WIRELESS IN NUCLEAR

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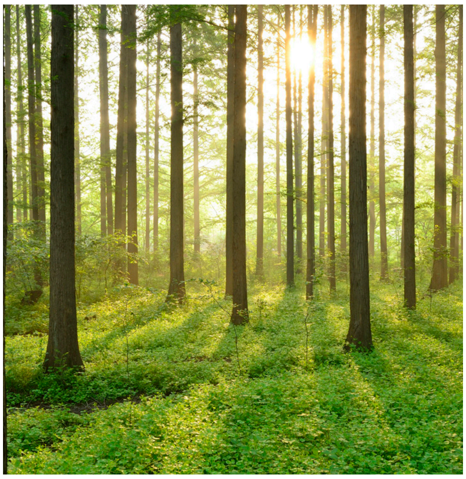

NUCLEAR

ENERGIFORSK NUCLEAR SAFETY RELATED I&C – ENSRIC

Energiforsk

Wireless in Nuclear

Feasibility study

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Foreword

Nuclear industry has been using traditionally wired systems in their nuclear power plants. Wireless technologies have developed in the recent years very fast and many vendors offer wide variety of wireless applications. Successful use of these technologies in various demanding industry fields is raising the interest also to start using wireless applications in the nuclear industry.

The aim of this study, Wireless in Nuclear - feasibility study, is to identify and compile information of existing wireless solutions used in Nuclear industry and other demanding environments (e.g. mining sites and factories), which could be applicable in the Nuclear industry.

This study has been carried out within Energiforsk's ENSRIC - Energiforsk Nuclear Safety related I&C research program and in its emerging technologies focus area by senior scientists Arto Laikari, Jacek Flak, Ari Koskinen and Janne Häkli at VTT Technical Research Centre of Finland Ltd.

The aim of the ENSRIC program is to extend the lifetime of existing nuclear plant instrumentation and control systems, finding new systems and new technologies, and studying security-related instrumentation and control systems in nuclear power plants. The results of the program will assist the nuclear industry and the Radiation Safety Authorities when analyzing how to replace systems and methods - choosing a new technology or finding a way to stay with the present solution - with maintained safety and promoting a low life cycle cost.

ENSRIC program is financed by Fortum, Karlstads Energi, Skellefteå Kraft, Teollisuuden Voima, Uniper, Vattenfall and the Swedish Radiation Authority.

Sammanfattning

Syftet med studien är att identifiera och sammanställa information om existerande trådlösa lösningar inom kärnkraftsindustrin samt annan verksamhet (t. ex. gruvindustrin, fabriker och militären), vilken kunde användas även inom kärnkraftsindustrin.

Utvecklingen av trådlös teknologi har under de senaste åren snabbt framskridigt, och ny sensor- och radioteknologi ger möjligheter att skapa omfattande trådlösa sensornätverk för monitorer och kontroll-system. Framstegen har också möjliggjort rörligheten av personal liksom också applikationer som skapar nya sätt att optimera verksamheten inom hela företagssektorn.

Det var redan känt före denhär studie att kärnkraftsindustrin har varit mycket försiktig med att ta i bruk trådlös teknologi. Orsakerna är strikta regler angående säkerhet och tillförlitlighet, rädsla för nya hot mot cybersäkerhet och elektromagnetiska störningar i systemen med andra kärnkraftverk. Trots detta visar studien att det finns ett ökat intresse bland ägarna och operatörerna av kärnkraftverk att använda trådlös teknologi. Olika trådlösa lösningar har redan testats i många länder i flera år. Forskargrupper tillsammans med kärnkraftsindustrin har undersökt möjligheter att övervinna återstående hinder och restriktioner som är spesifika för kärnkraftsindustrin.

I dethär avslutande kapitlet diskuteras orsaker till varför använda eller inte använda trådlös kommunikation i olika verksamhetsfaser (normal verksamhet, årliga driftsavbrott, service före avveckling och avveckling). Vår studie påvisar såsom redan antogs att annan industri redan använder trådlös teknologi på otaliga sätt. Den påvisar också att kärnkraftverk, standardiseringsorgan och reglage är i process att godkänna eventuell användning av trådlös teknologi i kärnkraftverk.

Denna studie baserar sig på intervjuer med utvalda experter från nordiska kärnkraftverk, litteratur-översikt från olika källor, erfarenhet man fått från väsentliga forskningsprojekt och på den egna praktiska erfarenheten.

Summary

The aim of this study was to identify and compile information of existing wireless solutions used in nuclear industry and other industries and services (e.g. mining sites,factories and military), which could be applicable to the nuclear industry.

Technological development of wireless technologies has advanced in recent years very much and novel sensors and radio technologies provide the opportunity for creating extensive wireless sensor networks to monitor and control complex systems without wires. These advancements have also enabled the mobility of personnel as well as applications creating new ways to optimize the operations in all business sectors.

It was already known prior to this study that nuclear industry has been very cautious to adopt wireless technologies. Reasons for this are the strict regulatory issues concerning safety and reliability and fear for new cyber security threats and electromagnetic interference with other nuclear power plant (NPP) systems. However this study reveals that there is an increasing interest among NPP owners and operators to start using wireless technologies and various wireless pilots have already been tested in many countries for several years. Research communities together with the nuclear industry are studying opportunities to overcome the additional obstacles and restrictions specific to the nuclear industry.

In the concluding section of this study, reasons why to use or not to use wireless communication in different plant phases (normal operation, annual outage, service operation before decommissioning and decommissioning) are discussed. Our study has revealed, as expected that other industries are already using wireless technologies in countless ways. It shows also that the NPPs, standardisation bodies and regulators are in the process to accept eventually the use of wireless technology in the NPPs.

This study is based on interviews with selected experts from the Nordic nuclear power plants as well as on literature reviews from various sources, experience gained from relevant research projects and own practical experience.

Abbreviations

2G - 2nd generation mobile networks / 2nd generation wireless systems

3G - 3th generation mobile networks / 3th generation wireless systems

4G - 4th generation mobile networks / 4th generation wireless systems

5G - 5th generation mobile networks / 5th generation wireless systems

AI - Artificial Intelligence

AR - Augmented Reality

ATEX - Appareils destinés à être utilisés en ATmosphères EXplosibles

BER - Bit Error Rate

BLER - Block Error Rate

CBM - Condition-Based Maintenance

CM - Condition Monitoring

COTS - Commercial Off-The-Shelf

CRP - Coordinated Research Project

DECT - Digital Enchanced Cordless Telecommunications

DOE - U.S. Department of Energy

EMC - ElectroMagnetic Compatibility

EMI - ElectroMagnetic Interference

ENSRIC - Energiforsk Nuclear Safety related I&C research program

EPRI - Electric Power Research Institute

ERS - Emergency Response System

FoF - Factory of the Future

GPS - Global Positioning System

IAEA - International Atomic Energy Agency

I&C - Instrumentation and Control

IEC - International Electrotechnical Commission

IEEE - Institute of Electrical and Electronics Engineers

IIoT - Industrial Internet of Things

IoT - Internet of Things

IP - Internet Protocol

IPSec - Internet Protocol Security Architecture

IPv4 - Internet Protocol version 4

IPv6 - Internet Protocol version 6

IWLAN - Industrial Wireless Local Area Network

LTO - Long Term Operation

M2M - Machine to Machine

NFC - Near-Field Communication

NPP - Nuclear Power Plant

NRC - U.S. Nuclear Regulatory Commission

OSI - Open Systems Interconnection

PDA - Personal Digital Assistant or Personal Data Assistant - a mobile electronic device

RFID- Radio Frequency IDentification

SCADA - Supervisory Control And Data Acquisition

SDS - Short Data Services

SSM - Swedish Radiation Safety Authority

STUK - Radiation and Nuclear Safety Authority of Finland

TCP/IP - Transmission Control Protocol / Internet Protocol

TETRA - Terrestrial Trunked Radio

UHF - Ultra high frequency

UWB - Ultra-WideBand

VoIP - Voice over Internet Protocol

VR - Virtual Reality

WLAN - Wireless Local Area Network

WMAN - Wireless Metropolitan Area Network

WPAN - Wireless Personal Area Network

WSN - Wireless Sensor Network

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1 Introduction

1.1 OBJECTIVE

The aim of this study is to identify and compile information of existing wireless solutions used in Nuclear industry, especially in the Nordic countries, but also in the international NPPs. These include the existing systems in use but also information of research experiments in nuclear power plants have been searched. Additionally examples of wireless technology use from other industry fields (e.g. mining sites, factories, harbours), which could be applicable in the Nuclear industry, have been collected.

This study is based on interviews with selected experts from the Nordic nuclear power plants (Olkiluoto, Loviisa, Hanhikivi, Ringhals, Oskarshamn and Forsmark), utility owners and regulators as well as literature reviews. Interviews have been done via filled questionnaires, phone or video interviews. The questionnaire, which was used to guide the interviews, can be found from the Appendix A.

Utilizing the information in the earlier chapters, the concluding chapter of the study depicts and takes into account reasons why to use or not to use wireless communication in different plant phases (normal operation, annual outage, service operation before decommissioning and decommissioning). Some consideration on the cyber security issues and possible physical restrictions are also given.

As this document will be publicly available, material used in this feasibility study, has been collected from the publicly available sources in order to avoid the situation that we would be accidentally revealing some confidential information in this report.

1.2 BACKGROUND

Technological development of wireless technologies has advanced in recent years very much and novel sensors and radio technologies provide the opportunity to create extensive wireless sensor networks to monitor and control complex systems without wires. These advancements have also enabled the mobility of personnel and applications creating new ways to rationalise the operations in all business sectors. Additionally freedom from wires opens opportunities to develop systems into processes, where wired system would not be possible to be implemented.

These technologies have been widely adopted into use across various industry fields. All market prediction studies show rapidly growing trend of development with industrial internet of things (IIoT) and wireless technologies in industry. Nuclear industry however has not yet adopted wireless technologies widely in to use, because of regulatory restrictions and fear for electromagnetic interference or cyber security threats. [1]

1.3 STRUCTURE OF THE REPORT

This report is divided into five main sections. The first section is the introduction where the scope and the background of this study is defined.

In the second section short descriptions of some of the most common radio and wireless technologies are presented as the background for this study.

The third section presents the wireless usage in nuclear power plants (NPP). First part of this section is dedicated to the Nordic NPPs located in Finland and Sweden. Information in this first part is collected from the interviews with the representatives of the Nordic NPPs. In the latter part of this section examples of wireless technology usage in the international nuclear power plants is presented. Information in this latter part is based on the literature survey.

The fourth section presents wireless technology examples from other industries to encourage the nuclear industry to consider the possibilities of the wireless technology usage in the NPPs.

The last section summarizes the findings from the previous sections. Opportunities and challenges using the wireless applications in nuclear power plants are presented and some proposals of wireless application examples for different NPP phases, like normal operation, annual outage, service operation before the decommissioning and decommissioning are presented.

2 Wireless technologies

Modern wireless technologies can be used to transfer all types of information or data. Chosen technology does not normally restrict, what kind of information is transferred with it. Wireless transport technology is just a medium to move information, like a road, or a cable in the wired system. E.g. Wireless local area network (WLAN) can transport measurement data, audio information like music, or a two-way video call. Wireless communication technologies have advanced in recent years with big leaps and there are many radio technologies available for wireless communication. Several industry fields have already adopted wireless technologies in their operation and emerging 5th generation mobile networks (5G) is expected to increase this development.

For the interviews of this report, we have created four categories, to help the information collection from the Nordic nuclear power plants (NPP). These categories are: audio visual communication, surveillance, monitoring and control and large data transfers. Partly these categories are overlapping, as audio visual communication is also used in surveillance applications and in surveillance monitoring and control is often also included. All the applications in these categories can support the operation of a nuclear power plant, but under the monitoring and control category most interesting opportunities in novel wireless use in the NPPs can be expected, as they can replace traditional wired solutions, bring cost savings and new ways in instrumentation and control. As an example, wireless applications can also rationalize and speed up the annual outage executions processes.

The scope of this study is to map existing wireless applications in the Nordic nuclear power plants (NPP) and collect examples of wireless applications in the international NPPs. Another target of this study is to present wireless applications in other demanding industry fields, which could be applicable also in the nuclear industry and NPPs. As the scope is on applications, we are only presenting some of the most commonly used wireless technologies, which are widely in use. We have left out more detailed analyses of wireless design principles from this report, as each application has its own requirements and it would not be possible to cover them all in this study.

2.1 APPLICATION CATEGORIES FOR WIRELESS TECHNOLOGIES

2.1.1 Audio-visual communication

Audio-visual communication technologies have reached high maturity already several years ago and new advances and applications are being published constantly. E.g. 4G networks with novel end devices, like phones or tablets, mix several wireless technologies offering mobile services for location, identification, command and control besides communication and audio-visual services. These have been taken into active use across industries and consumers. The speed of development in this area is challenging for the nuclear industry, as the technologies used in the NPPs need to be standardised and approved by the regulators. In the perimeter of the reactor or plant, these technologies (4G etc.) can be used, if the information security rules of the plant operator allow it, but inside the plant, newest wireless technologies are mostly forbidden.

For the audio-visual communication in the plant area, normally older DECT or TETRA systems are used, which satisfies the basic communication needs. With these technologies also simple data/information transfer is possible.

2.1.2 Surveillance

Surveillance technologies are already in use in the perimeter of NPPs protecting the area for unauthorized entry, fire safety etc. Surveillance technologies include both wired and some wireless applications. These technologies are partly also in use inside the plants, but there the solutions are mostly still wired or using only very short-range wireless communication, like RFID access tags.

2.1.3 Monitoring and control

Monitoring and control is the most interesting category of wireless applications concerning the industry needs, including the nuclear industry. Research communities, equipment vendors, operators and consultants among others across the world are offering wireless applications and equipment, like sensors, networks, terminals to practically all imaginable industry areas.

2.1.4 Large data transfer

Large data transfers were separated to an own category, but during the Nordic NPP interviews it was found out that it is not in use nor is there any near future plans concerning this category. All future plans or expectations fall in the monitoring and control category.

2.2 WIRELESS TECHNOLOGY INTRODUCTIONS

2.2.1 2G/3G/4G Cellular Networks

The xG symbols refer to consecutive generations of the cellular (mobile) telecommunication standards introduced to the market in about 10 yrs. time-intervals. The first generation was analogue and became obsolete over the years. Starting with 2G, the communication is digital. Due to local regulations, different regions have different frequency bands assigned to each standard (e.g., 900/1800 bands in Europe vs. 850/1900 in North America). Usually, handsets remain ability to operate with (some) previous standards and to operate at several bands, thus allowing for roaming. A channel capacity and a set of possible applications has grown with each generation due to expanding frequency spectrum and new channel coding techniques. However, the higher bit rates of new generations come at the cost of smaller network cell size, i.e. maximal distance from a base station. Incremental improvements have also been made within each generation either gradually reaching the ultimate targets envisioned by each standard or forming a transitional step towards the following generation (e.g., 2.5G, 3.5G). The below

Table 1 compares the generations with respect to utilized frequency bands, channel coding, bit transfer rates, and finally applications.

Table 1 2G/3G/4G Cellular networks comparison

	Technology/ standards	bit rates (max)	Freq. bands in Europe (MHz)	Features and applications
2G	GSM, TDMA, CDMA,	14.4kbps	900, 1800	Voice communication, SMS, low-rate data services
2.5G	GPRS, EDGE	64kbps		
3G	UMTS, WCDMA, CDMA 2000	200kbps - 2Mbps	900, 2100	Voice, SMS, MMS, video conference, first mobile broadband, internet, mobile TV, video on demand, location-based services
3.5G	HSDPA /HSUPA,	7.2Mbps /5.8Mbps		
3.75G	HSPA+	21Mbps		
4G	WMAN-Advanced, LTE Advanced	100Mbps (moving) 1Gbps (stationary)	800, 1800, 2100, 2600	All internet protocol (IP)-based packet-switched nets, true mobile broadband

2.2.2 5G Networks

The 5^{th} generation of mobile networks (5G) is a proposal of a new upcoming standard with capabilities beyond the current 4G. The envisioned services go far beyond current mobile communications and internet access and include massive wireless machine networks (IoT), which means simultaneous broadband connections for hundreds of thousands of wireless sensors. Additionally, bitrates above 10Gbps should be possible for stationary users. Therefore, new frequency bands in the range of 20-60GHz are proposed along some lower frequencies for use within 5G networks. Moreover, the network should have reduced latency and better coverage compared to 4G. This will require significantly improved signaling-, spectral-, and energy-efficiency. The R&D work is ongoing, and remains to be seen what types of implementations will be introduced to the market after the year 2020 (as expected). 5G test networks are already running and in some countries commercial use of the 5G networks could start even earlier than year 2020.

2.2.3 Satellite communications

In addition to the satellite positioning and tracking of the assets described in Section 2.2.10, satellite communications are commonly used in remote areas where terrestrialt communication services are not available. They also provide an alternative that is not dependent on the operation of the terrestrial infrastructure during emergencies and other times when the normal services are not available or are inoperative. Satellite communications are used for transferring data e.g. from sensor systems or other systems, for person to person communication (audio & video calls) and to access the internet. Satellite communications can be accessed with fixed landstations for high capacity needs or with portable mobule terminals such as satellite phones.

Satellite communications service provides include Inmarsat who started with maritime communication services but who offers a wide range of solutions for different customers - as with the other service providers, the available services and options are highly varied due to the limited capacity in the satellite systems. In principle, all communication services that are available in terrestrial systems are available also via satellite, but the costs is usually considerable higher especially for large amounts of data and the data transfer rates are lower than with fibre optic connections but comparable to mobile solutions. Other service providers include for example Iridium Communications and Globalstar. There are also other companies proving satellite communications using the satellites operated by e.g Intelsat, Eutelsat and other satellite operators.

2.2.4 TETRA

Terrestrial Trunked Radio (TETRA) is European standard for professional mobile radio designed specifically for use by government agencies, emergency services (police, fire brigades, ambulance), transport services and army. Therefore, the system can operate in different modes. Typically, the switching and network management is handled by TETRA base stations (trunked-mode). However, direct mode operation is also possible, in which terminals can communicate directly (like a walkie-talkie). This becomes useful in the absence of network. Moreover, TETRA handsets can operate as gateways, relaying connections of terminals that are out of network range to the base station, or as repeaters extending the link between two terminals communicating directly. These functionalities are very useful for, e.g., underground operation or in the bunkers. TETRA supports one-to-one, one-to-many, and many-to-many types of connections. Terminals also include emergency buttons that allow for sending emergency signals, which override any other activity. Air interface is encrypted using TETRA encryption algorithm ciphers, providing the confidentiality and protection of signaling. The voice signals are compressed and error-protection encoded to assure the correct operation even in very noisy channels. The frequency bands used by TETRA are country-specific with typical implementations in the 380-470MHz range. The low frequency results in longer maximum distance, and thus less base stations needed for areal coverage. However, it means narrow channels and low data rates. TETRA uses TDMA with four user channels per radio carrier (with 25kHz spacing between carriers), and supports up to 115.2kbps in 25kHz channel. TETRA offers also Short Data Service (SDS) for data service, which is comparable to the cellular network SMS messages. SDS messages can be used both for text but also as short data messages.

2.2.5 DECT

Digital Enhanced Cordless Telecommunications (DECT) is technology used in cordless telephone systems. DECT allows for wireless communication between several handsets and a single base station (gateway to the fixed line network). Often the handsets can also communicate with each other as intercoms or walkie-talkie type devices even without the telephone line connection. Over time, the DECT standard has evolved into a series of NG-DECT/CAT-iq standards expanding beyond voice link providing additional call management features like: caller identification, phonebook, multiple lines, call waiting, call transfer, call intrusion, answering machine control, SMS, and even light data service and smart home connectivity (IoT).

In Europe, DECT operates in the 1880-1900MHz frequency range, making it immune to interference from WiFi networks, Bluetooth devices, microwave ovens etc. Typically, the band is divided into 10 frequency channels, each being further divided into 12 duplex-link time slots, resulting in 120 carriers with 32kbps bit rate. However, the DECT Packet Radio Service (DPRS) with multi-bearer support and efficient packet data handling can provide bitrates of 840kbps or even up to 5Mbps depending on advanced modulation level. With 10mW (250mW peak) transmission power, DECT allows for connectivity up to 500m in open space and tens of meters in offices. Originally, the communication between the handset and station was secured with 128-bit shared unique authentication key and 64-bit encryption. However, the NG-DECT/CAT-iq suit provides new authentication and encryption algorithms (both based on AES 128-bit encryption) as an option.

2.2.6 Wireless sensor networks

The purpose of wireless sensor networks is to connect a massive amount of sensors wirelessly to the monitoring and control systems. Wireless sensor networks can be built using several radio technologies and communication protocols. Radio technology provides the instrument to move the information and the protocols, how the information is moved. In the earlier implementations, point to point communication was used, where a sensor, or sensor hub sent the the information to the collecting master node. In the modern sensor networks, also mesh networking is used, where the nodes in the sensor network can relay messages and act as repeaters in the network. This topology will bring robustness in the network, providing multiple paths for the information, e.g. a faulty node can be automatically be passed and also better coverage for the wireless sensor network in demanding environments. In this chapter we introduce some of the most common sensor network radio technologies in use.

Wireless Personal Area Network (WPAN)

Wireless personal area network (WPAN) is a network for connecting devices within one’s workspace, i.e., in the range of few centimeters up to few meters. The WPAN can be implemented using different technologies, mainly the IrDA (infrared communication used primarily in remote controllers and sometimes for computer keyboard and mouse), ZigBee (low data rates up to 250kbps), and Bluetooth, which currently dominates the market. Typical applications are connections between computers and smartphones as well as their peripherals (printer, keyboard, mouse, speakers, headsets, wearable devices etc.).

Bluetooth

Bluetooth is a short range wireless technology for fixed and mobile devices to transmit and receive data. The operating frequency is 2.4-2.48 GHz at the industrial, scientific and medical (ISM) band. The communications are using a packet-based protocol with a master/slave architecture where one master may communicate with up to seven slaves.

Bluetooth operating range depends on the power class:

- Class 1: 100 mW, ~100 m.
- Class 2: 2.5 mW, ~10 m.
- Class 3: 1 mW, ~1 m.
- Class 4: 0.5 mW, ~0.5 m.

Bluetooth low energy provides reduced power consumption and cost while maintaining the communication range using the same ISM bandwidth by using the frequency different. The data rate is lower than with the regular Bluetooth. The protocol is not compatible with the ordinary Bluetooth.

Zigbee

Zigbee is a specification of communication protocols for low-power low data rate short range wireless personal area network. It is based on IEEE 802.15.4 standard emphasing very low cost short range communications. This standard specifies operation at 2.4 to 2.4835 GHz (worldwide), 902 to 928 MHz (Americas and Australia) and 868 to 868.6 MHz (Europe) ISM bands. The data rate is 250 kbit/s per channel in the 2.4 GHz band, 40 kbit/s per channel in the 915 MHz band, and 20 kbit/s in the 868 MHz band. . For indoor applications at 2.4 GHz the operating range is about 10–20 m, outdoors with line-of-sight, range may be considerably longer.

LoRa

LoRa is a wireless technology for low power wide-area network connecting wireless battery powered sensors and other Internet of Things (IoT) devices. It uses the ISM frequency bands - 868 MHz and 433 MHz in Europe. The features include long range, long power consumption and secure data transmission with easy interoperability with an open standard. The use of LoRa is promoted by the LoRa Alliance™.

WirelessHART

WirelessHART is based on the Highway Addressable Remote Transducer Protocol (HART) and it uses the 2.4 GHz band. It is based on the IEEE 802.15.4 standard and it is an open industrial standard used in the process industry. WirelessHART forms a flat mesh network, where every participating station acts simultaneously as a signal source and a repeater for other stations.

ISA 100.11a

ISA100.11a is a wireless networking technology protocol standard, IEC 62734, for industrial systems defined by the International Society of Automation (ISA). It is designed to be used in wireless industrial plant needs, including process automation and factory automation. ISA100 Wireless is designed to follow the Open Systems Interconnection (OSI) model and uses IPv6 with its security features for addressing the elements in the network.

2.2.7 WLAN

Wireless local area network (WLAN) is a wireless network providing communication between computers, smartphones, tablets etc. within a limited area, i.e., office building. The standards collected in the IEEE 802.11 suit are often branded as Wi-Fi. Typically, WLAN operates in infrastructure mode with connections passing through an access point, which usually also serves as gateway to other LANs or internet. However, an *ad hoc* mode with direct link between mobile terminals (peer-to-peer communication) is also possible. WLAN can operate at two frequency bands of 2.4GHz and 5GHz with maximum bit rate of 500Mbps, however typical transfers are in the order of tens of Mbps (depending on equipment and number of connected devices), especially if the packet conversion from WLAN to wired Ethernet is involved. The signal range can span from a single hall to an entire town using multiple access points (so-called hotspots). The maximum transmitted power in Europe is limited to 100mW in 2.4GHz band and either 200mW or 1000mW (depending on a channel) in 5GHz band. Several Wi-Fi networks can operate in the same area sharing the frequency spectrum and can be identified by their SSID - a 32-byte (maximum) character string ("network name"). Access to the WLAN can be open (insecure, available to all devices in the range) or protected by WPA/WPA2 protocols with either a 256-bit shared key (personal networks) or with more advanced authentication (enterprise networks).

2.2.8 WMAN/WiMAX

Wireless metropolitan area network (WMAN) is a network providing wireless broadband access over longer distances than WLAN up to several kilometers. The standards collected in the 802.16 suit were often marketed as WiMAX (Worldwide Interoperability for Microwave Access). The WiMAX used licensed spectrum bands of 2.3 GHz, 2.5 GHz and 3.5 GHz, and became popular in America and Asia. In Europe, however, the spectrum was not allocated to WiMAX. Its potential benefits in terms of coverage, power consumption, and spectral efficiency, made WiMAX a strong candidate for LTE core technology. In 2007, it was included in the IMT-2000 set of standards, and later as a WMAN-Advanced merged with LTE Advanced forming the fourth generation cellular system (4G).

2.2.9 Ultra-WideBand, UWB

Ultra-wideband (UWB) is technology in which short signal pulses are sent over a broad frequency spectrum (hence the name), typically spreading over at least 500MHz or 20% of the centre frequency. Use of such a wide frequency band leads to low power spectral density, and thus negligible interference with other types of radio systems. At the same time, it provides a high bandwidth needed for very high data throughput short-range communications, and robustness against multipath fading. In Europe, the UWB technology can operate at frequency bands of 2.2-8GHz or 6-9GHz. The possible applications include communications and sensor systems, ground- and wall-probing radars (through-wall imaging), medical imaging, precision location within buildings, and surveillance systems. Additionally, bands at 24 and 79GHz are assigned for automotive (anti-collision) radar systems.

2.2.10 Location, identification and presence

Technologies used to provide location or presence of persons or equipment and identification of them are presented in this sub chapter.

Radio Frequency Identification, RFID

Radio Frequency Identification or RFID in short is often considered as an electronic barcode for asset management. However, RFID is more robust technology for outdoor and industrial conditions and better suited for automatic identication and tracking of persons and assets - RFID does not required visible tags or markings so no line of sight is needed and radio waves go through many materials such as dirt, snow, mud or non-metallic coverings. The reading of the transponders or tags with the reader can be done at a range of several metres using passive transponders without batteries needing replacement and using active battery powered tags ranges up to tens of metres can be achieved.

RFID is based on a variety of wireless technologies operating at different frequencies, most commonly at low frequencies (LF) at 125 kHz, at high frequencies (HF) at 13.56 MHz and at ultra high frequencies (UHF) at 867 MHz. For active transponders 2.45 GHz frequency is often used. The LF and HF RFID systems are used in short range applications such as electronic key cards, passive UHF is commonly used for remote identication of items. Different types of transponders have been developed for different applications ranging from inexpensive adhesive labels for non-conductive surfaces such as cartboard to durable cased hard tags that can be mounted on metal. RFID readers can be portable hand-held devices for mobile applications or fixed readers for automatic operation for example in drive-through or walk-through doorways or gates or on conveyors. Typical applications of RFID technology include inventorying and tracking the whereabouts of high value assets, and location and movements of personnel for safety and security purposes.

Near Field Communication, NFC

Near field communication (NFC) is a RFID based technology operating at the frequency of 13.56 MHz utilising magnetic coupling between the loop antennas in the communicating devices. The operating range is short, up to 10-20 cm and typically less. The main application is contactless paying with smart cards e.g. credit cards with NFC antennas and microchips. Any other information can be also read or written wirelessly over the NFC interface which has data security features such as encryption than the common RFID technology. One advantage of NFC technology is that many smartphones include NFC allowing them to be used to communicate with other NFC enabled phones, smart cards and inexpensive NFC labels without needing an dedicated reader device. This communication can be used to identify labelled items, control personnel access and to obtain information on the marked items from their NFC label similarly to other RFID techniques.

Satellite positioning

A timing signal transmitted by satellites can be used to determine the 3D location of the receiver by precisely measuring the timing difference of the signals from several satellites to determine the distance to them. With the known position of the statellites, the receiver position can be calculated typically within 1-10 m. Global positioning systems allowing localisation and tracking of the receiver location (and the positioning of the persons and assets equipped with the receivers) include the US operated GPS, European Galileo and Russian GLONASS. The precision of the positioning can be improved by combining the location data from several positioning systems or by using differential techniques where a land station with known locations transmits a correction signal to help the receivers to locate themselves with higher precision.

Pseudolites

Pseudolite means basically a 'pseudo-satellite' i.e. a terrestrial device that acts like a satellite in a satellite based system. The most common us for pseudolites is positioning similar to satellite positioning - instead of signals from satellites signals from pseudolites are used to determine the location. The advantage of using local pseudolites instead of the global satellites is that the pseudolites and their operation can be controlled locally instead of relaying on external service provider. Another advantages is that the positioning can also work where there is no satellite signal such as indoors. The obvious disadvantage is of course higher cost of the system as separate pseudolites that need to be installed and maintained are required in addition to the the receivers - whilst a satellite positioning system needs only the receiver units.

2.2.11 Low frequency Wireless Technologies

For radiowaves to penetrate underground or underwater low frequencies are needed as the attenuation by conductive materials (water, soil, salt, metals, etc.) increases with the frequency. In the past extremely low frequencies (ELF, 3-300 Hz) have been used to communicate with submerged submarines. Low frequencies (30-300 kHz) are used for long range terrestrial communications for ranges up to thousands of kilometres e.g. to transmit timing signals. The other low frequency ranges in the band of 1 kHz-300 kHz have similar uses. At these low frequencies, the available bandwidth is low and thus the data transfer rate is also low.Wireless sensors using low frequency to transfer the sensor data are being investigated for underground and underwater applications. Research is being carried out for sensor solutions that allow obtaining measurement data though walls, soil and water.

2.2.12 Wireless power

Wireless communication is based on transmitting and receiving radio waves - typically the information is coded and used to modulate the transmitted signal which is then demodulated and decoded at the reception to retrieve the information. The radio signal carries power, the needed signal power levels for receiving a transmission depends on the sensisity of the receiver and typical receiver sensitivities are of the order of pW. Besides retrieving the information carried by the wireless signal, the power of the signal can be used. For example, passive RFID transponders (See Section 2.5.1) take their operating power from the signal transmitted by the reader.

The received wireless signal power can be harvested to charge a battery or other energy storage which in turn can be used to power electronic devices such as sensors. The minimum usable power level from which energy can be stored is of the order of 1 μW. The power of a electromagnetic signal decays exponentially and thus the wireless power transfer is best suited for short range power transfer with reasonably small power levels. Typical applications include wireless powering of devices on moving parts or objects were wires cannot be used - wireless power transfer is used to transfer the power over a small gap were there can be no wires. Wireless charging of mobile phones and laptops is available and wireless charging of electric cars has also been considered. In these systems the reason to use wireless powering is convenience - no wire connections are needed but the battery charging is less efficient due to the losses in the wireless power link.

2.2.13 Other wireless technologies

This study is constrained to wireless communication using radio technologies. There exists also other means for wireless communication, where the wireless communication is based on:

- Visible Light Communication (VLC)
- Infrared communication (IrDA)
- Audio communication

Mainstream for the industrial wireless communication is executed with radio technologies described earlier in this section, which will most likely be also the technology used in the future NPP wireless applications. Other than radio based wireless technologies would however be free from the electromagnetic interference (EMI) problems.

2.2.14 Evolution of wireless networks

As the service life of NPPs is several decades, it should be noted that the life cycles and development speed of wireless technologies is much faster. Availabitily of the chosen equipment in NPPs should be ensured for the whole service time of the NPP, although in practise this requirement will be impossible to implement, because of the long service times of the NPPs.

As an example, WiMAX (Worldwide Interoperability for Microwave Access) wireless broadband technology was standardized and published in 2002. In recent years the use of WiMAX has declined, many WiMAX networks have been shut down as newer communication technologies, like LTE, have replaced it.

3 Wireless applications in nuclear

Traditionally nuclear power plants (NPP) have been using wired communication in their instrumentation and control systems (I&C) and operations at the plant. As the life span of the NPPs is very long, many of the NPPs were built in the time, when feasibile solutions for complex NPP wireless instrumentation and control did not exist. Over the years, the wireless communication technologies have developed and nowadays they offer many solutions for data transfer, communication and I&C and many other industries have adopted them in to use. Nuclear industry has been very cautious with the wireless technology usage, as it is a very strictly regulated industry and realiability and safety have the top priority. Wireless technologies has been considered to bring out new challenges and even threats to the operation in the NPPs and wired solutions have been considered to be the only acceptable method for operations. Regulators and NPP operators have been sceptic about the reliability, cyber security and electromagnetic interference (EMI) of the wireless systems.

According to the IAEA's nuclear power reactors in the world (2017) report, there are 448 operational, 61 under construction and 80 planned nuclear reactors globally as of 31st of December 2016. [2] Already in 2008 IAEA was reporting that as of June 2007 approximately 25% of the nuclear power plants in the world had been in operation more than 30 years and about 70% more than 20 years. [1] Many of the member states are considering to prolong the operation of their nuclear power plants from the originally planned life time of them. Extension of the nuclear power plant is also known as long term operation (LTO).

Other industries have successfully started to utilize wireless technologies in their operations, which has caused also nuclear industry to show increasing interest towards the wireless technology usage in the NPPs. As there are currently several new reactors planned and under construction as well as modernisation of older reactors in their LTO programs ongoing, wireless technology has and will eventually move also into the nuclear power plants. The advanced digital I&C applications planned and implemented for the Generation III (Gen III) and Gen III+ plants as well as Gen IV in the future will be the road openers for these new technologies. E.g. in an IAEA meeting in Vienna, Austria May 2015 several of the IAEA member stated in their country report presentations on recommendatios for actions and plans concerning activities with wireless in nuclear.

3.1 REGULATORY REQUIREMENTS AND RESTRICTIONS

As nuclear industry is extremely well regulated, also the use of any wireless applications is strictly regulated. Requirements and restrictions vary depending on the country and the set of rules they are following.

The Radiation and Nuclear Safety Authority of Finland (STUK) supervises radiation and nuclear safety in Finland. STUK publishes regulatory guides describing the requirements for the safe use of radiation and nuclear energy. STUK guide YVL B.1, safety design of a nuclear power plant, published 15th of November 2013 sets the rule in the chapter 5.2, instrumentation and control systems for the Finnish nuclear power plants: “No solutions based on wireless data transfer may be used in the safety functions”. Additionally in the chapter 5.4.6 Electromagnetic compatibility (EMC) of electrical and I&C systems, due consideration is required to electromagnetic interference caused by wireless transmissions (e.g. human action, telephone systems, repair, maintenance and measuring devices) used at the nuclear plant. In this chapter, a radio frequency table is also required to be maintained to list all the radio frequencies allowed on the nuclear power plant site. [3] For the non-safety critical systems, STUK guide YVL 5.5, instrumentation systems and components at nuclear facilities, demands particular justification for the need to use wireless controls. “A device or a system comprising wireless control shall be designed such that the control action is possible only through a connection signal designed for the control and that the system or the device goes quickly enough in a state preferable from the safety point of view in case the control signal breaks off. [4]

Same approach has been also adopted in Sweden, where Swedish Radiation Safety Authority (SSM) supervises radiation and nuclear safety in Sweden.

In the United States Nuclear Regulatory Commission (NRC) and Electric Power Research Institute (EPRI) rely on the use of exclusion zones to protect plant equipment. The same restriction on use of wireless in safety functions is valid also in U.S. regulations, no wireless applications are allowed in safety funtions. NRC has been active on research of the possibilities of wireless applications in nuclear for quite some time e.g. NUREG/CR-6882, “Assessment of Wireless Technologies and Their Application at Nuclear Facilities from 2003-2005 [5] and 2008 NUREG CR-6992 Instrumentation and Controls in Nuclear Power Plants - An Emerging Technologies Update [6].

Strict attitude towards the use of wireless technologies in other countries across the world with the local radiation safety authorities likely applies.

3.2 WIRELESS APPLICATIONS IN NUCLEAR POWER PLANTS AND STANDARDISATION

As operation of nuclear power plants is strictly regulated, standards play important role in the adoption of new technologies in the NPPs. The International Electrotechnical Commission (IEC) technical committee TC 45 Nuclear Power Plant Control and instrumentation reported that they had an ad hoc meeting in Yokohama 2009, which resulted in to a recommendation to develop a technical report addressing the applicability of incorporating wireless technology throughout nuclear power plant systems. [10]

The International Atomic Energy Agency (IAEA) and the International Electrotechnical Commission (IEC) technical committee TC 45 Nuclear Power Plant Control and instrumentation have made an agreement that the IEC nuclear sector safety and security standards implement principles and terminology of the IAEA safety and security guides. Technical committee 45 has also a subcommittee SC 45A Instrumentation, control and electrical power systems of nuclear facilities. This subcommittee is working on a standard: IEC 62988 Nuclear power plants - Instrumentation and control systems important to safety - Selection and use of wireless devices. Work with this standard initiative has started in February 2015 and it is expected to be published in July 2018. IEC working documents are restricted only to the participating members and they are not open to the public.

IAEA is also working on a report on Wireless Implementation in NPPs, which is expected to be published in 2019.

Naturally there exists also several other standards which are required to be followed in the Nuclear Power Plants concerning digital communications, regardless is it implemented with wired or wireless communications, including several IEEE standards.

3.3 WIRELESS APPLICATION CONCERNS IN NPPS

The main concerns when considering wireless communications in the NPPs are reliability, security, electromagnetic compatibility (EMC), electromagnetic interference (EMI) and spectrum management.

Reliability is required for all communication methods (wired and wireless), but in the wireless communication there are more factors which can effect on the successful communication. Reliability of the communication can be measured by its bit error rate (BER) or block error rate (BLER), where the average ratio of faulty bits to the total transmitted bits is measured. Additional reliability issues concerning wireless applications include e.g. radio interference and obstacles for radio wave propagation. Modern error correcting transmission protocols can be used to ensure the high reliability of the wireless communication. Careful planning and use of repeaters and multiple antennas can ensure the needed signal strength for reliable communication.

Electromagnetic compatibility (EMC) and electromagnetic interference (EMI) are tightly connected to the requirement of spectrum management. Regulators require that the plants maintain a radio frequency table used in the NPP, which lists the allowed radio frequencies and transmission power levels. Radio spectrum management is also important for ensuring the coexisting of various wireless technologies, when they have been accepted to be used in the plant, as mixing several of the previously mentioned (section 2.2) wireless technologies without planning can end up to interference problems. Especially in the older NPPs the EMC is a challenge as the plant operator need to prove that the wireless is electromagnetically compatible with the old I&C systems which are not planned to be used together with wireless communication systems. In the new NPPs wireless design can already be taken into account in the planning phase.

As the advanced wireless applications could open novel efficient operation possibilities in the NPPs, it opens also new security issues, which need to be taken into account in the design. These new risks include unauthorized access and control of adversaries who are in relatively close physical proximity but do not have direct physical access to the equipment, eavesdropping and jamming which would prevent the signals to be transferred among others.

All the above mentioned issues concern also other industries and they are carefully taken into account, but in the nuclear industry the regulatory acceptance processes are even more demanding. In the nuclear industry very heavy structures and walls preventing radio wave propagation make the implementation of wireless systems very challenging and radiation either restricts or requires additional protective means to be created for the devices used. Research to support wireless component use in the radiation zones is ongoing and wish to use commercial off-the-shelf (COTS) equipment is very high, because use of COTS equipment guarantee high production volumes and reasonables costs. In higher radiation zones additional care to protect the electronics is however required [7] [8] [9].

The NPP regulation requires also to maintain not only physical and electrical independence but also data independence between safety and nonsafety systems, thereby guaranteeing that a transmission error in one channel or division will not cause the failure of another channel or division [6].

3.4 WIRELESS APPLICATIONS USED IN NORDIC NPPS

In the Nordic countries Nuclear Power Plants have been built in Finland and Sweden. In total there are 14 reactors in 5 nuclear power plants in operation, one in construction and one planned. These are listed in the following Table 2.

Table 2 Nordic reactors and operational reactor commercial starting years

Number of reactors, as of 31 Dec. 2016					
Country	**Operational**	**Commercial operation started**	**Construction**	**Shut down**	**Planned**
Finland	Loviisa-1 Loviisa-2 Olkiluoto-1 Olkiluoto-2	1977 1981 1979 1982	Olkiluoto-3		Hanhikivi-1
Total # Finland	4		1		1
Sweden	Forsmark-1 Forsmark-2 Forsmark-3 Oskarshamn-1 Oskarshamn-2 Oskarshamn-3 Ringhals-1 Ringhals-2 Ringhals-3 Ringhals-4	1980 1981 1985 1971 1974 1985 1974 1975 1981 1983		Agesta Barsebäck-1 Barsebäck-2	
Total # Sweden	10			3	
Total # Nordic	**14**		**1**	**3**	**1**

From the Table 2 it can be seen that all operational Nordic reactors have been built way before it was feasible to use wireless technologies in the nuclear power plants. Construction of Olkiluoto 3 has already started in 2005, which was too early considering wireless usage in a nuclear power plant. Currently there is only one nuclear reactor planned in the Nordic countires, Hanhikivi 1, but as the detailed planning is still in early phase, there are not yet final decisions in wireless technology adoption at Hanhikivi 1. As the previously mentioned STUK regulations [3][4] apply to all the Finnish nuclear power plants, they restric also the the new NPPs to adopt wireless technologies into use for the safety critical systems and in the other application areas the vendors are still mostly providing customary wired solutions.

Wireless technology usage in the Nordic NPPs later in this chapter has been collected via interviews with the plant representatives. Prior to the interview a set of questions was sent to the selected persons in the plants and they were encouraged to collect information also from their colleagues. These questions can be found from the Appendix A. The results were collected either with filled questionaires, phone or video conference interviews.

Results revealed, as was expected that the Nordic nuclear power plants are not very much using wireless technologies in their operations and they are using the few wireless applications in similar ways. Main reasons in the Nordic NPPs not to use the wireless applications are the existing old installed wired equipment, regulatory issues, non existing wireless infrastructure, fear of electromagnetic interference (EMI) and cyber security.

Plants have been designed and built to be operated with wires in the time, where no wireless technologies was expected to be used in the NPPs. For this reason the electromagnetic compatibility (EMC) with wireless systems and avoiding their harmful electromagnetic interference (EMI) was not considered in the design. In the Nordic NPPs there is no ready built infrastructure for wireless communication, which makes it harder to start using wireless applications, as the infrastructure needs to be first designed, approved and installed. An other major obstacle to start using wireless technologies in the NPPs is the Cyber security fears, as adopting wireless applications in to use will raise new security threats, like unauthorized access, denial of service/jamming or eavesdropping.

Although modernisation of old NPPs is happening in the LTO programs, replacing existing equipment with wireless solutions would raise a lot of discussion and debates with the regulators and will most likely not happen in the near future. For novel supporting applications wireless can have a place even in the old nuclear power plants. This will be discussed in the last chapter of this report. In the complety new NPPs, wireless technologies will most likely be adopted in to use, when the standardisation and IAEA guidelines help regulators to assess these technologies in the nuclear industry.

3.4.1 Audio visual communication

In the Nordic NPPs audio communication is done using DECT or TETRA phones or UHF radios. Some plants are also using short data messages, like TETRA SDS for data transfer. As an example, fire alarm system can send an SDS message of alarm information to dedicated TETRA phones.

Modern mobile phones are not allowed to be used inside the plants, because of interference (EMI), information security and contamination issues. In the administration and office areas however the modern cellular phones are allowed to be used.

3.4.2 Surveillance

Most of the surveillance systems in Nordic NPPs are using wired connections. Some wireless applications are in use for the surveillance, like short range RFID tags to open doors, TETRA SDS messages from fire alarm system delivering fire alarm and location information to the TETRA phones.

3.4.3 Monitoring and control

For the direct nuclear power plant monitoring or control systems no wireless applications are used in the Nordic NPPs. Some applications using wireless technologies in the Nordic NPPs include:

- Wireless control units are used for some of the cranes inside the NPPs.
- In the perimeter of the NPP an wireless system to measure radiation is in use.
- A wireless system detecting at the gate the missing dosimeter, when entering restricted area, where dosimeters are required.
- Global time synchronization from a GPS satellite is acquired wirelessly and then propagated to the plant systems with wires.

3.4.4 Other wireless usage

In the administration and office areas of the NPPs normal wireless office systems using WLAN, Bluetooth and modern cellular networks are in use.

3.4.5 Future wishes for wireless usage

Although there are the doubts and obstacles mentioned earlier in this chapter, also Nordic NPP operators would like to investigate and consider using wireless technologies in their plants. Succesful experiments in other NPPs and in other industries encourage this development and adopting first some wireless applications in to use, it can be a road opener for more wireless applications. On the wireless application wish list there are topics like:

- wireless data retrieval
- movable wireless cameras
- movable temporary wireless measurements e.g. during maintenance
- wireless dosimeter system across the plant
- movable wireless detectors e.g. for radiation, gas or oxygen
- wireless document retrieval during inspections

3.5 WIRELESS APPLICATIONS USED IN INTERNATIONAL NPPS

In this chapter, the material has been collected with literature surveys. As already mentioned earlier, there has been numerous different projects related to wireless applications in NPPs e.g. IAEA Coordinated Research Program on advanced, surveillance, diagnostics and prognostics techniques used for health monitoring of systems, structures and components in nuclear power plants and wireless data transfer has been one area of interest also in sustainable nuclear energy technology platform (SNETP).

In this section, we are briefly presenting some wireless implementations, research projects and research proposals for wireless applications in the international NPPs. As the list of wireless projects in NPPs is constantly increasing, our list in this report is not an all inclusive, but it will show the trend that wireless technologies are coming into the NPPs. We have picked examples from large scale complex wireless systems but also some small scale wireless systems to encourage to consider the benefits of the wireless technologies.

3.5.1 Wireless Technologies in NPPs using cognitive radio system

Analysis and Measurement Services AMS, located in Knoxville, Tennesee U.S. has been active on numerous wireless studies and applications and in their recently published paper in NPIC&HMIT 2017 Conference titled "Implementation of Wireless Technologies in Nuclear Power Plants' Electromagnetic Environment Using Cognitive Radio System" describes well how wireless applications could be used in NPPs [12]. They state that at the moment the existing guidance from the Nuclear Regulatory Commission (NRC) and Electric Power Research Institute (EPRI) rely on the use of exclusion zones to protect plant equipment and this could hinder the usage of wireless devices in nuclear facilities. As at the moment it is unknown how different wireless devices will operate in close proximity to one another in the harsh electromagnetic environment of a nuclear power plant, AMS has developed a cognitive radio system that has the ability to generate and output multiple wireless signals (e.g. Wi-Fi, Bluetooth, cellular communications at varying power levels and frequencies). System can be used to test equipment in training areas, simulators as well as in actual plant environment, and with it radio spectrum for usage in other plant focuses can also be monitored (e.g. cyber security). [12]

3.5.2 Wireless sensor network trials in Comanche Peak Nuclear Power Plant and Arkansas Nuclear One (ANO) power generating station

Jiang et al. describes in their paper a state of the art review on wireless sensor networks (WSN) in NPPs. In U.S. few experimental WSNs have been deployed in Comanche Peak Nuclear Power Plant and Arkansas Nuclear One (ANO) power generating station. In Comanche Peak NPP 802.11b wireless network infrastructure was established in the plant that incorporates wireless sensors for equipment condition monitoring and diagnostics. It was stated that about one hundred wireless sensor nodes have been installed in the plant to collect information for monitoring purposes on varieties of non-safety related system equipment. In ANO power generating station investigation on wireless vibration sensors used to monitor the condition of the containment cooling fans is ongoing. It is stated that the system is designed to acquire and to transmit vibration data once a day to the base station as the current practise is to collect the data manually on mothly basis. [13]

3.5.3 Research project for the U.S. Department of Energy

January 2009 R.J. Jarrett, H.M. Hashemian, G.W. Morton, B.D. Shumaker, and C.J. Kiger summarized in the Automation IT article “Nuclear power comeback sure to employ wireless tools” that in 2009 wireless was used in NPPs for wireless dosimetry, voice communication, equipment monitoring, laptops and PDAs, camera monitoring and heavy equipment operation. Voice communication was the most prominent wireless application in the plants at this time. [11]

In the same article an example of equipment to be measured wirelessly in the nuclear plant was presented. These are listed in the following Table 3.

Table 3 Proposed points to measure wirelessly in a nuclear plant [11]

Nuclear Plant System	Wireless Measurement(s)	Application
Heat Exchangers	Temperature	Monitor ambient temperature to take into account the effects of seasonal changes in weather.
Secondary Side Valves	Position Indication	Replace periodic labor-intensive valve indication readings with continuously monitored wireless measurements.
Inlet Water Intake	Level, Temperature, Flow	Monitor factors that affect performance such as changes in level, seasonal temperature variations, and intake flow.
Rotating Equipment (pumps, valves, motors, compressors, fans)	Temperature, Level, Vibration, Motor Current	Monitor temperatures, vibration signatures, and load fluctuations to assess condition and improve performance.
Diesel Generators	Temperature, Level, Vibration, Motor Current	Augment existing sensor readings to provide redundancy and comprehensive performance assessment.
Spent Fuel Dry Cask Storage	Temperature, Radiation	Eliminate need for underground cabling and conduit by monitoring temperature and radiation with wireless sensors.
Weather Station	Temperature, Wind Velocity, Pressure, Humidity etc.	Improve monitoring by replacing failure-prone equipment and cabling with wireless measurements.

3.5.4 Wireless radiation monitoring

In the previously mentioned paper by Jiang et al. also WSN based radiation dose monitoring case study was described as well as multiple studies related on radiation monitoring including one case on application of a wireless system to acquire data on the condition of the nuclear waste in a sealed underground nuclear repository. In the dose monitoring study ZigBee based devices were used and all readings are reported to the team leader, who assumes the responsibility of taking necessary actions to ensure the safety of everyone in the group. The measurements are also simultaneously forwarded to a control station for further analysis. [13]

Various other solutions for using wireless equipment to measure radiation in or in the perimeter of NPPs has also been published.

Jemimah Ebenezer et al. describes in the Deployment of Wireless Sensor Network for Radiation Monitoring at Kalpakkam nuclear complex, India. System is comprised of 17 snesor nodes, 29 router nodes and 1 basestation. Zigbee has been reported to be used as for the wireless communication. [14]

S. Deme et al. describes already in 2003 of portable standalone radiation monitoring system using a gamma dose-rate detector equipped with solar cell and rechargeable battery and a radio modem for wireless communication in PAKS NPP in Hungary. [15]

Wireless radiation measurement in the plant perimeter is also used in some of the Nordic nuclear plants, e.g. in Olkiluoto.

3.5.5 Seismic Monitoring System for Nuclear Power Plants

Seismic Monitoring System (SMS) for Nuclear Power Plants is need to be able to recognize and mitigate potential effects of an earthquake. In the Geosig SMS Ambient vibration testing in the system is optionally offered fully wireless. System also includes the option to retrieve common time from the GPS satellites wirelessly. [16]

Similar wireless time synchronization utilizing GPS-grade time precision is also used in some of the Nordic NPPs in some other applications.

In the Ignalina Nuclear Power Plant (INPP) in Lithuania, a seismic early warning system was installed for a nuclear power plant already in the year 1999. The values measured by the field SMS seismometers were combined into data packets, which were transmitted to the power plant by radio communication using Ultra High Frequency (UHF) band. [17]

3.5.6 Ultra Wide Band (UWB) transmission pilot at the MIT research reactor

For any wireless applications, Nuclear Power Plant is electromagnetically relatively harsh environment due to heavy constructions including thick metallic and concrete installations. To tackle this issue F. Nekoorag et al. has studied the possibilities of Ultra-wideband (UWB) technology use in electromagnetically harsh environments. Secondly they present a novel UWB remote powering scheme that allows for battery-free operation of sensors to increase their lifetime. And finally they present the experimental results of piloting the UWB signalling at MIT research reactor. [18]

They state that UWB technology studied can offer key benefits to the existing and next generation nuclear reactors by providing firstly secure, reliable data transmission with high bandwidth in harsh metallic and obstructive environment of nuclear reactors without interfering with legacy radio signals. And secondly remote powering to some of the existing and/or future sensors to eliminate their need for batteries, or extend the battery life of certain sensors to improve efficiency. For the remote powering aspect it is clearly stated that the main difference between UWB and narrowband signals is the fact that after overcoming the diode drop, narrowband signals do not have enough power left to remotely power any electronics circuit from a far distance. However, for the same average power, UWB signals are capable of powering electronic circuits from a farther distance even after compensating for the voltage used in diode drop. [18]

The pilot tests performed in electromagnetically harsh environment at MIT research reactor used UWB transmitters in various challenging locations inside the equipment room and a receiver placed inside the control room with closed door, receiving temperature data. In between there was roughly 1,2 meters thick concrete wall and heavy metallic channel in the equipment room, including a fully closed metallic door. The tests showed that UWB signals propagated through heavy metallic and concrete structures. [18]

3.5.7 Pilot for a NPP Wireless emergency response system (ERS)

G.-S. Son et al. describe how the Fukushima accident effected on wireless communication application development in certain field in Korea. A study was conducted on wireless emergency response system (ERS) with mobile control station (MCS) placed 30km away from the plants. In the terrestrial communication system, the system is designed based on the IEEE 802.11. and according to the tests it is shown that the requirement of bit error rate (BER) of 10^{-6} and throughput of 1Mbps can be sufficiently satisfied with the setup. The maximum data capacity of the terrestrial communication system is 16Mbps. and as they are designing this system for 12 NPPs located near each other the data capacity per a plant is 1.3Mbps. This means that video signal transmission with this system is not possible but they also mention that it could be possible with more advanced wireless technologies e.g. 802.11n which supports higher throughput. [19]

3.5.8 WSN for Temperature and Humidity Monitoring in a Nuclear Facility at Sadhana loop, India

D. Baghyalakshmi et al. describe a wireless sensor network (WSN) implementation, where continuous monitoring of temperature and humidity are performed in the Sadhana loop, which was commissioned at the Indira Gandhi Centre for Atomic Research (IGCAR). Sensors were installed in the chimney outlets and inlets in various heighs and monitored in the lower level control room of the plant. In house developed WSN node is operating at 2.4 GHz ISM band. [20]

3.5.9 EPRI project - Distributed antenna systems in NPPs Catawba Nuclear Station U.S.

An article in the Nuclear Energy Insider mentions an EPRI research project, which has created a combination of point-source antennas and radiating cables to build up a distributed antenna system to support voice communications, equipment monitoring, and other new technologies that the industry is adopting. With the distributed antenna system, wider coverage and greater penetration of wireless signals can be provided. System has been installed at the Catawba Nuclear Station, U.S.

In the article is it also brought out that in addition to deploying wireless sensors and automated monitoring, nuclear plants can reduce labor costs and optimize maintenance with effective digital tools and resources for workers. With 3-D graphics technology, EPRI is developing interactive applications that can be loaded on a laptop as well as interactive PDFs with embedded videos and animations. [21] [22]

3.5.10 IAEA CRP project - Application of Wireless Technologies in Nuclear Power Plant Instrumentation and Control Systems

IAEA launch a Coordinated Research Project (CRP) I31028 based on the recommendation of the Technical Working Group on Nuclear Power Plant Instrumentation and Control on 12/2014. Project is researching battery operated devices, wireless systems in the electrically noisy environment of a nuclear power plant. The scope of the research will cover issues including: electromagnetic compatibility, cybersecurity, reliability, transmission delay, cost, issues surrounding deployment of additional sensors on existing network infrastructure, communication spectrum management, power and cabling concerns, etc. Participating countries are: Canada, China, Egypt, France, Hungary, Italy, Pakistan, Republic of Korea, Russian Federation and United States of America. Project is expected to end in 12/2018. "The results of this CRP are planned to be published in a Nuclear Energy Series report when the work of the CRP is completed. The report will include all of the results achieved during the course of this CRP and will serve as a source of information to support the application of wireless technologies in nuclear power plants in the IAEA Member States". [23]

3.5.11 Emerging ICON-project - Design of a wireless nuclear control system, UK

Altran, Moltex Energy and the University of Bristol announced in their press release in January 2018 that they were awarded UK funding to design a wireless nuclear control system. ICON (Intelligent Control for efficient Nuclear applications) research project will explore the feasibility of designing a nuclear control system using wireless technology. Project is starting in 2018 [24].

3.5.12 Nuclear decommissioning - Wireless applications in Sellafield and Magnox UK

Tom Nobes and Chris Murphy describe in their paper UK Nuclear Industry First Wireless Applications, how modern wireless instruments were installed in the Sellafield and Magnox to aid monitoring during plant closure. In the decommissioning phase new control and instrumentation is needed and wired installations would be costly and time consuming to implement.

In Sellafield new wireless steam measurement equipment was installed to provide more data than the original legacy instrumentation could provide. Originally only pressure was measured but in the decommission preparatory phase also temperature was going to be measured. For later phase additional measurements were planned for further flow measurements, the monitoring of relief-valve and steam-trap positions and some vibration monitoring.

In Magnox wireless applications included temperature monitoring of a reactor pile-cap crane, wind speed and air humidity monitoring, the monitoring of surface rainwater drainage and collection in sumps and bunds and fire alarm communications to remote buildings. Also a feasibility study for off-site plant monitoring, temporary wireless monitoring of defueled reactor's legacy thermocouples and wireless SCADA (i.e. on a tablet computer) for mobile plant monitoring was under consideration. [25]

3.5.13 Use of robotic techniques in NPPs

OECD's R&D and Innovation Needs for Decommissioning Nuclear Facilities report handles several topics concerning research and development needs in the decommissioning and also general NPP phases. These include complex autonomous wireless networks for hazardous environment monitoring and response and use of robotic techniques in NPPs.

The use of robotics can reduce exposures to workers by having the operator control the device from a safe distance, which makes them appealing to be used in the hazardous areas. Robots can be used in the decommissioning phase or in an accident recovery, like they were used e.g. in Three Mile Island, Chernobyl and Fukushima. This OECD report presents several robot cases and also analyses the research needs concerning robotics in nuclear. [26]

4 Wireless applications in other industries

Other industries refer in this report context all other industries outside of nuclear industry. As the industries outside of nuclear industry have already adopted the wireless systems into use, vendors for sensors, networks and other equipment provide countless amount of wireless solutions to practically every imaginable problem. Carsten Maple has collected in his article "security and privacy in the internet of things" published in the Journal of Cyber Policy a long list of IoT domains and their key applications collected from several other published papers. Some of these are picked in the following Table 4 [27].

Table 4 IoT domains and sample applications

Domain	Applications
Transportation and logistics	assisted driving, environment monitoring, augmented maps, autonomous vehicles, smart parking, intelligent traffic systems, supply chain monitoring, autonomous ships, drones
Healthcare	tracking, identification and authentication, data collection, sensing, health monitoring, assisted living, tele healthcare, smart hospitals
Industry	supply chain management, transportation, condition based management, M2M systems, indoor locations, Virtual Reality (VR) and Augmented Reality (AR) based maintenance, robots
Energy	smart grids, tank level monitoring, smart meters, M2M
Smart cities	Smart parking, structural health, noise urban maps, smartphone detection, electromagnetic field levels, traffic congestion, smart lighting, waste management, smart roads, smart homes
Environment	environment monitoring, meteorological station networks, smart water, forest fire detection, earthquake early detection, landslide detection, snow level monitoring, flood monitoring and control
Agriculture	Green house monitoring and control, smart farms, offspring care, animal tracking, toxic gas level monitoring

ISA wireless architecture for industrial internet of things promotion document lists 250 major companies, who have been involved in defining the ISA100 Wireless standard. These include both the technology providers as well as the technology users of the wireless systems. The same document lists also as an example list of applications, where the ISA100 wireless has been used:

- Machine health monitoring
- Basic process control
- Monitoring of well heads
- Remote process monitoring
- Leak detection monitoring
- Diagnosis of field devices
- Condition monitoring of equipment
- Environmental monitoring
- Tank level monitoring
- Gas detection
- Fuel tank gauging
- Steam trap monitoring
- Open loop control
- Stranded data capture

Various market research estimates predict huge increase in the amount of installed wireless industrial IoT units and the market value of them. Estimates vary being in 2016 or 2017 between ~580 million USD up to ~3795 million USD and the value is expected to be double till 2023. Producing an exhaustive list of all existing wireless applications from various industries would end up to a huge list, so instead of long lists, we have described how various industry fields are using wireless technologies in their operations in the following sub-sections.

Emerging 5G wireless technology promotes that it will enable a fully mobile and connected society by addressing a broad range of use cases and business models. Proposed Use Cases cover all industry and consumer sectors including massive scale industrial IoT and ultra-reliable low latency services [28].

4.1 FACTORIES

Wireless technologies are becoming ubiquituous in factories, allowing for better monitoring and control of the processes as well as production automation. With self-organizing networks, where each device acts as an data source and/or connector, the reliability of communication is greatly improved (no single point of failure, automatic rerouting around the obstruction/block). Either a WirelesssHART or WiFi standards are used for creating a plant wireless network, usually connected with data centers for measurement data integration, analysis, and process control. To prevent wireless eavesdropping and other external attacks, all data transmissions are robustly encrypted with provision for user authentication. Another application of wireless technologies is the location tracking. It can be used to improve the operational efficiency (tracking the assets) of security (tracking the personnel). Technologies used for location tracking include WiFi, RFID, GPS, and UWB, depending on the particular needs and restrictions. Finally, for personnel communications, voice over WLAN (VoWLAN, VoIP) as well as cellular networks are dominating technologies.

4.2 MINING INDUSTRY

Nowadays, the mining industry is increasingly network reliant in order to improve efficiency and safety of its underground operations. Wireless sensor networks are implemented for condition monitoring (temperature, humidity, gas detection), and thus they aid to prevent accidents. Reliable voice communication and location tracking are valuable for operational efficiency improvement and are indispensable in case of emergency rescue incidents. Variety of proprietary systems are on the market, often providing integrated solutions for all these services. [29][30][31] Although they differ in implementation details, they usually rely on similar set of wireless technologies. [32]

One option for underground communication is the so-called leaky feeder, in which a set of long cables are entering the underground and running along main corridors. Connected to the transmitters, these cables with accompanying signal amplifiers act both as signal conveyors and long antennas. Such systems usually operate at VHF (~150MHz) or UHF (~450MHz) bands. Another option is a robust mesh network with wireless communication between nodes and terminal-to-node. These networks can either rely on UHF or WiFi (with VoIP) technologies. Medium frequency (MF) communications systems, typically operating at ~500kHz are also used. At these frequencies, the radio signals couples onto metallic conductors like pipes or power lines, which can easily extend its working range upto kilometres without a need for a repeater or amplifier. However, the MF radios and antennas are considerable larger and heavier than VHF/UHF/WiFi radios and thus usually limited in to use as secondary (redundant) communications system or a system used for emergencies. Through-the-earth (TTE) communication technology relies on low frequency signals (<10kHz), which can propagate hundreds of meters through the earth. However, the practical antennas are much smaller than a wavelength limiting its efficiency. Given the constraints on antenna size, signal power, message size (very low bitrate) and delivery delay, the use of TTE systems is limited to emergencies. In rescue operations, the emergency services can also rely on TETRA systems.

Another application of wireless technologies in mining industry is location tracking. This is especially important in case of emergency. The nature of this application calls for an improved RFID version with active tags to extend the reading distance. The readers are installed at certain locations, and miners wear tags that transmit a unique identifier. Alternative option is the reverse RFID with large number of tiny low-power tags installed at fixed known locations, and the readers integrated into miners’ radio communication terminals. Location tracking is also possible by measuring the received signal strength by the communication nodes at fixed, known locations (reference) and comparing with other nearby nodes. This can be performed in either UHF or WiFi networks.

Wireless sensor networks used for condition monitoring are usually based on RFID and/or WLAN technologies. However, sometimes the operation conditions require customized solution. For example, low frequency (125kHz) inductively coupled wireless communications can be used for data transfer from buried sensors [33].

Finally, the personnel at the surface are able to use alternative communications means, and cellular networks (LTE) are becoming an integral part of the complete ICT solutions [31].

4.3 TRANSPORT

Wireless technologies are widely used in transportation providing means to improve the efficiency (fleet management, traffic aware navigation), safety (remotely controlled traffic lights and signs, emergency alerts, accident location detection), and passenger experience (real-time informations, internet access). Depending on the type of transportation different applications and underlying technologies are used.

4.3.1 Maritime

Wireless technologies used in maritime transportation can be divided into two location scenarios: harbour and open sea. In a harbour, many technologies can be used such as ZigBee and WiFi for sensor networks, WiFi and WiMAX for other data transfer (including internet access for passengers), RFID for identification and location tracking of either personnel/equipment or shipment containers, cellular networks for voice and data transfers, TETRA for personnel communication, as well as VHF, UHF and satellite communications with ships [34].

At open sea, there is no coverage of typical cellular networks, therefore the communications links are limited satellite systems (long range ship-to-ship and ship-to-shore super-high frequency (SHF) and SATCOM), commercial satellite (e.g., INMARSAT B), UHF/VHF line-of-sight (LOS), HF extended line-of-sight (ELOS), and high-frequency (HF) beyond line-of-sight (BLOS). Satellite communication can provide high-bandwidth but at high delay and high costs (due to costs of launching satellites into orbit and required stabilizers for on-board antennas). On the other hand, VHF/UHF links have small capacity and cannot support high data rate applications. Therefore, multiple attempts are made at developing maritime wireless mesh networks (MWMNs) with ships, buoys and land stations forming the nodes to convey the communications [35]. MWMNs can be based on the abovementioned technologies, but also new alternatives such as WiMAX in the sub-GHz bands released after migration from analogue to digital terrestrial TV (especially 698-862MHz, but possibly also 450-470MHz). Naturally, the ships can also be (and ususally are) equipped with satellite positioning/navigation systems such as GPS or GALILEO.

4.3.2 Aviation

Multiple wireless technologies are inherently supporting the airport operations, depending on the application. Passengers are naturally provided with access to cellular networks and WiFi for typical voice and data communication. However, a lot more technologies are used for airport management and basic operations.

TETRA-based systems for high-reliability ground personnel and safety communication, which provide consistent coverage for high-density, high-volume voice and data communications with no single point of failure [36].

VHF AM multimode radio and UHF digital radio for ground-to-air communication. These radios provide excellent audio and RF performance in tough electromagnetic environments, VoIP, AM and FM modulation, remote control via simple network management protocol (SNMP), and high mean time between failures (MTBF).

RFID, super-sensitive GPS and/or real-time locationing system (RTLS) enable accurate location of a vehicle, mobile personnel and equipment, which is crucial for efficient management of resources, access, incidents and service disruptions.

Some airports adopt optical wireless communication either as additional means for data transfers or a backup solution to their cable system. The optical approach has a number of advantages such as immunity to radio noise, interference, interception. It can provide a very high bandwidth (tens of Gbps) over a long distance (several km) [37]. However, these systems require a direct line of sight, and their performance can somewhat be degraded by atmospheric conditions (very strong sunlight, , fog, rain, snow, dust/smog or refractive index variations due to e.g., engine exhaust).

4.3.3 Land transport

Land transport probably makes the widest use of wireless technologies, many of which are contributing to the so-called intelligent transportation systems (ITS). The applications may include navigation (GPS, GALILEO, Glonass), traffic signal control systems, container/vehicle fleet management systems, variable message roadsigns, automatic number plate recognition for surveillance or electronic toll collection (also, WLAN sensors network or RFID can be used), speedmeter cameras (radar) or security CCTV systems, automatic emergency calls (cellular networks), passenger infotainment systems, vehicle-to-vehicle (radar, lidar for e.g., collision avoidance) and vehicle-to-infrastructure communications (traffic intensity measures, congestion warnings, weather monitoring information).

While personal and business applications may rely on the public communications services (GPS, cellular networks, municipal WLAN/WMAN), authorities and safety agents (controllers, maintenance and security staff) need also additional means for reliable communication, especially in case of railway and underground (metro) transportation. The widely used technologies are TETRA, and Dedicated Short-Range Communications (DSRC). DSRC is based on IEEE 802.11p amendment to the 802.11 (WLAN) standard operating in licensed (dedicated) frequency band of 5.9GHz. Moreover, in Europe there is a dedicated GSM-R band (873-880MHz UL, 918-925MHz DL) of spectrum for railway applications. Nevertheless, rapid development in technology and deployment (coverage) as well as flexibility of cellular communications (4G) make it attractive alternative for railway communication [38].

4.4 EMERGENCY

The emergency services require two types of communications: one-to-one and one-to-many (broadcasting). Depending on the type of emergency event, authorities may need to issue alerts or provide information and instructions to the public concerned. In such situations, one-to-many communications can be provided by special broadcast interrupts on TV, radio, and cellular networks. Also, a specific dedicated info websites can help offload the one-to-one communications traffic with týpical emergency call centers (e.g., 911 in USA or 112 in EU) [39]. Moreover, additional means is needed for the emergency services (police, firefighters, army, medical) to communicate with each other during rescue actions in case of disasters. TETRA is the main type of wireless system at hand, designed specifically for such services, provides point-to-point and broadcasting channels (useful in co-ordinating the actions). Also, a satellite communications can be used at very distant locations. For daily routines, however, rapidly developming cellular networks provides the emergency services with sufficient communications means.

4.5 HEALTHCARE

Healthcare domain currently spans over two main environments - patient's home and hospitals. At home, small medical devices can monitor patient's parameters (blood pressure, glucose/insulin or cortisol level, heart rate, physical activity, etc.) usually using Bluetooth for sending the data to the computer or mobile phone for either a local analysis or to convey it to a doctor at remote location. Hospitals, on the other hand, are much more complex environments. RFID and NFC technologies are used for identification and location tracking of equipment (IV pumps, respirators, wheelchairs, etc.) or personnel (nurses, doctors, guards, technicians, cleaners) as well as for restricted access control [40]. Pagers (also known as beepers), very popular in 1980s and '90s for personnel communications, are nowadays replaced by smartphones. Smartphones and tablets provide instant access to medical records in centralized databases removing the need of manual data inputs and file transports. Room environment conditions (temperature, humidity) can be remotely monitored and controlled using RFID or WiFi networks. Also, patient status is often monitored wirelessly in real-time using Bluetooth or WiFi communications. This allows for automation and optimization of treatment (e.g., drug dosage) while also increases convenience of moving patients around the hospital. These applications of wireless technologies bring however a number of security issues (data confidentiality, possible interference with medical electronic equipment, etc.) and robustness, which need to be addressed [41]. Therefore, medical-grade equipment is subjected to thorough testing and certification.

4.6 OFFICE, HOME & CONSUMER APPLICATIONS

Modern wireless office applications offer a big variety of wireless applications, which have been adopted widely in use across all business areas. They are also used by the nuclear industry in their offices.

Home and consumer segments in the wireless business offer a wide variety of applications. These include home automation, entertainment, wireless control of countless devices as well as personal wireless gadgets and applications. Although from this segment many examples could be picked out, many of them are not designed considering the requirements of the demanding industrial environments.

As the nuclear industry is still taking the first steps in moving to the wireless technology usage, examples from this category are not the primary candidates to be taken into use. However, it is good to follow the progress of wireless applications also in this segment, because in the later phase consumer applications could be adopted with some modifications also by the nuclear industry.

4.7 MILITARY

Military landscape is changing with large-scale troops in open battlefields being replaced by small-scale specialized force deployments better suited for an asymmetric warfare within densly populated cities. These changes call for an unified network-centric tactical communications systems. Historically, technologies for military applications have led the development beyond state-of-the-art, while their commercial adoption has followed (e.g., radars, satellite communications, GPS). In recent decades, however, with reduced military R&D budgets and extremely rapid progress of commercial-off-the-shelf (COTS) technologies (due to economy of scale and growing user demands), it's an opposite situation, and the military solutions are currently adopting COTS technologies [42][43]. Nevertheless, the commercial technologies often need to be altered to meet the stringent performance requirements (security and survivability in harsh environments) of military applications. Stronger encryption algorithms, hardened kernel for Android devices and mobile ad hoc mesh networks are among the possible solutions [44]. Satellite communications for global connectivity, multipoint microwave radios for linking line-of-sight enclaves, WLAN networks for mobile users, and a 100 THz infrared (IR) LAN for short range applications within a shelter are just some examples of the military wireless communications technologies [45]. Another class of military application is a wireless sensor network. With different operation scenarios, a variety of sensors and communications schemes might be applied. Often, however, preferences are on self-organizing networks for their robustness (no single point of failure) and easier deployment (nodes can be dropped from, e.g., a drone). The nodes utilize UWB communications for secure (it is harder to spot and/or jam their signal) and robust operations in opaque environments [46][47].

4.8 SMART CITIES AND SMART ENVIRONMENTS

Digitalization is spreading in to all corners of the cities. Digital applications with wireless communications can be found from vehicles, road network, energy grids, buildings, security systems as well as water and waste management. Together these are considered as Smart City concept and although they are still fractured, tendency is to combine them together as bigger ensembles, which work together interconnected. As the landscape of this field covers so many fields, practically all previously presented wireless technologies can be found from a smart city. Smart city concept also overlaps with several other sectors mentioned here, like transport, emergency, healthcare and office as well as home & consumer applications.

4.9 EXAMPLES OF INDIVIDUAL WIRELESS CASES IN NON-NUCLEAR INDUSTRY

4.9.1 Wireless instrumentation network on the Gudrun platform

Aibel and Statoil designed and implemented a wireless sensor network for the offshore Gudrun Deck. Two options were used for redundancy, although for the implemented WSN was used only for monitoring. Wireless gateways and wireless pressure and temperature transmitters were modelled in the 3D-model to ensure a reliable network. Trial included the study for coexistence of WSN and WLAN. Wirelessly measured parameters were temperature, pressure and vibration and the selected technology was WirelessHART. Experience was reported to show that the engineering methods used during engineering of a wireless network were quite different from traditional engineering methods used during engineering of ordinary hardwired transmitters. [48]

Offshore Gudrun Deck resembles the harsh environment of NPPs with the complex structure and ATEX requirements (EU directive for environment with an explosive atmosphere) among others.

4.9.2 MoDeRn2020 research project for repository monitoring programme

The overall objective of the Modern2020 Project is to provide the means for developing and implementing an effective and efficient repository operational monitoring programme, that will be driven by safety case needs, and that will take into account the requirements of specific national contexts (including inventory, host rocks, repository concepts and regulations, all of which differ between Member States) and public stakeholder expectations (particularly those of local public stakeholders at (potential) disposal sites). [49]

EU commission funded MoDeRn2020 research project topics include R&D on monitoring technologies, including wireless monitoring and demonstration of monitoring technologies at full-scale and under in-situ conditions.

Harsh environment underground resemble the demanding environment in the NPPs and project has also done tests and studies concerning radioactive influence on monitoring.

Predecessor of the projcect was the MoDeRn project funded from the EU Commissions framework 7 programme and its target was to provide a reference framework for the development and possible implementation of monitoring activities and associated stakeholder engagement during relevant phases of the radioactive waste disposal process.

4.9.3 Wireless in Steel, driverless stacker trucks and crab cranes at SSAB

In Borlänge, SSAB Tunnplåt AB runs a 15,000-square-meter warehouse for steel coils in three warehouse buildings. In these warehouses, manually operated forklift trucks were replaced with driverless stacker trucks and crab cranes on the ceiling that use wireless failsafe communication. Both standard communication and safety communication were integrated into the same wireless system using real-time and TCP/IP communication. Navigation of the automated stackers takes place by rotating lasers on top of the stackers, which are in contact with the mirrors distributed throughout the warehouse. [50]

4.9.4 Wireless at Power Plants

Non-nuclear power plants have already adopted wireless technologies into use. Vendors and magazine articles list countless amount of implemented applications.

Article in Power Engineering 2011 lists five case examples of wireless usage in power plants [51]:

- San Diego Gas & Electric wanted to implement a wireless architecture throughout the Palomar Energy Center combined cycle plant to access data that was previously unattainable through traditional wired solutions. Emerson installed five applications of its WirelessHART network, which have been used to provide access to additional plant and process data and helpful in improving operational efficiencies.
- Verizon Wireless deployed BlackBerrys integrated with SAP at a utility's power plant. This capability gave the workforce access to tools leading to increased production.
- A power plant in Europe recently used Honeywell wireless temperature transmitters to measure steam used for heavy oil burners. The transmitters were used to replace a wired solution that would have taken two months to install. The wireless solution, however, took two days to install.
- A Nebraska power plant installed Honeywell wireless technology to monitor its remote oil tanks. The plant is now able to efficiently monitor water runoff where electricity is not available.
- Central Iowa Power Cooperative (CIPCO) collects power measurements each month for both billing purposes and planning initiatives. The cooperative was previously using a process called probing that required field workers to physically collect meter data using an analog phone. The process was costly and time-consuming. CIPCO decided to install Sierra Wireless' AirLink Raven XT solution, enabling remote management, configuration and troubleshooting capabilities. The system has enabled CIPCO to monitor and control its network of wireless gateways from one central location, lowering the total cost of ownership.

Few examples of wireless technology usage picked from various sensor and system vendor reference cases:

- RWE Westfalen power plant in Germany uses an environmental monitoring system measuring temperatures and water levels in the plant perimeter, which is powered by solar panels and transmitted via wireless mesh network using licence free 2,4GHz channel to the plant central system.

- Niederhausen hydro plant in Germany, measures wirelessly water levels in the reservoir as well as flood and ground water pump states, which are wirelessly transmitted to the dam towers, from which the data is further transmitted with wireless SHDSL modems to the plant. Wireless mesh solution is used by the Glendale Power & Water municipal utility located in Los Angeles County, California to collect remotely read 84.000 electric and 30.000 water smart meters remotely.
- Suncor Energy in Canada, uses wireless mesh network for securing refinery operations with access control and video. Network is installed in the middle of metal storage tank farm creating a difficult environment for wireless communications.

4.9.5 Conscious Factory - case Nokia

Nokia is using its own factory in Oulu, Finland as a living lab for Factory of the Future (FoF) and industrial IoT system trials. Wireless technologies used in the concept include narrow band IoT, LTE, WiFi, LoRa and emerging 5G networks. Testers, instruments, sensors, robots and actuators are planned to be connected to the network. Some implemented wireless applications include monitoring of environmental parameters and engineering support in final assembly line using smart wearables.

Path to conscious factory starts from the design solutions enabling automation, intelligent manufacturing and automated assembly, which is supported by automated material logistics. Next steps are the single IoT Use Case implementations, which is followed by the complete IoT platform with big data in the cloud and wireless connectivity. [52]

Requirements of the factory’s wireless systems are ultra-reliability and virtual zero latency, which enables real-time monitoring of sensors and the performance of components, collaboration between a new generation of robots. Additionally wireless connected wearables and augmented reality provide increased productivity and mobility for the workers. [53]

5 Final considerations and future work

5.1 SUMMARY

This report presents a short overview of existing wireless solutions used in nuclear power plants (NPP) and other industries, which could be applicable in the NPPs.

In the second chapter of this study, we have briefly presented the most common radio technologies used across the industries, as they are the most probable candidates to be used also in the NPPs. Nuclear industry want to use technologies, which are mature and well standardized to ensure the reliability and safety of all its operations, so very exotic pilot solutions are probably not seen in the NPPs.

Third chapter presents the wireless application use in the NPPs. First part describes the background and requirements, which is followed by a view of the wireless status in the Nordic NPPs based on interviews with selected personnel. Last part of the chapter presents case examples of wireless applications in international NPPs as examples, which could also be considered to be adopted in the Nordic NPPs.

In the fourth chapter we present the wireless technologies used in non nuclear industries. Wireless use has become mainstream operation in most of the industry fields and equipment vendors and system providers with research communities can offer wireless solution to practically every possible problem. After general use case areas, we present summaries of wireless technologies in various industry sectors, which is followed by some brief individual case examples.

In this concluding fifth chapter, we list reasons why to not use and why to use wireless in the NPPs. Also some proposals for wireless applications to be used in different NPP phases are created. Main emphasis of the recommendations is to the Nordic utilities, as one of the aims of this study is to support the operation of the Nordic NPPs, although these considerations are applicable also in other nuclear plants.

5.2 FINAL CONSIDERATIONS

5.2.1 Reasons not to use wireless technologies in the NPPs

As with all technological areas, also wireless technology has its pros and cons. In literature review it became clear that the major concerns regarding the implementation of wireless technologies in nuclear industry include interference, both electromagnetic and radio frequency interference, cyber security, reliability, compliance with regulatory guidelines, and installation issues such as the coverage of the wireless signal and integration with existing data networks. In nuclear industry the operation environment differs also greatly from quite many other industrial areas due to presence of radiation. This can have a direct negative effect on the wireless component electronics sensitivity and performance [13] [54] [55].

In the following Table 5, we have collected some issues, why wireless applications should not be used in the NPPs. As the trend seems to be that nuclear industry is most likely starting to use wireless in anycase in the future, we have also listed some countermeasures to mitigate these disadvantages.

Table 5 Disadvantages of using wireless applications in NPPs.

Disadvantage of wireless	Issue	Countermeasures
cyber security	Various attack scenarios, which concern both wired and wireless networks.	Follow guidelines and design principles of wireless cyber security experts. Follow guidelines and design principles of military electronic warfare and electronic counter-countermeasures.
information saturating radiowaves	Information is not transmitted via known dedicated cable routes, but information is spread to the whole space and even behind walls.	Design and control appropriate power levels for transmissions. Keep perimeter restricted, where wireless network is covered. Strong encryption of all transmitted data.
eavesdropping	Unauthorized persons can listen and monitor the data transmitted.	Strong encryption of all transmitted data.
unauthorized use	Unauthorized persons can control the systems.	Strong encryption of all transmitted data. Access and user authentication management. Monitor and log access events.
jamming	Blocking or interfering authorized wireless communication.	Use wide spectrum communication (e.g. UWB), frequenct hopping technologies and/or directional antennas. Use mesh network topology in wireless network (network provides several routes for the messages). Keep perimeter restricted.

Disadvantage of wireless	Issue	Countermeasures
		Use tools to detect unauthorized transmissions.
difficult planning	Wired connections are “easy” to plan. Designers have long experience in routing cables. Wireless networks are hard to design in harsh environments.	Model, test and design wireless networks with know principles and modern tools. Utilize lessons learned from other industries.
lower reliability	wireless communication can fail	Carelful planning of the network. Utilize lessons learned from other industries.
lower communication speed	Radio communication is slower than wired communication.	Novel radio technologies provide high speed communication. Many applications do not require massive data transfers, so speed is not a critical issue.
wireless technologies cannot be used	Heavy structures and obstacles for radio wave propagation prevents communication.	Carelful planning of the network. Utilize lessons learned from other industries. Use repeaters and appropriate antennas meant for harsh environments.
interference with other NPP systems	Electomagnetic compatibility (EMC) with other NPP systems is not guaranteed. Old systems are not designed concerning wireless equipment presence. Motors and other electrical equipment generate radio noise, which prevents or disturbs wireless communication.	In the new NPPs plants already in design phase EMC and EMI issues can be take into account. In the old plants: Use low signal levels. Shield and ground equipment. Use exclusion zones, filtering and other EMI protection methods.

Disadvantage of wireless	Issue	Countermeasures
interference with other wireless systems	Using multiple wireless technologies they can interfere and disturb each other.	Careful planning of the wireless system (loacations, transmission levels, coexistence, radio zones). Maintenace of the plant radio frequency table.
energy sources for the wireless devices	Service time for battery operated devices is limited.	Some equipment can use normal wired electrical supplies. When signal cables are not needed, it makes still sense to use wired supply. Energyharvesting for low power equipment. Usage of zeropower or nearly zeropower sensors.
radiation influence	Radiation disturbs the equipment operation or prevents it.	Radiation influences all electronic equipment, wired and wireless. Similar protection against radiation effect can be used. There exists also many areas in NPPs, where wireless applications are feasible and radiation is not an issue.

5.2.2 Reasons to use wireless technologies in the NPPs

On the other hand wireless technologies have been found to be relatively easy to install as e.g. the amount of cabling and needed cabling penetrations are much lower than in conventional technologies. It is also seen that wireless technology can reduce labor costs and optimize maintenance with effective digital tools and resources for workers. [13] [21] [22] [54].

In the following Table 6, we have collected some issues, why wireless applications would be beneficial to be used in the NPPs.

Table 6 Advantages of using wireless applications in NPPs.

Advantage of wireless	Issue	Notes
lower installation costs	No signal cable installation needed. Wireless base stations can be installed in	Cabling costs especially in a running NPP are very high. Hashemian has given an estimate of 2000$ per foot (~6000$ per meter) in his report Nuclear Power Plant Instrumentation and Control [56].
lower maintenance costs	No broken cable repairs needed.	
reduced connector failure	During time, cables and connectors can get damaged.	
rapid deployment	Installing sensors and base stations for communication is fast, when signal cables are not needed between them. No cable routing planning or mechanical work for cable installation needed.	
less or no wires	Signal cables are not needed. Power cables do not require long routes compared to signal cables. In some locations battery operated equipment can be used.	Battery operated equipment can be used for moving terminals and temporary / short period measurements or controls.
increased mobility and collaboration convenience of use	Network can be accessed from various locations, not only from fixed location terminals. Alarms can be transmitted to several locations and terminals, not only to control room fixed terminals.	
better access to information	Information and controls can be accessed everywhere.	E.g. in maintenance work information and support can be accessed wherer

Advantage of wireless	Issue	Notes
		needed with documents and AR & VR solutions.
easier network expansion	It is easy to expand wireless networks with existing equipment, whereas a wired network often requires additional wiring.	
easier network modifications	Without cables, sensors, nodes, terminals and other equipment can easily be relocated.	
security	All communication can be encrypted. Access can be managed and monitored.	
access to difficult locations	Locations, which are hard to reach can be covered with wireless communication. Without wiring more dense measurement points can be created.	
option for guest access	Temporary access can be granted for external maintenance personel.	
new operation possibilities	Mobility and reach of difficult places opens possibilities for novel applications not earlier used in NPPs.	Wireless technologies opens cost efficient ways to implement more dense measurement points than with cabled connections is feasible. Novel measuring e.g. of rotating equipment could be implemented.

5.2.3 Proposals for wireless applications in Nordic NPPs

Like earlier mentioned, Nordic NPPs are old and they have been designed before the era of of industrial wireless technologies. This makes the adoption of wireless technologies harder especially during the normal operation phase.

Olkiluoto 3, which is under construction was also approved for construction with the plans and regulations prior to the wireless use in NPPs, is also relying on wired communication. Same concern applies also to the currently only planned Nordic reactor of Hanhikivi 1. For Hanhikivi 1 there exists the option that atleast some supporting wireless applications could be adopted into use, when the plant has been built, as this will still take some years of time.

For the annual outage phase, some supporting wireless applications could be applied and when the time for decommissioning will be topical, advances in regulation, standardisation as well as in wireless technologies will most likely make it possible to adopt even more wireless solutions into use. Decommisioning phase differs also from the normal operation because it will be active only for a short limited time comparing to the long life time of normal operation.

Some pre-planning of wireless application use in emergency situations should also be considered, as in some emergency situations wireless applications could help to mitigate the damages or faster recovery from the emergency situation. Cables and equipment can be damaged in various accidents and fast setup of wireless systems even for temporary time could help taking the situation back to control.

In the following Table 7 we have collected some proposals of wireless applications, which could be adopted in use in the Nordic NPPs and start the era of wireless in them.

Table 7 Example proposals for wireless applications in Nordic NPPs

Wireless application candidate		Normal operation	Annual outage	Service operation before decommission	Decommission	Emergency
1.	Wireless infrastructure definition and setup	x	x	x	x	x
2.	Radiation monitoring in the perimeter of the plant	x	x	x	x	x
3.	Dosimeter monitoring inside the plant	x	x	x	x	x
4.	Document and information retrieval	x	x	x	x	x

Wireless application candidate		Normal operation	Annual outage	Service operation before decommission	Decommission	Emergency
5.	Augmented reality (AR) / Virtual reality (VR) applications for maintenance	x	x	x	x	x
6.	Movable temporary measurement systems for selected sensors and equipment	o	x	x	x	x
7.	Fixed short range measurements to demanding places	x	x	x	x	x
8.	Movable wireless cameras	x	x	x	x	x
9.	Visual drone inspections	o	x	x	x	x
10.	Drone inspections with carry on sensors	o	o	x	x	x
11.	Remotely operated robots with carry on sensors	o	o	o	x	x
		x - applicable o - optionally applicable				

1. Wireless infrastructure definition and setup

Plans for wireless usage should be done and infrastructure for connecting wireless stations to the control rooms and wired systems implemented. With existence of the supporting infrastructure, adoption of wireless applications is easier.

Some steps to create supporting infrastructure in some of the Nordic plants have already been done e.g. utilizing the old cabled telephone network.

2. Radiation monitoring in the perimeter of the plant

Wireless radiation monitoring system in the plant perimeter is more flexible than cabled one and also easier to expand and maintain.

Some Nordic plants are already using wireless perimeter monitoring systems.

3. Dosimeter monitoring inside the plant

Wireless dosimeter monitoring inside the plant area could provide additional security and early warning of possible problems. Combined with access control, systems, it could also monitor that all persons in areas where dosimeters are required are carrying them.

4. Document and information retrieval

Mobile wireless terminals could be used to retrieve documents and manuals to support maintenance and error diagnostics.

As an enhanced feature, also sensor values could be made visible in the mobile wireless terminal. Pure monitoring would be easier to receive license than possibility to also control the equipment via a mobile terminal.

5. Augmented reality (AR) / Virtual reality (VR) applications for maintenance

Augmented reality (AR) or Virtual reality (VR) applications could be used to support maintenance and diagnostic work, which is used in other industries.

6. Movable temporary measurement systems for selected sensors and equipment

For maintenance and diagnostics, temporary wireless measurement systems would bring cost savings and rationalize the work.

7. Fixed short range measurements to demanding places

New measurements using short range wireless sensors could be implemented into places, which are either hard or impossible at the moment to be measured. E.g. in rotating machines or physically demanding places where cabels are hard or impossible to be installed.

8. Movable wireless cameras

Movable wireless cameras can be used for maintenance, diagnostics and security.

Some Nordic plants habe plans to use moveble wireless cameras.

9. Visual drone inspections

In other industries, flying drones have been used for cost efficient visual structure inspections, which would be feasible also in the NPPs.

10. Drone inspections with carry on sensors

Drones carrying certain sensors in addition to the cameras could be used during the preparation for the decommissioning as well as during the decommissioning phase. They are also applicable in certain emergency cases.

11. Remotely operated robots with carry on sensors

Remotely operated robots with carry on sensors and maybe even onboard manipulators could be considered during the decommissioning phase. It is recommended to read e.g. the OECD report “R&D and Innovation Needs for Decommissioning Nuclear Facilities”, which presents many robotic use cases implemented both for the decommissioning and emergency cases.

5.3 FINAL CONCLUSION

Wireless technology has confirmed its place in non nuclear industries and rapid technological development ensures the increase of various new applications to be taken into use.

Nuclear industry, regulators and standardisation bodies have followed the development and are already on the way to start adopting wireless technogies in to use in NPPs. First wireless trials and pilots have been implemented already several years ago and when regulators and standardisation bodies have created frameworks for the wireless use, adoption of wireless can really start in the NPPs.

Development in the nuclear wireless standardisation and wireless activities in other international NPPs should be followed as especially for the older NPPs successful best practises adopted from other NPPs are the most probable way to start using wireless technologies. An other path to wireless is to create pilots with research communities and partners and seek approval for the new solutions together.

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Appendix A: Nordic NPP interview questions

Interview questions used with the Nordic nuclear plant representatives have been listed below.

Section 1. What kind of wireless technologies do you use in your utility during normal operation? (see also example list on the last page)

1.1 Do you use wireless technologies for audio-visual communications?

1.1.1 What kind of wireless audio-visual communication technologies do you currently use?

1.1.2 What kind of wireless audio-visual applications do you currently use?

1.1.3 Do you have plans to use some new applications or technologies for wireless audio-visual communications in the future?

1.1.4 What kind of new wireless applications would you like to have for audio-visual communications in the future?

1.1.5 Do you see some limitations, restrictions or reasons NOT to use wireless technologies for audio-visual communications?

1.2 Do you use wireless technologies for surveillance?

1.2.1 What kind of wireless surveillance technologies do you currently use?

1.2.2 What kind of wireless surveillance applications do you currently use?

1.2.3 Do you have plans to use some new applications or technologies for wireless surveillance in the future?

1.2.4 What kind of new wireless applications would you like to have for surveillance in the future?

1.2.5 Do you see some limitations, restrictions or reasons NOT to use wireless surveillance?

1.3 Do you use wireless technologies for monitoring and control purposes?

1.3.1 What kind of wireless monitoring and control technologies do you currently use?

1.3.2 What kind of wireless monitoring and control applications do you currently use?

1.3.3 Do you have plans to use some new applications or technologies for wireless monitoring and control in the future?

1.3.4 What kind of new wireless applications would you like to have for monitoring and control in the future?

1.3.5 Do you see some limitations, restrictions or reasons NOT to use wireless technologies for monitoring and control?

1.4 Do you use wireless technologies for large data transfers?

1.4.1 What kind of wireless large data transfer technologies do you currently use?

1.4.2 What kind of wireless large data transfer applications do you currently use?

1.4.3 Do you have plans to use some new applications or technologies for wireless large data transfer in the future?

1.4.4 What kind of new wireless applications would you like to have for large data transfer in the future?

1.4.5 Do you see some limitations, restrictions or reasons NOT to use wireless technologies for large data transfer?

1.5 Do you currently use wireless technologies for other purposes (not mentioned in the earlier questions)?

1.5.1 What kind of other wireless technologies do you currently use?

1.5.2 What kind of wireless applications do you currently use?

1.5.3 Do you have plans to use some new applications or technologies for other purposes in the future?

1.5.4 What kind of other new wireless applications would you like to have in the future?

1.5.5 Do you see some limitations, restrictions or reasons NOT to use wireless technologies for large data transfer?

Section 2. What kind of wireless technologies do you use in your utility during annual outage?

In case there are additional or different use of wireless technologies during annual outage compared to the normal operations, please mention them in this section for each differing sub-section as in section 1.

Section 3. Are there plans made for usage of wireless technologies for decommissioning phase?

In case there are additional or different use of wireless technologies during possibly planned decommissioning phase compared to the normal operations, please mention them in this section for each differing sub-section as in section 1.

Section 4. General questions about and attitudes towards the usage of wireless technology in nuclear utilities

4.1 How does your utility in general consider the usage of wireless technologies in the nuclear utility?

4.2 Do you have knowledge of wireless usage in other nuclear utilities, which could be applicable in your nuclear utility?

4.3 Do you have knowledge of wireless usage in other nuclear utilities, which would not be applicable in your nuclear utility? Why not?

4.4 Do you think there are regulatory restrictions in the use of wireless technologies in the nuclear utilities currently?

4.5 Do you think there will be a) more OR b) less regulatory restrictions in the use of wireless technologies in the nuclear utilities? Do you have additional comments on this issue?

Example list of some wireless technologies supporting the questions

2.2	WLAN
2.3	Wireless sensor networks
2.3.1	Wireless Personal Area Network (WPAN)
2.3.2	Bluetooth, Zigbee, LoRa
2.4	Ultra-WideBand, UWB
2.5	Location, identification and presence
2.5.1	Radio Frequency Identification, RFID
2.5.2	Near Field Communication, NFC
2.5.3	Pseudolites
2.6	2G/3G/4G Cellular Networks
2.7	5G Networks
2.8	Satellite
2.9	TETRA
2.10	DECT
2.11	Legacy Wireless Technologies
2.12	Low frequency Wireless Technologies
2.13	Emerging Wireless Technologies

WIRELESS IN NUCLEAR

This study reveals that although the Nordic nuclear power plants are not yet using very much wireless technologies because they have been built in the time before feasible wireless communication technologies were available, internationally there have been many projects testing and developing wireless technologies for the nuclear power plants.

Projects have been executed both by the research communities as well as technology vendors. Standardisation forums and International Iternational Atomic Energy Agency, IAEA are working on recommendations, which will help the local regulators better to evaluate these new technologies in the nuclear industry context.