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Wireless instrumentation for the water and wastewater industry

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Abstract

IEEE Std. 802.15.4 for low-rate wireless personal area networks has been the enabling technology for applications within the field of wireless instrumentation, with the oil and gas industries being an early adopter of the technology. The idea behind the presented work is that the water and wastewater industries can take advantage of technology and knowledge from the oil and gas industries rather than starting from scratch. Through our analysis we suggest several application areas within the water and wastewater infrastructures where wireless instrumentation could provide both operational and financial benefits.

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Keywords: wireless sensor networks; wireless instrumentation; safety systems; control systems; monitoring systems

1. Introduction

The first decade of the new millennium has been the stage for the rapid development of wireless communication technologies for low-cost, low-power wireless solutions capable of robust and reliable communication (Akyildiz et al., 2002; Petersen et al., 2008). IEEE Std. 802.15.4 for low-rate wireless personal area networks has been the enabling technology for numerous applications within the field of wireless sensor networks (WSNs) (Yu et al., 2006), and more recently, wireless instrumentation.

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Defined as the merger of WSN technologies and industrial field instruments, wireless instrumentation has become increasingly popular in the process industries since the recent ratifications of the WirelessHART and ISA100.11a specifications as described by Kim et al. (2008) and Petersen et al. (2011) respectively. By providing secure and reliable self-configuring and self-healing wireless mesh networks, these standards offer a cost-efficient alternative to traditional wired field instrumentation. Eliminating the need for cables also enables wireless instrumentation to be deployed in remote and hostile areas, as well as provide the opportunity for scalable, flexible and mobile installations (Petersen et al., 2007).

The oil and gas industries have been an early adopter of wireless instrumentation, where the flexibility and reduced installation cost are especially suitable for modification projects at brownfield (existing) facilities.

On this background, Oslo Water and Sewerage Works and the research institute SINTEF have joined forces to identify how wireless instrumentation can create added value within the water and wastewater facilities and infrastructures of Oslo. The idea behind this work is that land-based industry can take advantage of technology and knowledge from the oil and gas industry, and thus having a faster return on investment than if starting from scratch.

The paper will give an introduction to wireless sensor networks and wireless instrumentation technologies, as well as requirements, drivers and business cases from the oil and gas industries. These motivational factors will be backed by a case study from a deployment at a live operational facility. Building on the experiences, knowledge and lessons learned from oil and gas installations, the main contribution of this research is to examine the potential benefits of wireless instrumentation within the confines of the water and wastewater industries.

2. Technology

A *wireless sensor network* can be defined as a collection of autonomous sensor nodes which collaborate to measure physical phenomena such as temperature, pressure, flow and vibration. The sensor nodes communicate wirelessly with each other, and typically forward their measurements to a central network administrator / wireless gateway. Further, *wireless instrumentation* is defined as the merger of wireless sensor networks with industrial control systems (Petersen et al., 2012). A wireless field instrument can be a traditional industrial sensor or actuator equipped with a radio transmitter, antenna and a power supply (battery), thus eliminating the need for cables. The sensor or actuator elements are identical to the wired counterparts, so a wireless field instrument provides the same measurements with regards to characteristics such as precision, range and dependability. For wireless instrumentation, the wireless gateway functions as the bridge between the wireless instrumentation network and the wired automation network, and it has a wired (fieldbus) connection to the backbone systems such as controllers, control room and operational historian, as illustrated in Fig. 1.

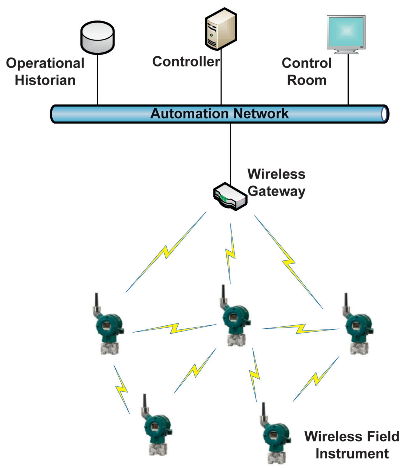

Fig. 1. Wireless instrumentation network

The performance requirements of an industrial field instrument depend upon the nature and criticality of the application it is serving. NAMUR, a user association for automation technologies in the process industries, defines the following three applications classes for wireless instrumentation in their recommendation document NAMUR NE 124 "Wireless Automation Requirements" (2010):

- Application Class A – Functional Safety
- Application Class B – Process Management and Control
- Application Class C – Display and Monitoring

For simplicity, the NAMUR application classes will hereafter be referred to as safety (A), control (B) and monitoring (C), respectively.

To date, most wireless instrumentation deployments in the process industries have been limited to non-critical monitoring applications (Petersen et al., 2012), but recent research activities are looking into the possibility for extending the usage areas into control and safety applications (Petersen et al., 2011; Akerberg et al., 2011; Akerberg et al., 2010).

3. International standards for wireless instrumentation

Wireless sensor networks specifications are described using a simplified version of the 7-layered OSI-model (International Electrotechnical Commission, 1994) where the presentation and session layers are not defined, as depicted in Fig. 2.

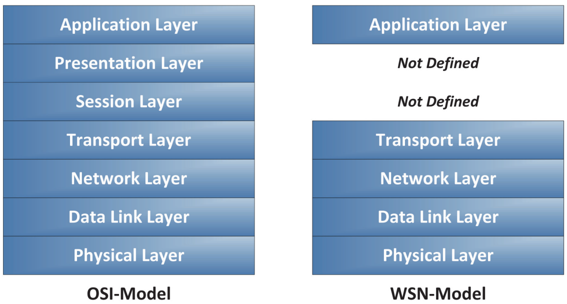

Fig. 2. WSN protocol stack

In the following section, a brief overview of the different international standards for wireless instrumentation is presented. Note that the term medium access control (MAC) layer used by some of the specifications is equivalent to the data link layer (DLL) of the OSI-model.

3.1. IEEE Std. 802.15.4

The IEEE Std. 802.15.4 (IEEE, 2006) defines the physical layer (PHY) and medium access control sublayer (MAC) for low-rate personal area networks. It was initially released in 2003, and updated in 2006 and 2012. Four different PHYs are defined; three in the 868/915 MHz band and one in the 2.4 GHz band. Employing features such as low power and low cost, the IEE Std. 802.15.4 is a suitable candidate for WSN applications (Yu et al., 2006), and with a steadily growing number of standards and solutions based on its PHY / MAC layers, it has become the de facto standard for WSNs.

3.2. WirelessHART

WirelessHART is a subset of the HART Field Communication Specification, Revision 7.0 (2007), which enables wireless connectivity for HART fieldbus devices. Being ratified in September 2007, it was the first international standard specifically addressing wireless communication for industrial automation applications. WirelessHART is based on the 2.4 GHz IEEE Std. 802.15.4 PHY, employing a combined TDMA (time-division multiple access) and FDMA (frequency-division multiple access) medium access method. With features such as full mesh network topology and self-configuring and self-healing mechanisms, WirelessHART offers a robust and reliable wireless multi-hop communication for industrial applications. From an application layer point-of-view, WirelessHART is bound to the HART protocol, and messages in the network must be transmitted in the form of HART Commands.

3.3. ISA100.11a

ISA100.11a (International Society of Automation, 2011) is the first standard to emerge from the ISA100 standards committee's work to deliver a family of standards for wireless systems for industrial automation. ISA100.11a was ratified in 2009, and is designed to offer secure and robust wireless communication for industrial automation applications. Similarly to WirelessHART, ISA100.11a is based on the 2.4 GHz IEEE Std. 802.15.4 PHY, employing a combined TDMA (time-division multiple access) and FDMA (frequency-division multiple access) medium access method. In addition, ISA100.11a also has support for a contention-based CSMA-CA (carrier sense multiple access with collision avoidance) medium access mechanism. ISA100.11a has an object-oriented application layer, and is capable of tunneling protocols as per the demand of the application.

3.4. WIA-PA

WIA-PA (International Electrotechnical Commission, 2011) is a specification for wireless industrial automation applications developed by the Chinese Industrial Wireless Alliance (CIWA), and ratified by IEC as IEC/PAS 62601 in October 2008. WIA-PA is based on the IEEE Std. 802.15.4 PHY and MAC, and it offers a star-mesh network topology. Only dedicated cluster head devices are capable of routing traffic from other devices in the network, and field devices are solely input/output devices, with no routing capability. Redundancy is achieved at the cluster head, by adding a redundant cluster head. However, there is no alternative route for broken links from field device to cluster head.

4. Lessons learned from the oil and gas industry

Among the process industries, oil and gas has been an early adopter of wireless instrumentation, mainly due to the good alignment of the capabilities of the technology with the challenges and business cases typically found in oil and gas facilities. This section will provide an overview of the main lessons learned from pilots and deployments of wireless instrumentation in the oil and gas industry, covering the drivers and motivations, the technical requirements and an example case study.

4.1. Drivers and motivation

The oil and gas industry is primarily driven by the desire to deliver high and optimized production for as low as possible capital and operational expenditures (CAPEX and OPEX respectively). In addition to the financial drivers, the safety of personnel, plant and the environment is essential, making HSE (health, safety and the environment) a top priority at all hazardous plants and facilities. All new technologies which are introduced into this domain must thus provide benefits that support and improve production and/or HSE performance, and at the same time reduce CAPEX and OPEX.

For oil and gas, the costs associated with engineering, deployment and commissioning of equipment and infrastructure are typically significantly larger compared to other industries, especially for offshore installations. At oil and gas producing facilities, the supporting infrastructure (wiring, junction boxes, cabinets and power supplies) and the engineering related to this, represent the largest contributions to the total cost of field instrumentation, so even a modest reduction in installation costs for field instruments can provide substantial cost savings. This aspect represents one of the major motivational factors for introducing wireless instrumentation in the oil and gas industry.

General benefits with wireless instrumentation compared to their wired counterparts are (Petersen and Carlsen, 2012):

- Reduced installation costs
- Installations in remote and hostile areas
- Flexibility and scalability
- Simplified engineering and commissioning for new facilities
- Fast and easy retrofitting at existing facilities

4.2. Technical Requirements

The oil and gas industry has identified the following technical requirements for wireless instrumentation (Petersen and Carlsen, 2012):

- **Unlicensed frequency bands.** The radio spectrum is a limited natural resource, and as a result, the frequency band usage is strongly regulated by the authorities. Most frequencies are licensed for specific applications and technologies, but there are still some portions of the frequency bands which are open for free, unlicensed operation. These bands are called ISM-bands (industrial, scientific and medical), and their availability varies by country and region.
- **Friendly coexistence with other wireless solutions.** Wireless technologies are becoming more ubiquitous, even in industrial facilities. When two or more wireless systems are deployed within radio range of each other, it is imperative that they are capable of friendly coexistence. This means that neither system should suffer critical performance degradation during operation. For wireless instrumentation, the most common source of interference will be from the popular IEEE Std. 802.11-based wireless local area networks (Wi-Fi).
- **Standardized and open solutions.** Standardized and open communication protocols provide the industry with the flexibility and freedom to choose between multiple vendors while having guaranteed interoperability. Standardized solutions also have the added benefit of longer lifespans for component availability and support compared to proprietary solutions, while at the same time preventing commitment to a single supplier.
- **Information security and privacy.** Wireless instruments transmit information over the air, which make them more vulnerable to eavesdropping and other security breaches than their wired counterparts. To ensure data confidentiality, authenticity and integrity, the wireless protocols must implement sufficient security mechanisms and algorithms to prevent unintentional and malicious threats and attacks.
- **Quantifiable network performance.** The performance of wireless communication is susceptible to environmental changes in the deployment area. Factors such as moving equipment and personnel, electromagnetic noise and interference from machinery, interference from other wireless systems, variations in temperature and humidity, and weather (e.g. rain and snow) might influence the quality of a wireless communication link. It is therefore important to be able to quantify within reasonable accuracy the expected and operational performance with regards to availability and reliability of wireless solutions. The specific requirements for the network performance vary depending on the usage area and application demands.
- **Battery lifetime.** The lack of cables is one of the main benefits and motivational drivers for wireless instrumentation. Unfortunately, this means that all power needed to operate the wireless instruments must originate from a local power source, typically a battery. It is also possible for the devices to harvest and scavenge energy from the environment (e.g. through harvesting energy from the sun, vibration, temperature fluctuations and so on).
- **Engineering, integration and commissioning.** Wireless instrumentation for industrial applications should provide identical electric and mechanical interfaces as wired systems. As wireless instrumentation is expected to live side by side to wired systems in the foreseeable future, it is imperative that the integration to existing networks, fieldbuses and back-end systems is made as smooth as possible. The mechanical quality and expected lifetime of a wireless instrument should be equivalent to a wired instrument, including the radio

communication part of the device. Mounting brackets and other mechanical details, as well as the quality of these, should also be identical to those of wired instruments. Wireless gateways should be mechanically designed to sustain harsh environments, while providing easy mounting and termination of field cables.

- **Provisioning.** Wireless instruments need to be configured before they can join a wireless network. The process of configuring new devices to join an existing network, commonly referred to as provisioning, should be implemented as straight forward as possible in order to ensure this becomes a simple task in the field.
- **Redundancy.** The wireless gateway represents a single point of failure. For most industrial applications, it is preferable with redundant gateway systems providing automatic fail-over in the case of loss of one gateway. For control and safety systems this should be an absolute requirement.

4.3. Case study

As an early adopter of the technology the oil and gas industry has been running pilots on wireless instrumentation as part of their technology qualification programs. The purpose of the pilots has been twofold; to address specific challenges at the targeted installation, and to gather operational data and performance analysis of the deployed systems to ensure that they fulfill the stated technical requirements. The pilot installation of wireless temperature monitoring at the Gullfaks Field will be used to illustrate the capabilities and potential of wireless instrumentation in oil and gas.

Wireless temperature monitoring at the Gullfaks Field (Carlsen et al., 2009)

The Gullfaks Field is located in the North Sea off the coast of Norway. It comprises three integrated facilities for processing, drilling and accommodation; Gullfaks A, B, and C. The Gullfaks reservoir consists of many small "pockets" of accumulated oil, and the typical lifetime of a perforation ranges from 6 months to 10 years. Unfortunately, at the tail-end stage of its production, a well production perforation occasionally suffers from decline in wellhead pressure which causes loss of flow from the well. At the Gullfaks facilities, this loss of flow is not readily detected, as there are no flow meters installed in the well flow lines. However, installation and maintenance of such a system is both complex and costly, and require a full production shutdown during installation. A simpler approach to determine the loss of flow is to measure the surface temperature of the well flow line, exploiting the principle that loss of flow causes a decline in temperature, as the well fluid temperature of approximately 60°C is significantly higher than the ambient temperature at the facility. This eliminates the need for invasive installation, and greatly reduces the complexity of the operation.

A further showstopper for introducing traditional field instruments in a live production environment is the need for wired power and communication. This requires wiring, junction boxes, cabinets and power supplies, which is complex and expensive, and sometimes not even possible, in a crowded facility with limited space. To eliminate these barriers, it was decided to deploy battery-operated wireless temperature transmitters. The installation of the wireless infrastructure turned out to be quick and efficient, and the wireless network was capable of delivering robust and reliable communication according to the requirements. Since the deployment, it has been proven that the combination of quicker and more reliable detection of loss of flow enabled by the wireless temperature transmitters, and the resulting capability of prompt action to re-establish loss of flow, has had an estimated annual net present value of $40M for the Gullfaks facility.

5. General drivers and motivation for wireless instrumentation in the water and wastewater infrastructure

As mentioned earlier, the main benefits of wireless instrumentation are related to the fact that the sensors are wireless, with a reduction in installation costs due to less wiring being the most obvious advantage. However, while this is an important driver in the oil and gas industries, installing wires in the water and wastewater industries would normally be a rather mundane task not requiring helicopter transport and adhering to explosion-safe procedures. Furthermore, the importance and relevance of various drivers will depend on several parameters, such as the location of the facility, the criticality of the process, whether the facility exists or is under planning, and which regulations are given by the authorities. Therefore one must expect that business cases in water and wastewater industries will have an even stronger focus on the practical benefits of wireless technology, such as flexibility in deployment, mobility of equipment and reduced planning efforts.

The basic technical properties of wireless instrumentation technologies are that they provide short-range and multi-hop communication in a network that is robust, self-configuring and self-healing. These characteristics make wireless instrumentation a viable candidate for collecting sensor data within both small-scale and large-scale facilities. For communication between *separate facilities* (or between separate wireless instrumentation networks) one should use dedicated back-bone links, as wireless instrumentation networks are not designed for high-speed transmission of data from one single point to another. This also applies to communication with independent and remote sensors, i.e. in sources and catchment areas, where it would seem more appropriate to use either the cellular network or proprietary long-range communication solutions.

On this background, the following facility types are considered to be most relevant for wireless instrumentation:

- Water treatment plants
- Water pumping stations
- Water tanks
- Underground utility vaults
- Wastewater pumping stations
- Wastewater treatment plants

Potential applications for wireless instrumentation deployments within these facilities will be discussed in more detail in the next section.

6. Potential applications for wireless instrumentation in the water and wastewater industries

Instrumentation in general can be divided into three different application classes; safety, control and monitoring. What distinguish the classes are not only the sensor measurements themselves, but also the requirements set for the communication with the sensors from a system point of view. On this background each application class will be treated individually when it comes to investigating potential uses of wireless instrumentation.

6.1. Safety applications

Safety can be defined as "freedom from unacceptable risk of physical injury or damage to the health of people either directly or indirectly as a result of damage to property or to the environment" (International Electrotechnical Commission, 2010). Further, a safety application can be described as an application that aims to reduce a risk from a level that is unacceptable high to a level that is acceptable.

Industrial safety applications, often called safety systems, can be divided into two different types. The first type is *prevention systems* that are constructed as a part of the individual industrial processes, though with separate sensors to ensure independent and redundant operation. These systems shall ensure that any process that gets beyond its safety margins is rapidly shut down. The second type of safety systems is *detection systems*, which shall detect incidents that have already happened in order to reduce the consequences, e.g. fire and gas detection. Detection systems are used both as stand-alone systems and as a second barrier around high-risk processes in case the process shutdown systems should fail. A triggering of a detection system would normally lead to initiation of preventive measures such as fire fighting, an activation of the emergency shutdown systems (either manually or automatically), and/or evacuation of personnel.

For safety systems all communication shall be initiated from the controller, and the controller shall perform periodical requests to verify that all alarm sensors are healthy. If a response is not received within a defined timeout window, the sensor will be declared as unavailable and the control system will trigger a system fault alarm. As there are also requirements on how fast the safety system shall respond when a sensor raises alarm, this sets some strict technical requirements on the communication solutions. Consequently most safety systems are still using wired communication. However, as shown by Petersen and Carlsen (2012) these strict technical requirements can be fulfilled by the use of wireless instrumentation, more specifically by using the standard ISA100.11a. One should therefore expect an increase in wireless safety applications in the near future.

As the water and wastewater industries mainly operate processes that by nature cannot get out of control, the need for prevention systems should be quite low. The need for various detection systems is nevertheless present, although some of these might not adhere to the stringent requirements of IEC 61508. One might also expect that high-cost safety systems that reduce indirect risks (e.g. damage to the environment) are not as readily prioritized as safety systems that reduce directs risks to the health of people, mainly because the costs of such systems are more difficult to justify. In these cases wireless instrumentation will have a natural advantage, as wireless sensors can easily be retrofitted or installed temporarily, without the need of extra wired infrastructure, and with no extensive planning, engineering and commissioning.

Examples of potential safety applications using wireless instrumentation would be fire and leakage sensors in all sorts of facilities, chlorine spill sensors and turbidity sensors in water treatment plants, and gas sensors in wastewater treatment plants.

6.2. Control applications

A control system can be defined as a "device or set of devices to manage, command, direct or regulate the behavior of other devices or systems" (Wang and Liu, 2008).

Control applications are handling the core functionalities of process industries, and they will normally be cost-efficiently installed in parallel with the processes they control. Therefore, using wireless technologies in control is not expected to be cost-efficient within the next few years, unless the process of planning and installing wired sensors is very costly (as can be the case in remote and hostile locations). As mentioned earlier, there are nevertheless on-going research activities on how to make wireless instrumentation more suitable for the strict real-time requirements set by many control applications.

Note also that there exists a sub-class of control applications that is called "open loop control". This application sub-class covers control applications with human operators in the loop, that is where the operator controls the operation of a process based on some relevant input and either formal or informal rules. Such applications will not have very strict real-time requirements as long as the reliability of the data is high. Examples of potential open loop control applications that could be implemented using wireless instrumentation consist of deciding on which water sources to use at a given moment based on environmental data, and whether or not to increase the chlorine dosage in water treatment plants based on turbidity measurements.

6.3. Monitoring applications

Monitoring simply means to "regularly check how [something] is changing or progressing over a period of time" (Collins Cobuild Dictionary, 1987), and this class of applications covers all applications that are not of immediate operational consequence, nor related to the safety prevention and detection systems. This does not mean that monitoring applications are not important; on the contrary they may be crucial to maintain a sound operation of any process or facility. But if they are absolutely crucial for the daily operations, they might be more correctly classified as either safety or control applications.

Monitoring applications may be targeted at either *processes* or *assets*, and they may either report *continuously* to operators by alerting/flagging or log data for *retrospective analyses*. In all these cases there is a need for reliable and correctly time-stamped sensor data, but it is not required that the data is received by the control system or operational historian (see Fig. 1) within a stringent time-limit. Because of this, monitoring applications are good candidates for benefiting from wireless instrumentation technologies.

Process monitoring includes both real-time verification of processes and optimization of processes using historical data. In the first case the wireless sensors would normally be connected to a control system, which would alert the process operators if a process does not work as intended. Examples of this could be redundant measurements of water quality in water treatment plants, and extra level and flow meters in wastewater treatment plants. In the case of optimizing processes the data would first be collected in an operational historian, and then used by experts to analyze whether and how the processes could be improved.

Asset monitoring is closely related to asset management, and aims to increase return on assets by extending asset life and decrease the risk of asset failure. Asset monitoring is often used as input for condition-based maintenance, which can either be flagged directly to the facility operators or used periodically as a basis for a planned maintenance strategy. Examples of asset monitoring applications are vibration monitoring of water and wastewater pumps, and pressure sensors in underground utility vaults for detecting leakages in pipelines.

7. Conclusion

During the last few years there has been a rapid development within the field of wireless instrumentation, and the oil and gas industries have been an early adopter of this technology. While the drivers and benefits from the oil and gas industries are not completely transferrable to other industries, the experiences from one industry should nevertheless prove valuable when starting to employ these technologies within other domains and areas.

For the water and wastewater industries it is expected that the initial business cases of wireless instrumentation will be found within safety detection systems and for asset monitoring, and primarily in enclosed facilities such as water treatment plants, water pumps, water tanks, underground utility vaults, wastewater pumps and wastewater treatment plants. As the technology grows more mature and is proven in initial deployments, one should also expect an increased desire to also deploy wireless instrumentation in other usage areas such as process monitoring and control.

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