-time applications. They depend on scheduling of data traffic on top of MAC-layer with the cycle time of 1–10 ms. Most of these wireless radio networks can be used in non-real-time applications, some of them in soft real-time applications, but industrial applications are often outside their capability because of challenging environments and ISM band limit.

Real-time operating systems require the following properties:

- multitasking
- interrupt handling
- task scheduling using priority-based event scheduling and/or time sharing using clock interrupts
- dynamic memory allocation

Band-limited channels:

Any communication channel can carry a finite amount of information per unit of time. In systems with large communication bandwidth, communication and control can be designed independently (Nair et al., 2007). However, recent industrial control networks (both wired and wireless) share a common digital communication network between multiple sensors and actuators. The total data transfer capacity of the network may be large, but each component can utilise only a small portion of it. This may lead to large quantization errors due to the low resolution of the transmitted data that deteriorate the control performance, making even a stable system impossible (Hespanha et al., 2007). The situation is especially difficult in energy-limited systems and in cases, where the number of components is high.

Network delay:

The network delay can be constant, with the time varying or even random, and it occurs when sensors, actuators, controllers and humans exchange data over the network. It depends on the network structure, media and protocol and it is divided into communication and computational delays. In slow process control, delays have only a small effect on the control performance. In fast control loops, the delays impair the performance and can even destabilize the system.

To transmit a continuous-time signal over a network, the signal must be sampled, encoded in a digital format, transmitted over the network, and finally the data decoded at the receiver side (Hespanha et al., 2007). The overall delay includes the network access delays and the transmission delays. They both depend on network conditions such as congestion and channel quality (Hespanha et al., 2007).

Another way of dividing network delays is given in (Mattina & Yliniemi, 2005):

- Waiting time delay is the delay, of which a source has to wait for queuing and network availability before actually sending a frame or a packet
- Frame time delay is the delay during which the source is placing a frame or a packet on the network
- Propagation delay is the delay for a frame or a packet travelling through a physical media

In the networked control loop of Fig. 5, the network delay consists of the following transmission delays

- communication delay between the sensor and the controller, τ_k^{sc}
- communication delay between the controller and the actuator, τ_k^{ca}

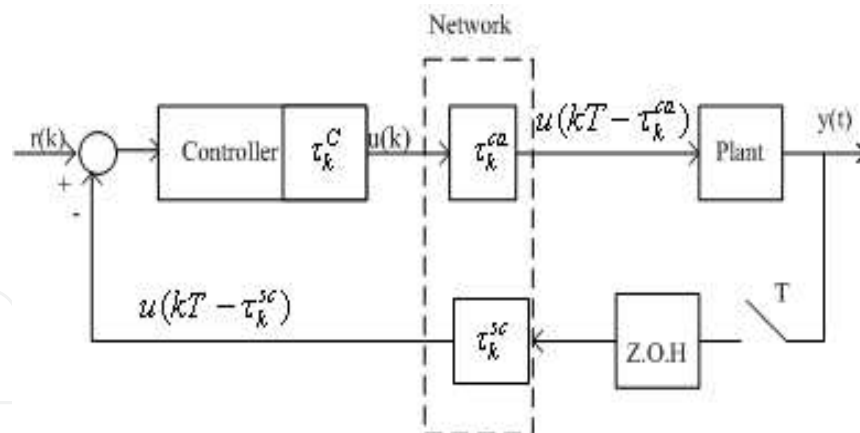


Fig. 5. Block diagram of the network-based control system with different delays (Yliniemi & Leiviskä, 2006).

The total network delay includes also computational delays, e.g. in the controller, but they can be embedded in the above-mentioned delays. In addition to transmission and computational delays, delays may be due to the network load and failures. Errors can occur in data transmission causing retransmission and increasing delay. Collision risks exist, if two nodes send messages at the same time. In cyclic networks based on token passing and TDMA (Time Division Multiple Access) the delay is caused primarily from the waiting time. In Ethernet, CAN (Controller Area Network) and Internet the delay behaves randomly due to the CSMA technology (Yliniemi & Leiviskä, 2006).

Fig. 6 compares experimental process responses with a sample frequency 1 Hz across Ethernet, Internet, FUNET, and without network (Yliniemi & Leiviskä, 2006). As the Figure shows, the control across Ethernet is similar to the control without the network. The control performances across Internet and FUNET are slower than across Ethernet as the responses show. The experiments with the sample frequencies 2 and 5 Hz give the similar results.

In (Yliniemi & Leiviskä, 2006), the ability of different wired networks to the process control was also examined by measuring the time which goes when a measurement signal is sampled to when it is used in the actuator. The sampling frequency in all experiments was 1 Hz. In Ethernet, this time is very small i.e. in average 1 ms. The corresponding time in Internet and FUNET is about 30 ms.

Several methods for compensating the network delay have been proposed. To take the randomness of the network into account, either as a constant probability function or as a Markov chain together with time stamping (Nilsson, 1998). Another application uses clocked buffers on the input of the controller node and in the actuator node to get rid of the time variations (Luck & Ray, 1990). Time-stamped model predictive control (TSMPC) makes possible to get better stability by decreasing the modelling error (Srinivasagupta, 2004). Also using the gain scheduling method for networked PI controller over IP network has been proposed (Tipsuwan & Chow, 2003). A fuzzy compensation method has been developed for a PI controller over the network with randomly varying delay (Almutairi et al., 2001).

Reference (Vatanski et al., 2009) proposes two methods for control over a network. The Smith Predictor-based approach was proposed for the control in the case when accurate delay measurements are accessible, and the robust control-based approach was used when only the estimate of the upper-bound end-to-end delays are available. A switched Ethernet

communication protocol was used to evaluate the performance of the methods for networked control.

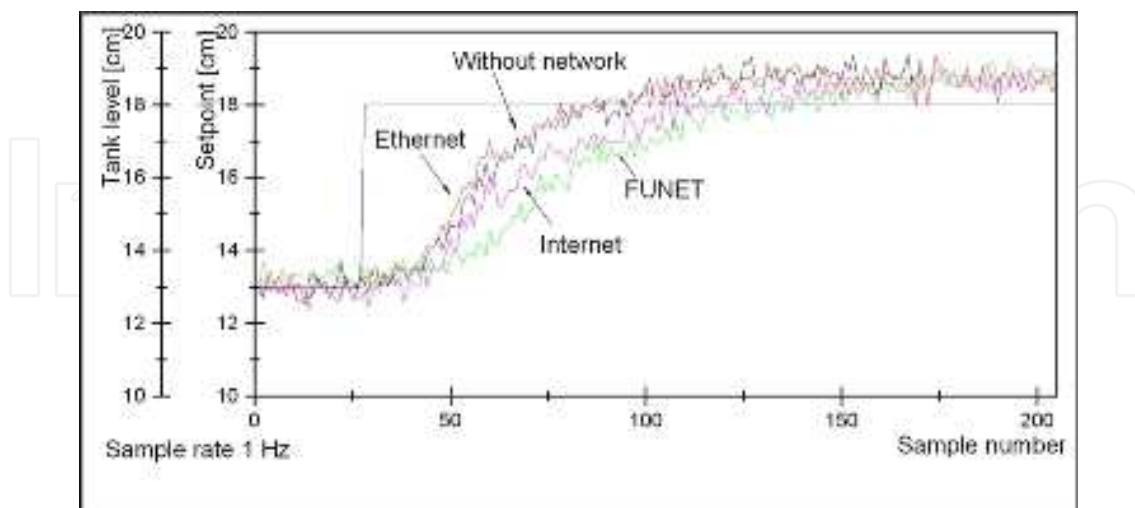


Fig. 6. Experimental process responses across Ethernet, Internet, FUNET and without network (Yliniemi & Leiviskä, 2006).

Data consistency (packet drop-out):

Opposite to standard digital control, in networked control data may be lost while in transferred through the network (Hespanha et al., 2007). Packet drop-outs result from transmission errors in physical network links or from buffer over-flows due to congestion. As mentioned earlier, this may lead to long transmission delays sometimes because of packet re-ordering. There are reliable transmission protocols, such as TCP, that could guarantee the delivery of packets, but they are not so much used in networked control.

Systems architecture:

Fig. 7 (Hespanha et al., 2007) shows the general architecture of an NCS. Encoders map measurements into streams of “symbols” that can be transmitted across the network. Encoders decide when to sample a continuous-time signal and what to send through the network. Decoders convert the streams of symbols into continuous actuation signals used finally for control. Controllers, on the other hand, take care of control calculations.

There are two points of view to architectural questions: network architecture and control architecture. According to (Fammini et al., 2009), the best solution for network architecture is to adopt small, reliable star networks that exploit time division for the network access policy. There are two alternatives for the control hierarchy (Mattina & Yliniemi, 2005): The simplest one is that the remote controller computes the setpoint for the local controller that takes care of the actual control with sensors and actuators. This approach also guarantees the continuity of control in case of bad data communication (Fig. 8 (Mattina & Yliniemi, 2005)). Another approach, also shown in the Fig. 8, is to make all control calculations in the remote controller. This approach is vulnerable for possible disturbances in the control system or data transfer.

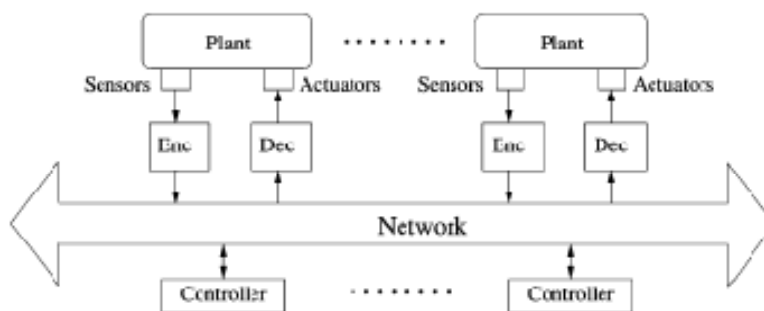


Fig. 7. General system architecture for networked control system. (Hespanha et al., 2007)

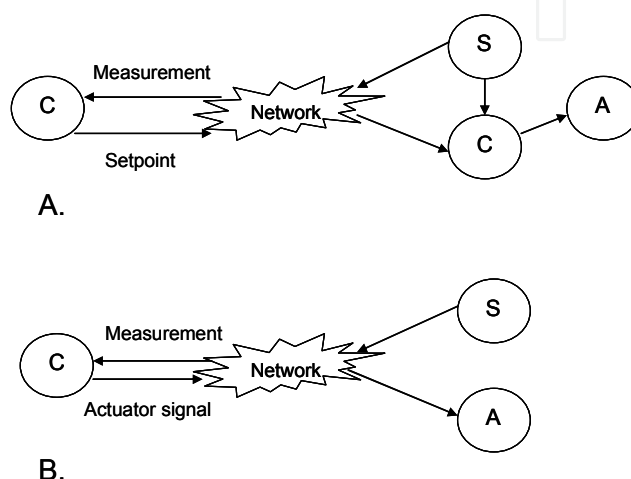


Fig. 8. Two alternatives for the control hierarchy (Mattina & Yliniemi, 2005). C denotes the controller, S the measurement and A the actuator.

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Factory automation has evolved significantly in the last few decades, and is today a complex, interdisciplinary, scientific area. In this book a selection of papers on topics related to factory automation is presented, covering a broad spectrum, so that the reader may become familiar with the various fields, and also study them in more depth where required. Within various chapters in this book, special attention is given to distributed applications and their use of networks, since it is one of the most relevant subjects in the evolution of factory automation. Different Medium Access Control and networks are analyzed, while Ethernet and Wireless networks are looked at in more detail, since they are among the hottest topics in recent research. Another important subject is everything concerning the increase in the complexity of factory automation, and the need for flexibility and interoperability. Finally the use of multi-agent systems, advanced control, formal methods, or the application in this field of RFID, are additional examples of the ideas and disciplines that experts around the world have analyzed in their work.

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